ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Halil Yaşar ÜSTÜNEL

MODELING AND SIMULATION FOR MITIGATION OF VOLTAGE SAGS IN VARIABLE FREQUENCY DRIVES

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

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ABSTRACT

MSc. THESIS

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In recent years, with the development of technology, significant progress has been experienced in the industrial field. Although these technological developments provide great convenience in industrial areas, they cause serious increases in the amount of energy consumed. Variable frequency drives are used in order to reduce the amount of energy consumed in industrial facilities. Although variable frequency drives are frequently used, they are extremely sensitive to power quality events. For this reason, the uninterrupted and continuous power supplied to the devices will increase energy efficiency along with the quality in the production process. In the literature, uninterrupted and continuous energy is explained together with the concept of power quality. The deterioration in power quality will adversely affect the production process in industrial facilities. Power quality problems can be basically defined as disturbances in current and voltage. One of the most common power quality problems is voltage sags. Variable frequency drives are adversely affected by these voltage sags. In this thesis, power quality problems occurring in an industrial facility and the effects of these problems on the facility are examined. By evaluating the existing methods in the literature, an active front end and energy storage based method, which is a hybrid method, has been developed and proposed. This proposed study is modeled with MATLAB/Simulink simulation program on variable frequency drives and applied in facility. As a result of this proposed study, all voltage sags that occur are prevented. This method has been found to be 44% more cost-effective than conventional methods.

Key Words: Power Quality, Voltage Sag , Variable Frequency Drives, Energy Storage Based Solutions, Bidirectional DC-DC Converters

ÖZ

YÜKSEK LİSANS TEZİ

DEĞİŞKEN FREKANSLI SÜRÜCÜLERDE GERİLİM DÜŞÜMLERİNİN AZALTILMASI İÇİN MODELLEME VE SİMÜLASYON

Halil Yaşar ÜSTÜNEL

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Son yıllarda teknolojinin gelişmesi ile birlikte endüstriyel alanda önemli ilerlemeler yaşanmıştır. Bu teknolojik gelişmeler endüstriyel alanlarda büyük kolaylıklar sağlamasına rağmen, tüketilen enerji miktarında ciddi artışlara sebep olmaktadır. Endüstriyel tesislerde harcanan enerji miktarını azaltmak amacıyla ayarlanabilir hız sürücüleri kullanılmaktadır. Ayarlanabilir hız sürücüleri sıklıkla kullanılmasına rağmen, güç kalitesi olaylarına karşı son derece hassas bir yapıya sahiptirler. Bu nedenle, cihazlara sağlanan gücün kesintisiz ve sürekli olması üretim sürecindeki kaliteyle birlikte enerji verimliliğini arttıracaktır. Literatürde, kesintisiz ve sürekli enerji, güç kalitesi kavramı ile birlikte açıklanlanmaktadır. Güç kalitesinde meydana gelecek olan bozulmalar, endüstriyel tesislerdeki üretim sürecini olumsuz yönde etkileyecektir. Güç kalitesi problemleri temel olarak akım ve gerilimde meydana gelen bozulmalar şeklinde tanımlanlanabilmektedir. En sık karşılaşılan güç kalitesi problemlerinden biri gerilim düşümleridir. Bu gerilim düşümlerinden ayarlanabilir hız sürücüleri son derece olumsuz etkilenirler. Bu tez çalışmasında, bir endüstriyel tesiste meydana gelen güç kalitesi problemleri ve bu problemlerin tesis üzerindeki etkileri incelenmiştir. Literatürdeki mevcut yöntemler değerlendirilerek, hibrit bir yöntem olan aktif doğrultucu ve enerji depolama tabanlı metod geliştirilerek önerilmiştir. Önerilen bu çalışma ayarlanabilir hız sürücüleri üzerinde MATLAB/Simulink simülasyon programı ile modellenip, gerçek ortamda uygulanmıştır. Uygulama sonucunda oluşan tüm gerilim düşümlerinin önüne geçilmiştir. Bu yöntemin klasik yöntemlere göre %44 daha uygun maliyetli olduğu görülmüştür.

Anahtar Kelimeler: Güç kalitesi, Gerilim düşümü, Ayarlabilir hız sürücüleri, Enerji depolama tabanlı çözümler, Çift yönlü DC-DC dönüştürüler

EXTENDED SUMMARY

In recent years, important changes have occurred in industrial areas under the leadership of important developments in technology. In parallel with these developments, device technologies used in industrial areas are also turning into a more complex structure.

These developments in the industrial field have had a positive effect on the increase in production and cause serious increases in the amount of energy used. The uninterrupted continuation of these developments is closely related to the continuity and quality of the energy supplied to the systems. One of the issues that has been frequently examined with the changes that have occurred in recent years is power quality. As it is known, electrical power consists of current and voltage. The continuity of the systems is closely related to the fact that these two parameters remain within the predetermined limits. Events in current and voltage that affect the normal operation conditions of devices are called power quality problems. As a result of voltage sags, serious economic costs may arise, as well as other problems such as equipment failure and production disruption.

Voltage sags, one of the power quality problems, are a frequently encountered problem. In this thesis study, when the distribution of power quality problems occurred in the industrial facility where the study was carried out was examined, it was determined that the most common problem was voltage sag. In the industrial facility where the study was carried out, in the production section where variable frequency drives are frequently used, serious economic losses are experienced as a result of voltage sags. The main reason for the production distruption was determined as the DC bus voltage of the variable frequency drives going out of the predetermined operation limits. There are various alternatives to eliminate the effects of voltage sags on the DC bus. Feed the variable frequency drives used in production through uninterruptible power supplies was the first solution that came to mind. As it is known, uninterruptible power supplies are not

affected by voltage sags and interruptions, and in this way, it can prevent the system it feeds from being affected by these events. The individual UPS system, which is an uninterruptible power supply-based solution, was another alternative evaluated. However, it was not preferred due to the workload and costs of maintenance activities. For these reasons, solution methods specific to variable frequency drives have been examined. These alternatives are divided into three main groups as driver-based, hardware-based and energy storage-based solutions. In this study, possible alternatives were evaluated and the battery system, which is an energy storage-based solution on the DC bus of variable frequency drives, was preferred. In the implemented system, the DC bus voltage is continuously measured with the help of voltage sensors, and when the voltage goes out of the predetermined operation range, the battery group is activated and it is designed to feed the DC bus of the variable frequency drives with the help of bidirectional DC-DC converter. When the system supply voltage returns to the normal, the battery unit recharges itself via a bidirectional DC-DC converter.

In this thesis, MATLAB/Simulink program was used to simulate the voltage sag events taken in real time with power quality analyzer devices. This program is an effective solution for analyzing the circuit with parameters that provide realistic results. As a result of the field studies, it was observed that the variable frequency drive, whose system was installed, continued its operation without being affected by the voltage sags. Thanks to this system, the effect of economic losses resulting from voltage sags will be eliminated and production will be ensured continuously. When the proposed system is compared with the classical systems, it has been seen that the initial investment cost is 44% more suitable than other methods. In addition, the payback period was calculated to be 1.58 years and it was determined that it contributed 3.11% to the production.

GENİŞLETİLMİŞ ÖZET

Son yıllarda teknolojide yaşanan önemli gelişmelerin öncülüğünde endüstriyel alanlarda da önemli değişimler meydana gelmektedir. Yaşanan bu gelişmelere paralel olarak endüstriyel alanlarda kullanılan cihaz teknolojileri de daha kompleks bir yapı haline dönüşmektedir.

Endüstriyel alanda meydana gelen bu gelişmeler üretimin artmasına olumlu etki yapmış olup , kullanılan enerji miktarında da ciddi artışların yaşanmasına neden olmaktadır. Bu gelişmelerin kesintisiz bir şekilde devam etmesi sistemlere sağlanan enerjinin sürekliliği ve kalitesi ile yakından ilgilidir. Son yıllarda meydana gelen değişimlerle birlikte sıklıkla incelenen konulardan bir tanesi de güç kalitesidir. Bilindiği üzere elektrisel olarak güç akım ve geriliminden meydana gelmektedir. Sistemlerin sürekliliği bu iki parametrenini daha önceden belirlenmiş olan sınırlar içerisinde kalması ile yakından ilgilidir. Akım ile gerilimde yaşanan ve cihazların normal çalışma koşullarını etkileyen olaylara güç kalitesi problemleri olarak adlandırılmaktadır.

Güç kalitesi problemlerinden gerilim düşümleri sıklıkla karşılaşılan bir problemdir. Bu tez çalışmasında incelemenin gerçekleştirildiği endüstriyel tesiste meydana gelen güç kalitesi problemlerinin dağılımı incelendiğinde en çok karşılaşılan problemin gerilim düşümü olduğu tespit edilmiştir. Gerilim düşümleri sonucunda ciddi ekonomik maliyetler ortaya çıkabileceği gibi ekipmanların arızalanması, üretimin aksaması gibi diğer problemlere de sebep olabilmektedir. İncelemenin gerçekleştirildiği endüstriyel tesiste ayarlanabilir hız sürücülerinin sıklıkla kullanıldığı üretim bölümünde gerilim düşümleri sonucu ciddi ekonomik kayıplı duruşlar yaşanmaktadır. Meydana gelen duruşların temel sebebi ayarlanabilir hız sürücülerine ait olan DC bara geriliminin çalışma limitleri dışına çıkması olarak tespit edilmiştir. Gerilim düşümlerinin DC bara üzerinde meydana getirdiği etkileri ortadan kaldırabilmek için çeşitli alternatifler bulunmaktadır. Üretimde kullanılan ayarlanabilir hız sürücülerini kesintisiz güç kaynakları aracılığıyla beslemek akla gelen ilk çözüm olmuştur. Bilindiği üzere kesintisiz güç kaynakları gerilim düşmesi ve kesinti durumlarından etkilenmemekte ve bu sayede beslemiş olduğu sistemin bu olaylardan etkilenmesinin önüne geçebilmektedir. Çalışmanın gerçekleştirildiği tesiste mevcutta bulunan elektriksel altyapı uygun olmadığı için bu alternatif değerlendirilememiştir. Kesintisiz güç kaynağı tabanlı çözüm olan bireysel ups sistemi de değerlendirilen bir diğer alternatif olmuştur. Fakat bakım faaliyetlerinin meydana getireceği iş yükü ve maliyetlerden dolayı tercih edilmemiştir.Bu sebeplerden dolayı ayarlanabilir hız sürücüleri özelindeki çözüm yöntemleri incelemiştir. Bu yöntemler sürücü tabanlı , donanım tabanlı ve enerji depolama tabanlı çözümler olmak üzere üç ana gruba ayrılmaktadır. Bu çalışmada olası alternatifler değerlendirilmiş olup ayarlanabilir hız sürücülerinin DC barası üzerinde enerji depolama tabanlı çözüm olan akü tabanlı sistem tercih edilmiştir. Uygulaması gerçekleştirilen sistemde DC bara gerilimi gerilimi sensörleri yardımıyla sürekli ölçülmekte olup , gerilim daha önceden ayarlanmış olan çalışma aralığının dışına çıktığında akü grubu aktif edilerek çift yönlü DC-DC dönüştürücü yardımıyla ayarlanabilir hız sürücüsüne ait olan DC barayı besleyecek şekilde tasarlanmıştır. Sistem besleme gerilimi normale döndüğü zaman akü grubu çift yönlü DC-DC dönüştürücü aracılığıyla kendini şarj etmektedir.

Bu tez çalışmasında güç kalitesi analizör cihazları ile gerçek zamanlı olarak alınmış olan gerilim düşümü olaylarını simule edebilmek için MATLAB/Simulink programı kullanılmıştır. Bu proğram gerçeğe yakın sonuçlar elde edilmesini sağlayan parametrelerle devreyi analiz etmek için etkili bir çözümdür.Yapılan saha çalışmaları sonucunda sistem kurulumu gerçekleştirilen ayarlanabilir hız sürücüsünün meydana gelen gerilim düşümlerinden etkilenmeden operasyonuna devam ettiği gözlenmiştir. Bu sistem sayesinde gerilim düşümleri sonucu meydana gelen ekonomik kayıpların etkisi ortadan kaldırılabilecek ve üretim sürekliliği sağlanabilecektir.Önerilen sistem klasik sistemlerle karşılaştırıldığında ilk yatırım maliyetinin diğer yöntemlere göre %44 daha uygun olduğu görülmüştür. Ek olarak amortisman süresinin 1.58 yıl olduğu hesaplanmış ve üretime %3.11 oranında katkı sağladığı tespit edilmiştir.

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ABBREVIATIONS

AC	: Alternating Current
ASD	: Adjustable Speed Drive
Ah	: Amper Hour
APF	: Active Power Filter
ANSI	: American National Standars Institute
BIFRED	: Boost Integrated Flyback Rectifier/Energy storage DC–DC converter
CSI	: Current Source Inverter
DC	: Direct Current
DVR	: Dynamic Voltage Restorer
D-STATCOM	: Dsitribution Static Compensator
EPDK	: Energy Market Regulatory Authority
EMI	: Electromagnetic Interference
HB	: Half Bridge
HP	: Horse Power
IEC	: International Electrotechnical Comission
IEEE	: Institute of Electrical and Electronics Engineers
IGBT	: Insulated Gate Bipolar Transistor
ITIC	: Information Technology Industry Council
IT	: Information Technology
KW	: Kilowatt
NPC	: Neutral Point Clamped
PCC	: Point of Common Coupling
PI	: Proportional Integral
PLL	: Phase Locked Loop
PQ	: Power Quality
PWM	: Pulse Width Modulation

PU : Per Unit
RMS : Root Mean Square
SMPS : Switch Mode Power Supply
SMES : Superconducting Magnetic Energy Storage
SLG : Single Line to Ground
SOC : State of Charge
SVC : Static Var Compensator
TCR : Thyristor Capacitor Reactor
TDD : Total Demand Distortion
THD : Total Harmonic Distortion
TSC : Thyristor Switched Capacitor
UPFC : Unified Power Flow Controller
UPS : Uninterruptible Power Supply
UPQC : Unified Power Quality Conditioner
VFD : Variable Frequency Drive
VSD : Variable Speed Drive
VSI : Voltage Source Inverter
4L : Four Leg
2C : Two Split Capacitor
1P2W : Single Phase Two Wire
3P3W : Three Phase Three Wire
3P4W : Three Phase Four Wire
I_{SC} : Maximum Short Circuit Current
I_L : Maximum Demand Load Current

1. INTRODUCTION

In this chapter, an introduction to the thesis with its general perspectives, background and research motivation, scope and objectives, contributions and outline are given.

1.1. Background and Research Motivation

Since energy has a wide range of uses from daily life to agricultural activities, from industry to transportation, the need and dependence on energy continues to always increase. According to the data of the International Energy Agency, the change in the distribution of energy consumption by various sectors in 2007 and 2030 is shown in Figure 1.1.

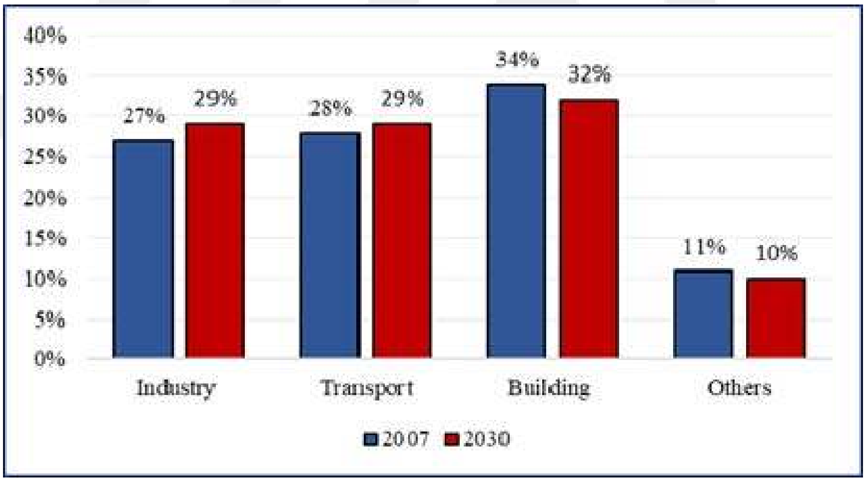

Figure 1.1. Final Energy Consumtion Distribution of Sectors in 2007 and 2030.

As can be seen in Figure 1.1, it is seen that the energy consumption in the industry will increase in the coming years. The recent events in the world, decrease in fossil fuels used as the main energy source and the increasing usage of energy in parallel with the development of the industry have led to the emergence of different approaches. This situation increases the importance of energy and the need for energy is tried to be met with the increase in the use of renewable resources. Figure 1.2. demonstrates the changes in the installed power of the renewable energy source in the last 10 years.

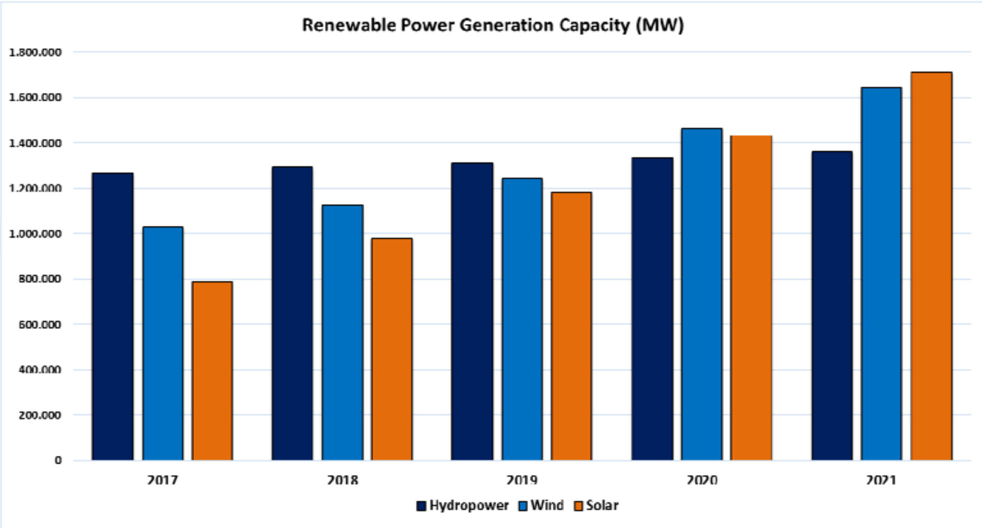

Figure 1.2. Change of the installed power of renewable energy sources (International Renewable Agency)

With the globalized world, trade between countries around the world is accelerating and industrial organizations are in competition with global competitors in every field. The biggest goals of industrial organizations are to use energy in the most efficient way, to reduce energy costs, which constitute a significant part of input costs, and to produce high quality products. In this way, they can contribute to the national economy and compete in the international market. The importance of energy also plays a key role precisely in this competition. For large industrial facilities to contribute to the country's economy, it is extremely important that energy reaches these facilities uninterruptedly and with high quality. At this point, the concept of power quality emerges, and its importance is increasing day by day. Electrically, power is based on the formulation of current and voltage. Simply, power quality can be defined as variations in voltage and current (Bollen, 2001).

According to another definition, power quality can be defined as variations occur in current, voltage and frequency that cause malfunction or improper operation of the equipment of the end user (Emanuel and McNeill, 1997).

High quality electrical power is required for industrial facilities with extremely critical and sensitive processes to operate properly and produce products with certain quality specifications. The industrial facilities have an extremely complex structure, and its sensitivity of components to the electrical events are quite different from each other. The problems that will occur in the electrical power cause the disruption in the production process, loss of production, decrease of income, shorten the life of the equipment, and wasted energy in these facilities. According to a study carried out in 25 countries that are members of the European Union, the annual loss of problems arising from power quality problems is approximately 151 billion dollars, and 90% of this loss belongs to the industrial facilities (Targosz and Manson, 2007).

Power quality problems are divided into various groups such as voltage sag, voltage swell, transients, harmonics, voltage unbalance etc. Voltage sag can be defined as'' is a reduction of voltage or current in rms value at rated frequency to the range between 0.1pu and 0.9 pu and lasting 0.5 cycle to the 1 minute (IEEE 1159-2019). Approximately, 24% of the losses in the study mentioned in the previous paragraph are due to voltage sags (Targosz and Manson, 2007). In this thesis, the adverse effects of voltage sags on industrial facility and the measures taken to eliminate these effects is examined. The most important equipment that voltage sags affect in the facility, where study carried out, is the variable frequency drive. In this study, the methods in the literature are evaluated to prevent the variable frequency drives from being affected by voltage sags, and the application and simulation study of the battery-based solution is carried out.

1.2. Scope and Objectives of the Thesis

This thesis examines the negative effects of power quality problems, especially voltage sag problems, on an industrial facility in detail. In this study, the economic effects of the power quality problems have been examined compherensively. Variable frequency drives are the equipment most frequently affected by voltage sags in the facility where the study carried out. To mitigate this situation, methods to reduce the effects of voltage sags in variable frequency drives have been evaluated and battery-based solution is chosen because of its low investment cost and short payback period. In addition, the method that is decided to be applied was simulated by the MATLAB/Simulink program. The recorded events with the help of power quality analyzers are simulated during the simulation studies and it is determined that the chosen method is not affected by voltage sags. Additively, to reduce energy consumption and develop environmentally friendly systems, during the simulation study, it is tried to integrate the solar energy system to the DC bus of variable frequency drives and positive results are obtained in the simulation results.

1.3. Contributions of the Thesis

This thesis provides the following contributions to the research and application area of mitigation techniques of voltage sags on variable frequency drives.

- The wide literature survey for voltage sags and its effects on the variable frequency drives has been accomplished.
- The economic effects of voltage sags on industrial facilities are explained. The importance of the concept of power quality is once again demonstrated with concrete examples.

- The simulation study of battery-based system is realized, and DC busbar of variable speed drive is protected from the voltage sag.

1.4. Outline of the Thesis

This thesis is organized as follows:

In Chapter 2, classification and description of power quality events, their factors and effects, related power quality standards and financial aspects of power quality events are given.

In Chapter 3, literature review of the devices developed to mitigate the effects of power quality problems and the comparison of these devices with each other are given.

In Chapter 4, the causes, effects, and solution methods of harmonics, which is one of the important power quality problems, are discussed.

In Chapter 5, the effects of power quality problems on industrial facilities and variable frequency drives in these facilities and the solution methods applied in these devices are evaluated.

In Chapter 6, the obtained data with the power quality analyzers of the facility where the study is carried out and the economic aspects of the power quality events of this facility and the methods evaluated for the solution are analyzed.

In Chapter 7, simulation results of the battery-based solution for two events that is taken from the power quality analyzer are given and analyzed. According to the results obtained, it has been confirmed that the proposed method is an effective solution against voltage sags.

In Chapter 8, general conclusions of this thesis work are given and recommendation for the future works is explained.

2. POWER QUALITY TERMS AND ANALYSIS

Thanks to the developing technology and the sensitive equipment brought by these technologies, the concept of power quality has become an extremely important issue todays. There are many various perspectives about the concept of power quality. Briefly, power quality can be defined as the ability of power system to transmission and distribution of electricity to the end users within the acceptable predetermined limits. As it is known, electrical power is based on the calculation that is performed according to the specific formulation of current ,voltage and frequency. In other words, since power quality is closely related to current, voltage and frequency, it can be examined in three basic groups, mainly voltage quality,current quality and frequency quality(Sannino et al., 2003).

Voltage Quality: Electrically, the ideal voltage can be defined as a alternating current waveform with a constant frequency and magnitude. The factors that will cause the voltage to deviate from its ideal waveform are called voltage quality problems. It may also interpret the quality of the product that delivered to end user by the utility side (Bollen, 2001).

Current Quality: Just like ideal voltage, ideal current can be defined as a alternating current waveform with constant frequency and magnitude. The factors that cause the current to deviate from its ideal waveform are called current quality problems. In ideal situation, current must be in phase with the supply side voltage waveform. Since current and voltage are two terms that are extremely closely dependent each other, any deviation of one from the ideal situation will affect the other (Bollen, 2001).

Frequency Quality: Current and voltage, which are electrical power parameters, consist of a certain frequency value.Increment or decrement in the frequency can cause variation of current and voltage. A frequency variation might last anywhere between a few cycles and several hours.

Power Quality: The term of power quality consists of voltag, current and frequency quality. Since the power is formulated according to the relation between voltage, current and frequency, in its simplest form, power quality can be defined as variations in these parameters. (Bollen, 2001).

Since electricity generation, transmission, distribution, and the usage by the end user are closely related, the definitions explained above can be interpreted differently for all elements in these circles. From the point of view of the energy supplier, means that utility side, the concept of power quality can be defined as a voltage of constant magnitude and frequency for 24/7. Due to the various faults, natural events and load characteristics in the electrical power system, deterioration in electrical power quality may occur. The end-user side is another side that uses the power provided by the energy supplier and is most affected by this situation. The deviation of the electrical power provided by the supplier from the ideal situation can cause serious economic and technical problems at the end user side. According to the end user, power quality term can be defined as "any power problem manifested in voltage, current, or frequency deviations that result in failure or misoperation of customer's equipment.'' As can be understood from the definitions, power quality has a various definition according to various perspectives. Because of this situation, there is no agreed and clear definition of electrical power quality. Power quality events that occur both at the end end-user side and on the utility, side are issues that are closely related to each other. These situations affect each other and can cause serious problems. According to a study, 70% of power quality events occur at the end user side, while the remaining part 30% are related to the utility side (Emanuel and McNeill, 1997).

To standardize the definition of power quality, IEEE-1159-2019 Recommended Practice for Monitoring Electric Power Quality standard defines the power quality as'' It is the proper establishment of the conditions necessary for the proper operation of an electrical equipment. (Bollen, 2001 and IEEE 1159-2019). On the other hand, IEC defines power quality as "It is the comparison of the characteristic features of the electrical parameters current, voltage and frequency with a reference value." (Electropedia Web Page).

2.1. Classification of Power Quality Problems

Power quality problems can cause various problems on the end user-side such as equipment malfunction, system synchronization fault, production, and data losses, mainly. In systems with equipment that is sensitive to the power quality problems, some precautions should be taken against these power quality problems. In this part of this thesis, the most common power quality problems are explained in details. In Figure 2.1, power quality problems are shown according to their durations and magnitudes (Dugan R.C and Mcgranaghan M.F., 2012).

Categories of the power quality problems	Typical spectral content	Typical duration	Typical voltage magnitude
1.Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5-ns rise	<50 ns	
1.1.2 Microsecond	1-μs rise	50 ns-1 ms	
1.1.3 Millisecond	0.1-ms rise	>1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	<5 kHz	0.3-50 ms	0-4 pu
1.2.2 Medium frequency	5-500 kHz	20 μs	0-8 pu
1.2.3 High frequency	0.5-5 MHz	5 μs	0-4 pu
2. Short duration events			
2.1 Instantaneous			
2.1.1 Interruption		0.5-30 cycles	<0.1 pu
2.1.2 Sag (dip)		0.5-30 cycles	0.1-0.9 pu
2.1.3 Swell		0.5-30 cycles	1.1-1.8 pu
2.2 Momentary			
2.2.1 Interruption		30 cycles-3 s	<0.1 pu
2.2.2 Sag (dip)		30 cycles-3 s	0.1-0.9 pu
2.2.3 Swell		30 cycles-3 s	1.1-1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s-1 min	<0.1 pu
2.3.2 Sag (dip)		3 s-1 min	0.1-0.9 pu
2.3.3 Swell		3s-1 min	1.1-1.2 pu
3. Long duration events			
3.1 Interruption, sustained		>1 min	0.0 pu
3.2 Undervoltages		>1 min	0.8-0.9 pu
3.3 Overvoltages		>1 min	1.1-1.2 pu
4. Voltage unbalance		Steady state	0.5-2 %
5. Waveform distortion			
5.1 DC offset		Steady state	0-0.1 %
5.2 Harmonics	0-100th harmonics	Steady state	
5.3 Interharmonics	0-6 kHz	Steady state	
5.4 Noching		Steady state	
5.5 Noise	Broadband	Steady state	0-1 %
6. Voltaee fluctuations	<25 Hz	Intermittent	0.1-7 %

Figure 2.1. Power quality problems (Dugan R.C and Mcgranaghan M.F., 2012)

2.1.1. Transients

The term of transient can be used to express an instantaneous and undesirable situation in power systems. In other definition, transients are defined as the bursts of energy which is induced upon power, data, or communication lines. Transients are divided two main categories that is impulsive and oscillatory, respectively.

Impulsive transients can be defined as the frequency variations that occur at a steady state condition in current, voltage, or both, that contains values in either positive or negative polarization (IEEE 1159-2019).

Impulsive transients can be categorized basically according to their rise and decay times. The lightning is the most common cause of impulsive transients. Another cause of impulsive transient is an electrostatic discharge. The sudden electrostatic discharge can affect electronic equipment in bad ways. In Figure 2.2, impulsive transient that is caused by the lightning is demonstrated.

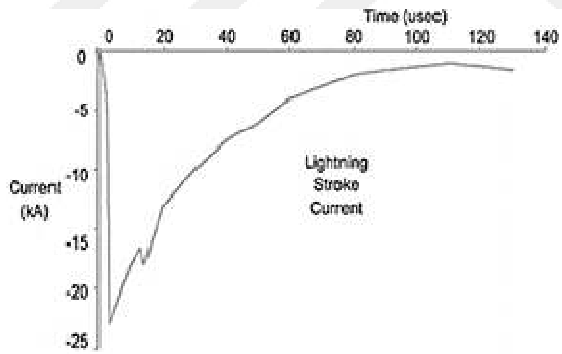

Figure 2.2. Impulsive Transient (IEEE 1159-2019)

Oscillatory transients can be defined as the frequency changes that occur at a steady state condition in current, voltage, or both, that contains values in both positive and negative polarization (IEEE 1159-2019). Oscillatory transients can be categorized basically according to the its predominant frequency, magnitude, and duration. Main causes of oscillatory transient are energization of capacitor bank and transformer ,ferro resonance, back-to-back capacitor switching and cable switching, respectively. In Figure 2.3, oscillatory transient that is caused by back-to-back is demonstrated. (Dugan R.C and Mcgranaghan M.F., 2012).

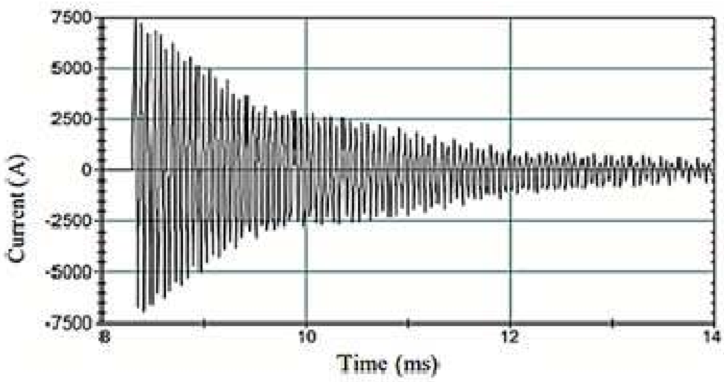

Figure 2.3. Oscillatory Transient (IEEE 1159-2019)

2.1.2. Long Duration Voltage Variations

Long-duration voltage variations involve rms changes at power frequencies which last more than one minute. Long durations variations are overvoltages and undervoltages. As opposed to popular belief, the biggest reasons for the occurrence of overvoltage and undervoltage events are the changes in the amount of load and switching operation in the system.

2.1.2.1. Overvoltage

Overvoltage can be defined as the increment in the effective value of the voltage between 1.1 and 1.2 pu last a period of one minute. The main causes of the overvoltage are activation of capacitor banks, cutout of large loads and incorrect tap changer settings of transformers, respectively (Dugan R.C and Mcgranaghan M.F., 2012).

2.1.2.2. Undervoltage

Undervoltage is defined as the decrement of the effective value of the voltage between 0.8 and 0.9 pu last a period of one minute. The main causes of the undervoltage are deactivation of capacitor bank, activation of large loads, respectively (Dugan R.C and Mcgranaghan M.F., 2012).

2.1.3. Short Duration Voltage Variations

Short duration voltage variations include voltage dips and short interruptions. Based on the event duration, short duration voltage variation is divided into three main groups as instantaneous, momentary and temporary. Short duration voltage variations are related to the system fault conditions. When large loads are energized, high starting currents drawn from the mains or loose wiring are examples of causes of short-term voltage variations.

2.1.3.1. Types of Interruptions

An interruption event happens when the supply voltage of the system drops below 10% of its nominal value for a period not exceeding 1 minute. Power system faults, equipment failures, natural factors (wind etc.) control malfunctions are the main reasons of interruptions. Interruptions are divided into groups according to their durations. Utility protective devices and fault can determine the duration of an interruption at the power system grid. The duration of interruption can be considered as a measure of the closing capability of the protective device. Interruptions may cause data and production loss, tripping of equipment and stoppage of production etc. Momentary voltage interruption is demonstrated in Figure 2.4.

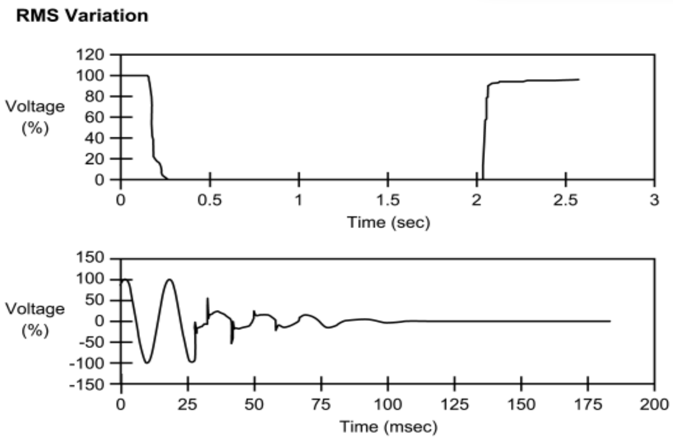

Figure 2.4. Momentary Voltage Interruption (IEEE 1159-2019)

It is observed that supply voltage is 0 approximately 1.7 seconds. In the first graphic of Figure 2.4, RMS variation of the whole event can be observed at the same figure instantaneous voltage variations can be seen from the second graphic.

2.1.3.2. Voltage Sags (Dips)

One of the most popular power quality problems is the voltage sags in modern power systems. Voltage sag can be defined as a reduction of voltage or current in rms value at rated frequency to the range between 0.1 pu and 0.9 pu and lasting 0.5 cycle to the 1 minute. (IEEE 1159-2019). Natural events (lightning), starting of the large induction motor, inrush currents of transformer, switching of large loads, SLG fault are the main reasons of the voltage sags (Farhadi-Kangarlu et al., 2017).

An induction motor starting is the one of the reasons of voltage sags. During the start up period, an induction motor draws 6 to 10 times its full load current These high currents cause voltage sag on the electrical power system. The voltage sag caused by the induction motor is demonstrated in the Figure 2.5.

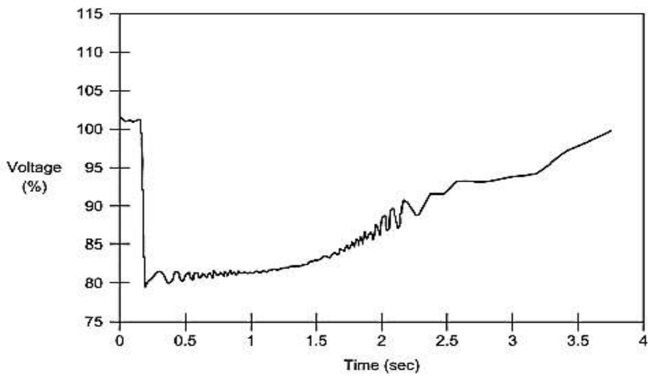

Figure 2.5. Motor starting (IEEE 1159-2019)

2.1.3.3. Voltage Swell

Voltage swell is much less common compared to the voltage sags. Voltage swell is defined as an incrementation of voltage or current in rms value at rated frequency to the range between 1.1 pu and 1.8 pu and lasting 0.5 cycle to the 1 minute. Load shedding and capacitor switching operations, SLG fault and system faults are the main reasons of voltage swells. Overheating and tripping of equipment are the main effects of voltage swell on the system (Cuma, 2010).

Voltage sag and swell are demonstrated in Figure 2.6. This graph is related to SLG fault. SLG faults cause a voltage sag in the relevant phase and a voltage swell in the other two non-faulted phases.

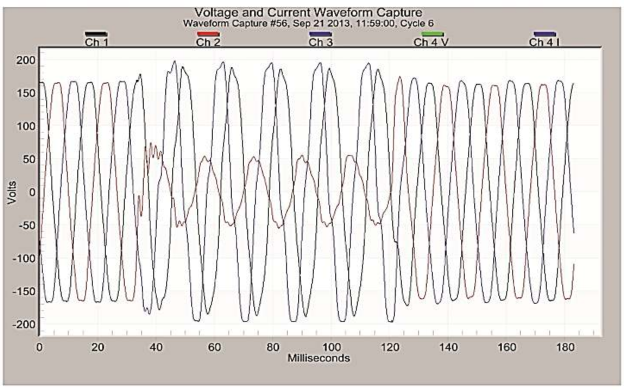

Figure 2.6. Voltage swell (IEEE 1159-2019)

2.1.4. Voltage Unbalance

A three-phase power system is named as balanced or symmetrical if voltages and currents of three-phases have same phase angle and magnitude. If any of this condition is not fulfill, system become unstable or non-symmetrical. Voltage unbalance is defined as a percentage. It is divided into two groups as below 2% (called minor unbalance) and above 5% (called severe unbalance) according to the severity of current or voltage imbalance in the system. The main reason for imbalances below 2% is single-phase loads in three-phase systems. Unbalance also occurs because of a fuse blown in one phase of the capacitor cells in the three-phase system used for reactive power compensation. Severe unbalance may occur single-phasing conditions. Voltage unbalance of the residential feeder is demonstrated in Figure 2.7. (IEEE 1159-2019).

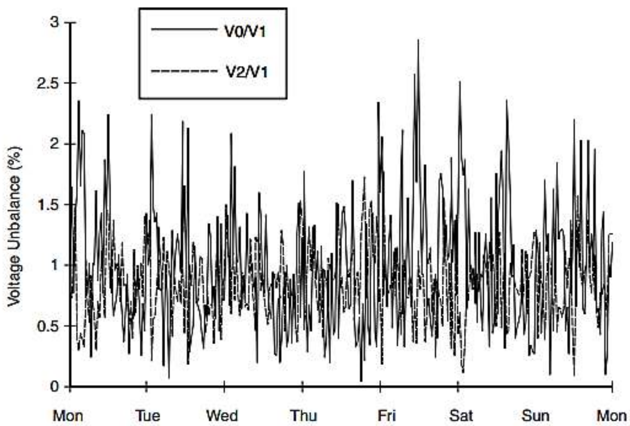

Figure 2.7. Voltage unbalance trend for a residental (Dugan R.C and Mcgranaghan M.F., 2003).

2.1.5. Waveform Distortion

In electrical power systems, fundamental quantities (voltage and current) are expressed as alternating current waveform. Waveform distortion can be defined as unexpected changes in the alternating current waveform, simply. Waveform distortion is divided into four main categories: DC offset, harmonic, notching, and noise, respectively.

2.1.5.1. DC offset

DC offset can be defined as a disturbance in an AC power system manifested by the presence of a DC voltage or current. The main reasons of DC offset are geomagnetic disturbance or rectification process. The DC offset has adverse effects on the system. The DC offset causes additional heating in transformers and causing damage to their insulation. Because of these reasons usage life of transformers is shortened. DC offset also damages the connectors used for grounding (Dugan R.C and Mcgranaghan M.F., 2012).

2.1.5.2. Notching

Notching is a periodic voltage disturbance phenomenon that occurs when current passes from one phase to another phase during the normal operation of power electronic equipment. It repeats itself periodically and has high frequency. Thanks to this feature, it can be evaluated both as a transient event and as a harmonic distortion. During the notch event, current passes from one phase to another, momentary short circuit occurs between two phases. Source inductance, isolation inductance and magnitude of the current are the most important parameters that determine the severity of notch (IEEE 1159-2019).

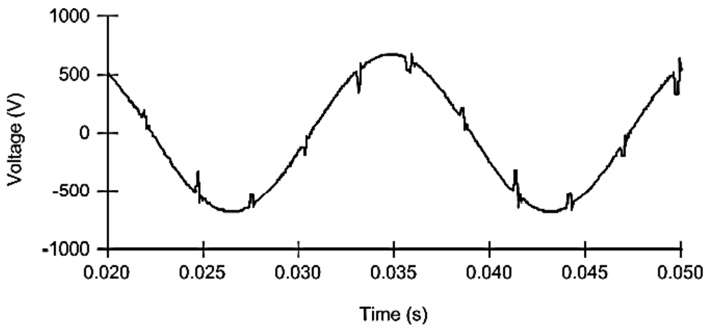

Figure 2.8. Example of voltage notching by converter operation (IEEE 1159-2019).

2.1.5.3. Noise

Noise can be briefly defined as an undesirable electrical problem that has a frequency value of less than 200 kHz where occurs on phase, neutral and signal lines. It is different from harmonic distortion and transient events. Switch mode power supply, power electronic devices, control circuits, solid state rectifiers, and arcing devices are the main causes of the noise problem. It affects the microprocessors, microcomputers, programmable logic devices and electronic control circuits.Noise problem is mitigated by using an appropriate equipment such as filters, isolation transformers, and line conditioners (IEEE 1159-2019).

2.1.5.4. Harmonics

Harmonics can be defined as; a wave whose frequency is a multiple of the fundamental frequency and varies in a sinusoidal form. They produce waveform distortion of the voltage and current waveform. Nonlinear characteristic of loads, switch mode power supplies, rectifiers, rotating machines, variable frequency drives, and distributed energy sources are the main contributor of the harmonics. In recent years, the increase in the usage of power electronics devices has led to an increase in harmonics in power systems. The THD parameter has been developed to measure how much the fundamental waveform is distorted. Current waveform and harmonic spectrum for an VSD input current is illustrated in Figure 2.9.

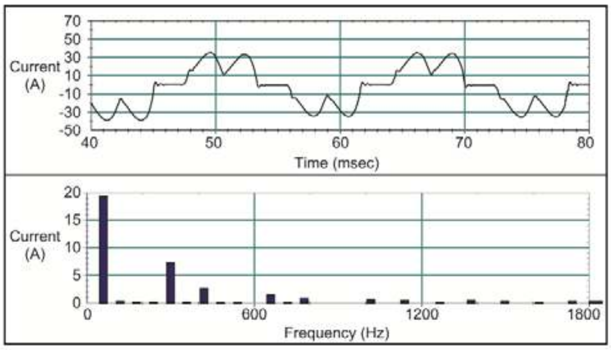

Figure 2.9. Current waveform and harmonic spectrum for an VSD input current (IEEE 1159-2019).

The negative effects of current and voltage harmonics on the system are mainly as increase the voltage drops, waveform distortion, explosion of capacitors, excessive heating of devices, and faulty operation of protection and control systems (Apay, 2008). Power quality problems, their causes and effects are given in the Table 2.1.

Table 2.1. Types of PQ Events

Power Quality Problem	Definiton	Causes	Effects
Voltage Transient	Short duration spikes	Lightining Electrostatic discharge Nonlinear loads Capacitor switching	Insulation damage
Interruption	Loss of power supply	Weather condition Power system faults Fuse blown	Halt of production Data loss
Undervoltage	Reduction of supply voltage less than 0.9 pu	Deactivation of capacitor bank Commisioning of large loads	Effect most equipment
Overvoltage	Increase of supply voltage more than 1.1 pu	Activation of capacitor bank Incorrect tap changer adjustment	Effect most equipment
Momentary Interruption	Short duration power loss	Circuit breaker tripping Bus transfer	Effect most equipment
Harmonics	Distorted waveforms	Nonlinear loads IT & office equipments Distributed energy source	Voltage drops Insulation damage Overheating
Voltage Swell	An incrementation of voltage in rms between 1.1 pu and 1.8 pu	Load shedding Capacitor switching SLG faults	Overheating Tripping
Voltage Sag	An reduction of voltage in rms between 0.1 pu and 0.9 pu	Natural events SLG faults Starting of large motors	Halt of production Data loss
Voltage Unbalance	Ratio of the negative components to the positive componetnts	Unbalanced distribution of loads	Effect most equipment

2.2. Factors of Power Quality Problems

2.2.1. Power electronic devices

Power electronic devices and equipments are used in various applications with its developing technology in recent years. These devices cause non-linear current drawn from the power grid and harmonic distortions. One of the most widely used application of power electronics devices in the industry is variable speed drives. Variable speed drives affect both the power grid and affected from it. The basic working principle of variable speed drive is based on the switching feature of the semiconductor elements. This situation causes the switching harmonics.

2.2.2. IT and Office Equipments

The usage of the IT and office equipment cause the increasing of the third, fifth and seventh harmonics due to the SMPS that contain. The increase in the third harmonics causes an increase in the current passing through the neutral conductor and overheating problems in the transformers and other electrical equipments. SMPS is also used in fluorescent lighting applications which consists of the nearly half of the loads of buildings. To mitigate the effects of third harmonics cross-sectional area of neutral conductor may increase and appropriate filters may be used.

2.2.3. Arcing Devices

Arcing devices are loads that have nonlinear load characteristics and include electric arc furnaces, arc welders and electric discharge lamps. These devices are the main sources of harmonic distortion, and these loads can be represented as a source of voltage harmonics. Since arc furnaces have the feature of operating in various modes, they cause phase imbalances on the system. It is very difficult to reduce these effects on the system. Moreover, arc welders cause transient currents on the system due to their switching feature. In this case, other electronic equipment must be protected from these adverse effects. Also, ballasts which is used to limit the current in fluorescent lamps are also one of the most important sources of third harmonics.

2.2.4. Load Switching

When switching is performed on heavy loads in the system, short-term, high-voltage, low-energy transients are occurred. Other electronic equipment in the system may be affected by these transients. The protection of other equipment can be ensured by means of electrical isolation.

2.2.5. Large Motor Starting

An induction motor draws 6 to 10 times its full load current during start-up. (Dugan R.C and Mcgranaghan M.F., 2012). This start-up procedure will cause a voltage sag until the motor is fully activated in the system. This voltage sag depends on the electrical impedance and the acceleration time of the motor. This event is illustrated in Figure 2.10.

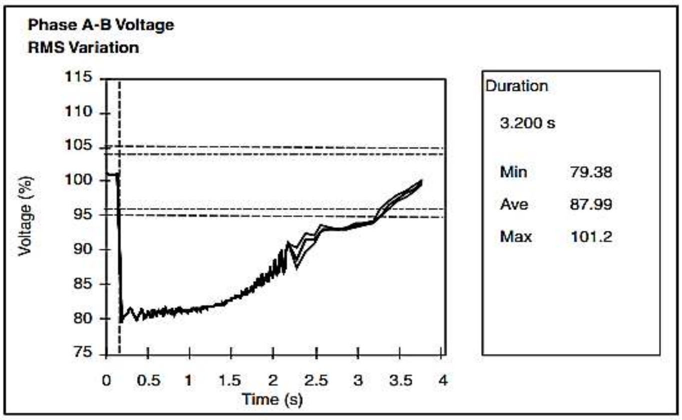

Figure 2.10. Motor starting situation (Dugan R.C and Mcgranaghan M.F., 2003).

It takes a certain time for the motor to reach its rated speed. Because of that reason some measures are taken to minimize the effects of starting of motor. Thanks to the developed starting methods, high currents drawn at the beginning of this start up period can be controlled. Variable speed drives and soft-starters which is developed by means of using power electronics elements such as IGBT, thyristor can control the high starting current. Also, autotransformers, series capacitor and resistors are used to limit the high starting current in old applications.

2.2.6. Environment Related Damage

Lightning strikes are one of the biggest candidates of failure in electrical power systems. Lightning is a potential source of impulsive transients and may cause interruptions depending on where it strikes. Other important factors affecting the occurrence of interruptions are strong storms and winds. Snow also has a severe effect on the overhead lines. Sea mists around the overhead lines can cause of flashover between conductors. To prevent flashover, conductors need to be cleaned regularly at certain intervals. Also, dust and heavy dew can cause similar flashover problems at hot and humidity region. Finally, birds colliding with overhead lines, and tree branches touching live conductors can cause power quality problems such as interruptions (Bayındır 2006).

2.2.7. Capacitor Switching

Capacitor banks are used to compensate the reactive power losses to increase the capability of the voltage and energy transmission of the transmission grid. Figure 2.11. shows the waveform distortion of large capacitor bank energization. It can be understood from Figure 2.11. capacitor energization or switching can cause transient on the waveform.

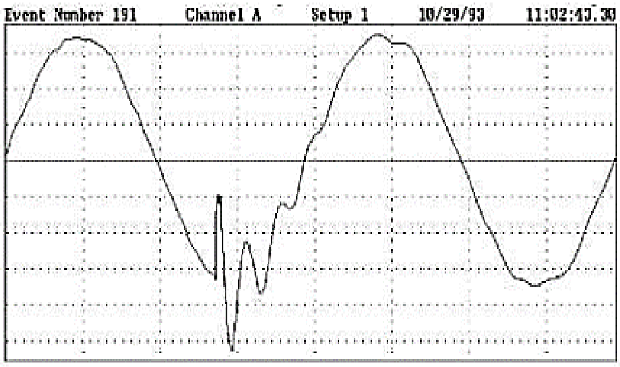

Figure 2.11. Capacitor switching (David Mueller et al.,)

2.3. Power Quality Standars

Various standards have been defined by IEEE, IEC and ANSI to define and standardize electrical power quality and these standards are shown in the Table 2.2.

Table 2.2. Power Quality Standards

Phenomena	Standards
Classification of Power Quality	IEC 61000-4-30-2008, IEEE 1159-2009 IEC 61000-4-4-2012, IEEE 1409-2012
Voltage Sag/Swell and Interruptions	IEC 61009-1-2012, IEEE 1159-2009 IEC 61000-4-7-2002
Transients	IEC C6241-1991, IEEE 1159-2009
Harmonics	IEC 61000-3-14-2011, IEEE 519-1992
Voltage Flicker	IEC 61000-3-3-2008

2.4. Financial Aspects of Power Quality Problems

Deteriorations in electrical power quality cause great negative effects on sensitive equipments and systems. These deteriorations increase the economic losses on the end user side. Voltage related power quality problems especially voltage sags are the main causes of economic losses in industrial facilities. Half of the power quality problem consists of voltage sag and swell events as shown in Figure 2.12.

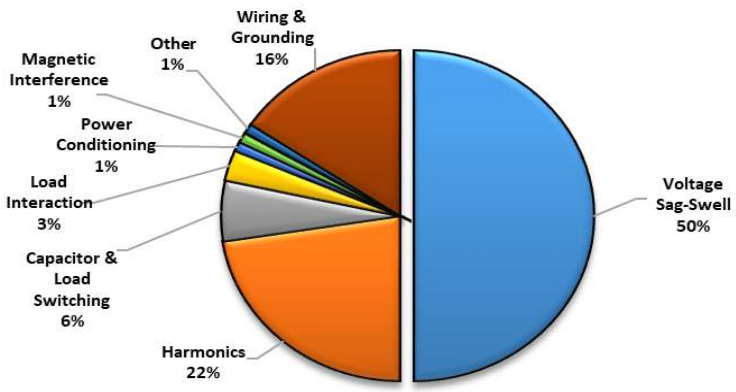

Figure 2.12. Percentage distribution of power quality events (Melhorn et al.,)

One of the most important parameters that affect the economic losses in industrial facilities is the sensitivity and load characteristics of these facilities to the power quality events. The effects of voltage sag-induced losses on the different industries are shown in Figure 2.13.

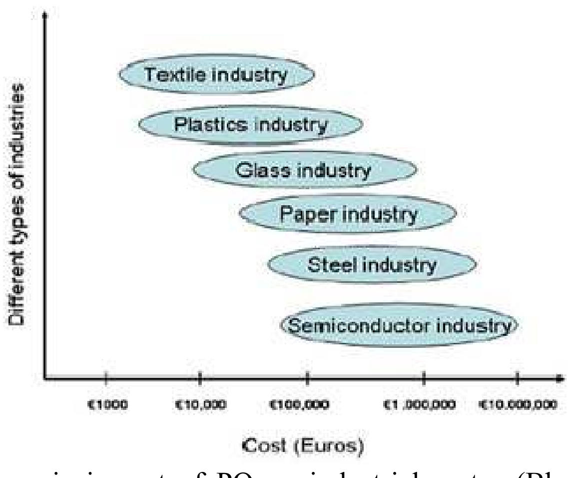

Figure 2.13. Economic impact of PQ on industrial sector (Bhattacharyya et al., 2007).

The effects of voltage sags on the sectors may differ and voltage sag problem constitute a significant part of the losses in these sectors. This situation is depicted in Figure 2.13. Because of the difference of the process stage and sensitivity of these sectors also differ from enormously from each other. For example, when the losses in the textile sector and semiconductor sector are compared, the level of precautions to be taken in these two facilities are different from each other.(Bhattacharyya et al., 2007).According to another research that is named as European Union PQ report, the approximate cost of power quality problems on the countries is € 150 billion per year. The percentage distribution of the € 150 billion cost according to the types of power quality problems is illustrated in Figure 2.14. (Targosz and Manson, 2007).

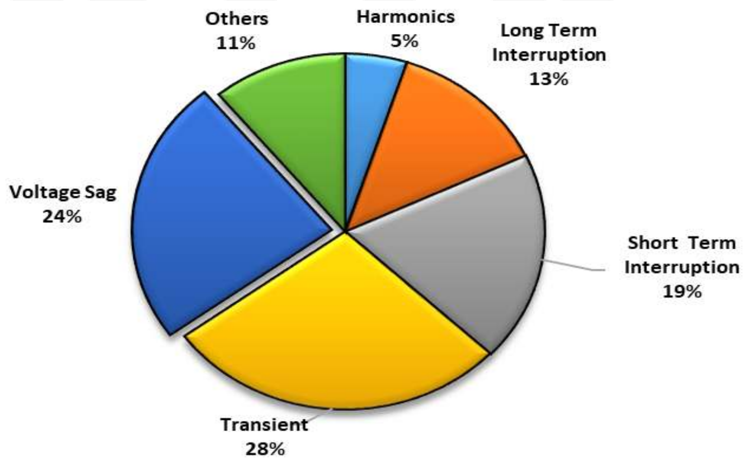

Figure 2.14. Percentage distribution of PQ costs in EU-25 countries (Targosz and Manson, 2007)

When the distribution is analyzed, while voltage-related problems stand out at a rate of about 24%, another important factor is interruptions with a distribution of 32%. Transient and surges consist of the 28% of this cost distribution. As can be seen from the studies carried out, power quality problems have a serious economic impact on countries and industries.

3. PQ MITIGATION DEVICES

In this chapter, devices that is designed to mitigate the effect of power quality problems are given. Uninterruptible Power Supply (UPS), Dynamic Voltage Restorer (DVR), Unified Power Quality Conditioner (UPQC) and Distribution Static Compensator (D-STATCOM) is reviewed.

3.1. Uninterruptible Power Supply (UPS)

The need for continuity of electrical energy and quality in power demand is very important in many critical systems. Sensitive and critical loads such as data center, airline computers, medical systems and communication systems need clean, conditioned, uninterrupted, and undistorted electrical energy due to their nature. These sensitive loads and equipment's are significantly affected by interruptions, sags, surges, overvoltage, undervoltage and bad harmonics. To provide uninterrupted, undistorted, and high-quality power for vital loads uninterruptible power supplies are used in many different applications. In general means, UPS provides a conditioned output voltage with a low total harmonic distortion value and a high-power factor, without being affected by changes in the mains supply. In this chapter, classification, modes of operation, topological classification, and hybrid storage systems of UPS are given.

3.1.1. Classification of Uninterruptible Power Supplies

Uninterruptible power supplies can be categorized three main groups as static, rotary and hybrid UPS systems.

3.1.1.1. Static UPS

Static uninterruptible power supplies are widely used type of the UPS. It is used in a wide range from small power applications to medium and large power applications. Static UPS systems have high efficiency and reliability and low THD value. While there are advantages, static ups systems have some disadvantages. It has low performance with nonlinear loads. In the systems with these loads, the things done to improve the performance of static UPS system cause an increase in the investment cost. Static UPS systems are divided into three main categories as on-line, off-line, and line interactive.

3.1.1.1.(1). Off-line UPS

Off-line UPS systems comprised of battery charger unit (AC-DC converter), static switch, an inverter (DC-AC converter) , battery unit and a filter can be used at the output of the UPS. This filter is used to improve the quality of the output voltage. Off-line UPS systems are also named as standby UPS systems (Kamran and Habetler, 1998) Basic circuit diagram of offline UPS is illustrated in Figure 3.1.

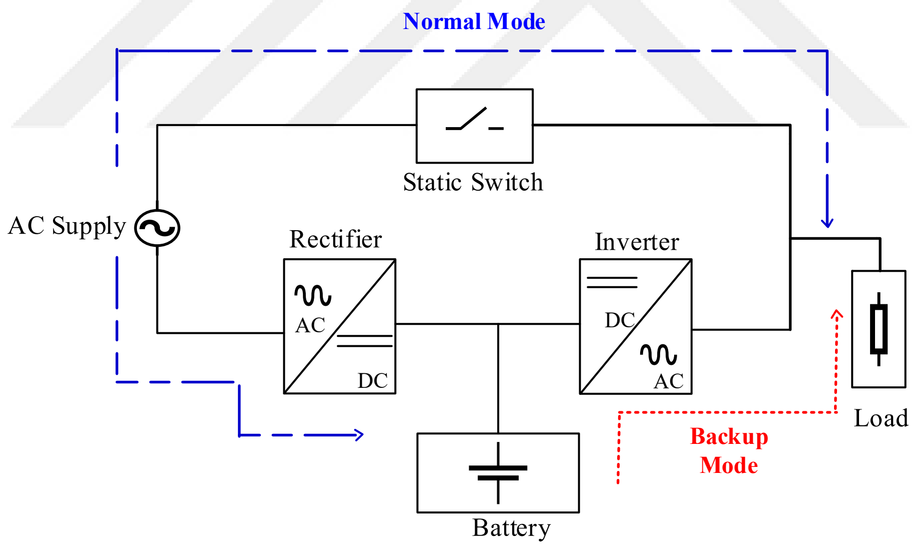

Figure 3.1. Basic circuit diagram of off-line UPS (Aamir et al.,2016)

The mode of operation of off-line UPS is divided into two stages. At first stage, the main supply is not cut off or does not go beyond the predetermined limits means that, when the system is in normal mode and the static switch is in the on position. The inverter is deactivated at normal operation mode. Batteries are charged by the battery chargers during the normal mode of operation. During the normal condition, load is supplied from the grid side. When power failure occurs, the second stage of the operation mode is activated. During this mode of operation, inverter is activated, and load is supplied by the battery units through the inverter. The switching time has great importance to prevent the loads at the output of the system from being affected by the interruption. Simple design, low cost and small dimensions are the positive aspects of the off-line UPS system. The negative aspects of the off-line UPS are the low potential work with nonlinear loads, the lack of isolation between the load and the system, and the long switching time. (Aamir et al.,2016).

3.1.1.1.(2). On-line UPS

On-line UPS systems comprised of battery charger unit (AC-DC converter), static switch, an inverter (DC-AC converter) and battery unit. On-line UPS systems are also named as double conversion UPS systems (Karve,2000). Basic circuit diagram of on-line UPS is illustrated in Figure 3.2.

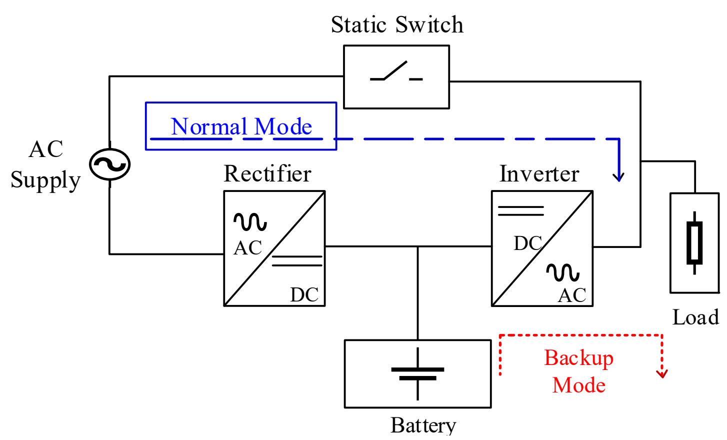

Figure 3.2. Basic circuit diagram of on-line UPS (Aamir et al.,2016)

During the normal mode, load is continuously fed by rectifier and inverter unit. AC/DC and DC/AC conversions are named as double conversion. Simultaneously, batteries are charged by the AC/DC converter to obtain constant DC link voltage to feed the load when power failure occur. When power failure occurs, inverter unit and batteries continue to supply the load by means of battery banks without any outages. Thanks to the inverter, the power free from harmonics is supplied to the output without any interruption on the load side. The main advantages of on-line UPS are that, unlike off-line UPS, there is isolation between the load and the system, and the switching time is very short. Low efficiency, low power factor and high THD value can be considered as the main negative features of these devices (Aamir et al.,2016).

3.1.1.1.(3). Line Interactive UPS

Line interactive UPS systems comprised of, static switch, bidirectional converter/inverter, and battery unit. The battery bank is connected to the load via bidirectional converter/inverter. When the system is in normal mode, grid side feeds to the load and bidirectional converter/inverter charges the batteries.

During the power failure, load is disconnected from the grid supply and load is supplied by the bidirectional converter/inverter. Since the power conversion consist of only one stage efficiency is higher than the on-line UPS system. Another advantages of line interactive UPS are the small dimensions and low cost. On the other hand, the major drawback of the line interactive UPS is that it does not have voltage regulation in normal mode. Basic circuit diagram of line interactive UPS is illustrated in Figure 3.3.

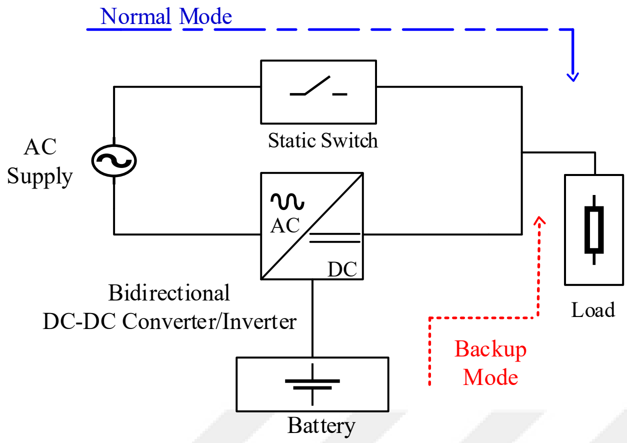

Figure 3.3. Basic circuit diagram of line interactive UPS (Aamir et al.,2016)

3.1.1.2. Rotary UPS

Rotary UPS systems comprised of AC motor, a DC machine, an AC generator, and a battery unit. Basic circuit diagram of the rotary UPS is depicted in Figure 3.4. Electrical machines are mechanically connected. There are two different operating modes in rotary UPS as in static UPS devices normal and stored energy, respectively.

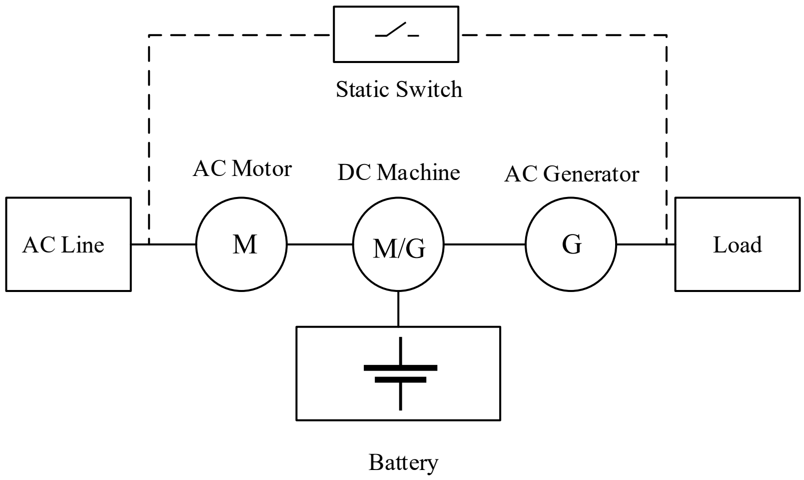

Figure 3.4. Basic circuit diagram of rotary UPS

When the system is in normal mode, grid supplies the AC motor that drives the DC machine. Then the DC machine drives the AC generator connected to it and AC generator feeds the loads at the output. During the stored energy mode, the battery bank supplies the DC machine, which connected to the AC generator. And then AC generator supplies the loads.

3.1.1.3. Hybrid UPS

Hybrid UPS is a combination of static and rotary UPS systems. It comprised of bi-directional AC/DC converter, an AC motor, an AC generator, a battery bank, and a static switch. Hybrid UPS system is appropriate for the high-power applications. Their main advantages are low output impedance, high reliability, and low maintenance requirements (Windhorn,1992). Basic circuit diagram of the hybrid UPS is depicted in Figure 3.5.

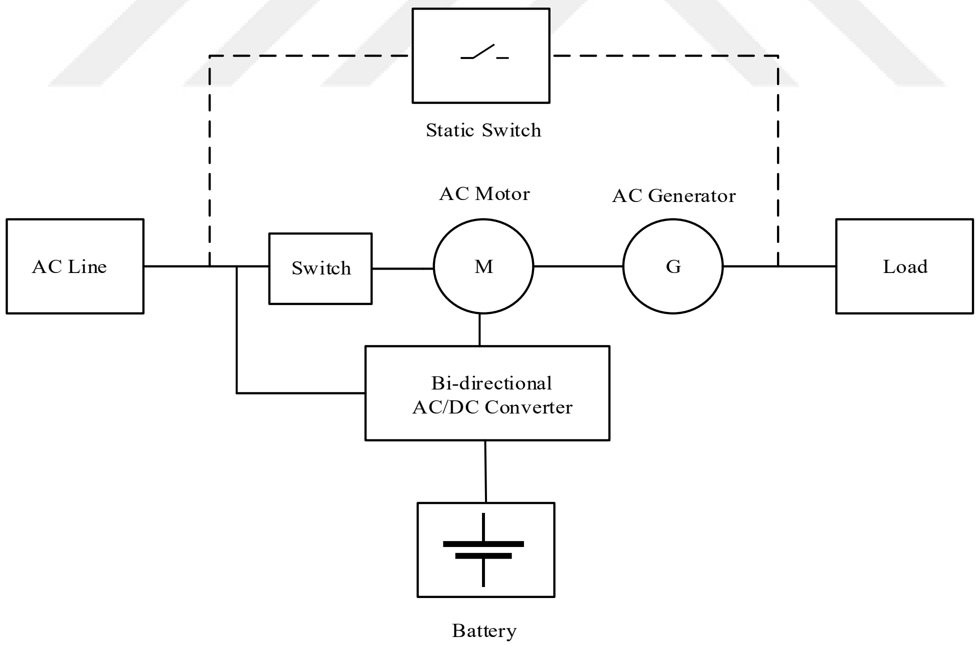

Figure 3.5. Basic circuit diagram of hybrid UPS

3.1.2. Topology Based Classification of UPS

To meet the different applications requirements, uninterruptible power supplies are categorized according to their circuit topologies. The main types of UPS systems are divided into three subcategories transformer-based, transformerless, and high frequency transformer based.

3.1.2.1. Conventional Transformer Based UPS System

Conventional transformer-based UPS systems are comprised of rectifier, an inverter, line frequency transformers, and a bypass circuit. As it is well known, AC voltage is converted into the DC voltage by using the rectifier to charge the batteries and obtain the constant DC link voltage by converting AC to DC. The load group that is connected to the output of the system is fed by the inverter, which converts DC voltage to AC voltage and gives conditioned power to the load group.

As can be seen from the Figure 3.6, there are two power transformers at the circuit of conventional UPS system. The power transformer that takes place at the input side is used to step down the grid voltage to the low voltage of battery unit. On the other hand, second transformer that takes place at the output side is used to step up the battery unit voltage to the grid voltage level (Batteron and Pinhero ,2007).

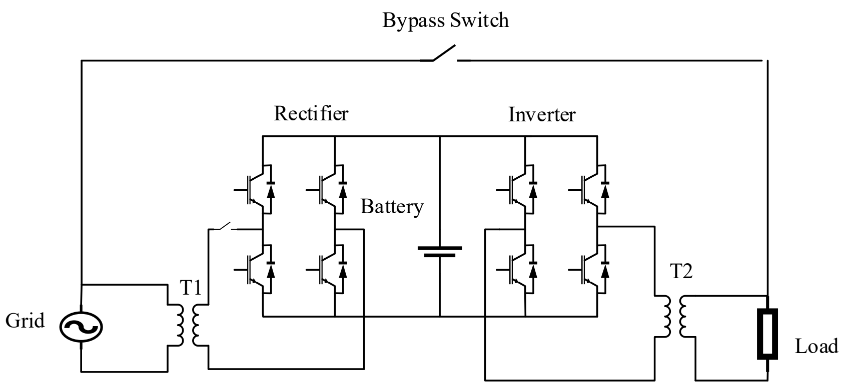

Figure 3.6. Basic circuit diagram of conventional UPS system (Aamir et al.,2016)

It is possible to provide galvanic isolation against transient and spike events that occur in the line side with this topology. By the way, this topology is appropriate for the high-power applications. Due to the two power transformers in the system operate at the grid frequency, it causes an increase in the size and cost of the system to be designed. High current flows in the circuits because of the switches connection to the low voltage side of battery bank and this event causes stress on the switches. Due to this situation efficiency of the system decreases (Aamir et al.,2016).

3.1.2.1.(1). Three-Leg Type Converter

It is possible to reduce the number of switches in the system by using a three-leg type converter. An UPS designed by using three leg type converter is examined in (Choi et al.2005). The first and common leg of the three leg type converter behave like AC/DC converter that charge the battery units. Simultaneously, the common leg and third leg behave like DC/AC converter. The usage of the common leg of the three-leg type of converter increases the overall efficiency of the designed system, as well as reduces the number of switches to be used. Basic circuit diagram of three leg type converter is depicted in Figure 3.7.

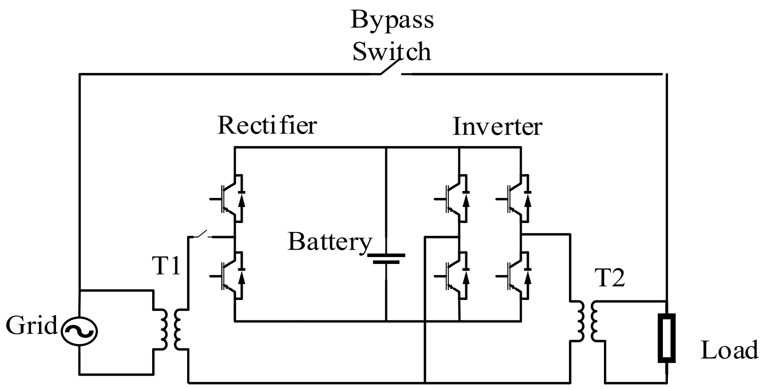

Figure 3.7. Basic circuit diagram of three-leg converter based UPS (Aamir et al.,2016)

At the input and output of the three-leg type converter, there are two leakage frequency transformers. By means of these two transformers system cost can be reduced. Although number of switches are reduced, two low frequency transformer is enhanced overall size and weight of the designed system. There are high number batteries that is connected to the DC link and simultaneously charging, and discharging of these batteries occur. This charging and discharging events can affect the battery life in bad ways (Choi et al.,2005; Chiang and Lee,2000).

3.1.2.1.(2). Single Stage UPS System with Trapezoidal AC Supply

The designed circuit of single stage UPS system with trapezoidal AC supply is very resembling to the conventional UPS systems. Basic circuit diagram of single stage UPS system with trapezoidal AC supply is depicted in Figure 3.8.

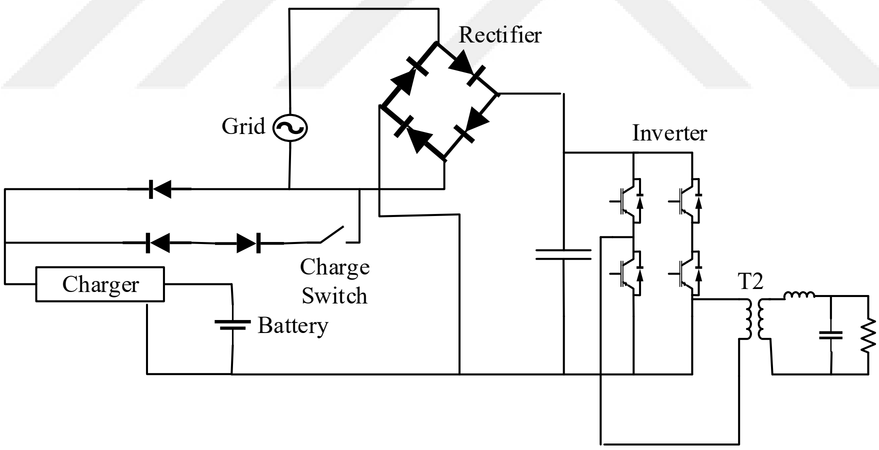

Figure 3.8. Basic circuit diagram of Single-phase UPS system with trapezoidal AC Supply (Aamir et al.,2016)

The main difference of this topology from the conventional UPS system is that the DC link capacitor used in the circuit is smaller and there is no power factor correction circuit. The reason of using a smaller DC link capacitor is to eliminate the current harmonics produced by the inverter is that the trapezoidal output voltage is synchronized with the input supply voltage. As mentioned before, the power factor value is very low due to not using the power factor circuit. Because of that reason UPS system based on this topology is not convenient for high power applications (Jain and Espinoza,1998).

3.1.2.2. High Frequency Transformer Based Topology

Significant developments have been achieved in the semiconductor industry in recent years. With the parallel of the significant developments in semiconductor area, many circuits elements show the almost ideal characteristics. With this development, transformers can be used at high frequency values. The most important advantages of using transformers at high frequency are that they reduce the volume, provide galvanic isolation, and increase the overall efficiency of the system. Although the overall designed system is in reduced size, the installation cost of the system increases and its overall efficiency decreases, due to the large number of switching elements are needed to operate the transformer at high frequency (Aamir et al.,2016).

3.1.2.2.(1). A UPS with 110-V/220-V Input Voltage and High-frequency Transformer Isolation

This UPS system can operate at input supply values between 110 volts and 220 volts. When the system is in normal mode, that is, when the mains input voltage is presence, the chopper circuit converts the AC voltage to DC voltage and transmits high frequency pulses to the primary of the high frequency transformer. To charge the battery units, DC voltage is stepped down by using the high frequency transformer. In the absence of grid power supply, battery bank voltage is stepped up by means of boost converter and transmit to the inverter to obtain regulated output voltage. The basic circuit diagram of described system is depicted in Figure 3.9.

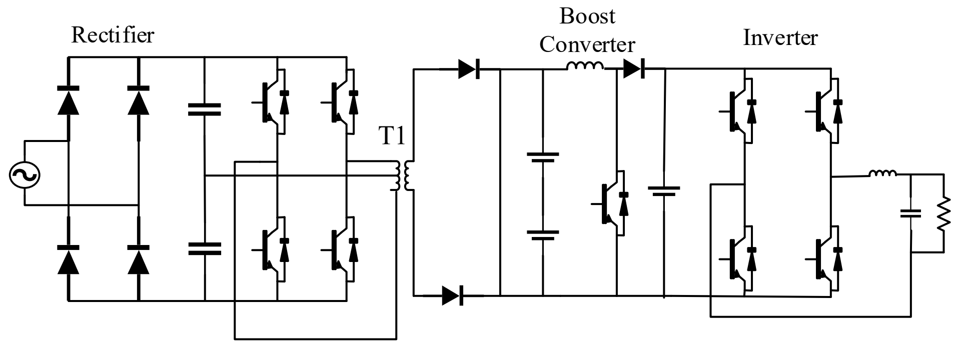

Figure 3.9. A High Frequency Transformer Isolation 110V/220V Input Voltage UPS System (Aamir et al.,2016)

Although the overall designed system is in reduced size, the installation cost of the system increases and its overall efficiency decreases, due to the large number of switching elements are needed to operate the transformer at high frequency. Additionally, power conversion stage increases the complexity of the circuits (Torrico-Bascope et al.,2006).

3.1.2.2.(2). Boost integrated flyback rectifier/energy storage DC–DC converter (BIFRED) Based UPS Topology

Boost integrated flyback rectifier/energy storage DC–DC converter is used in this topology to obtain stable DC link voltage to supply the conventional bidirectional converter that is used for the charging and discharging the batteries. BIFRED converter provides the electrical isolation, advanced power factor correction and increased system size (Nasiri et al.,2008) The basic circuit diagram of described system is illustrated in Figure 3.10.

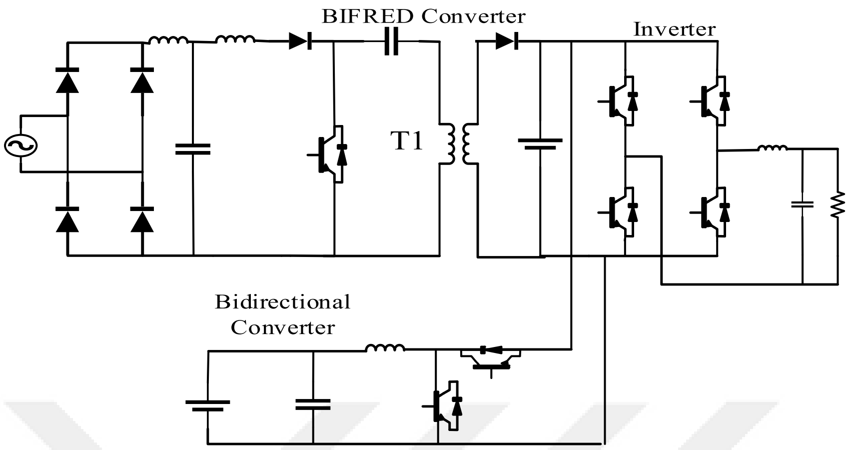

Figure 3.10. Basic circuit diagram of the BIFRED based ups topology (Aamir et al.,2016)

3.1.2.2.(3). Two Stage UPS with High Power Factor Correction

This topology is the combination of a flyback converter and boost inverters. As the name suggests, the system consists of two parts. In the first stage, to charge the batteries, obtain high power factor and high frequency isolation flyback converter is used. The flyback converter is integrated with the battery unit. In the second stage is comprised of the boost inverters. The boost inverter can provide the conditioned output voltage. This proposed topology is not appropriate for the high-power applications due to the flyback converter that operate at discontinuous mode (Vázquez et al.,2002). The basic circuit diagram of described system is illustrated in Figure 3.11.

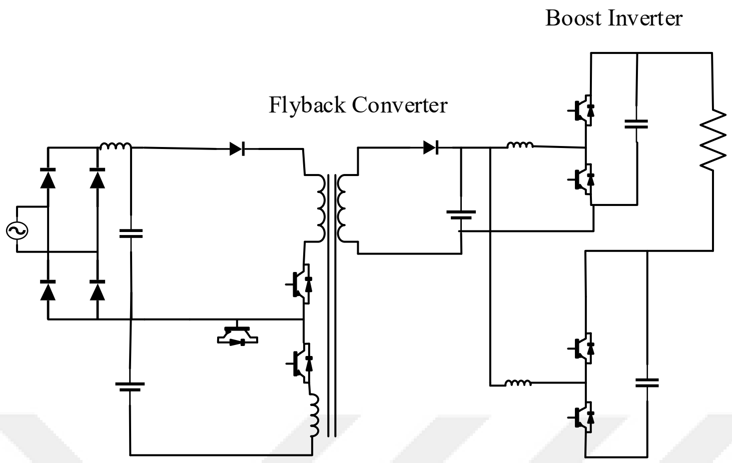

Figure 3.11. Two stage UPS with high power factor correction (Aamir et al.,2016)

3.1.2.3. Transformless UPS Based Topology

Day by day, with the developments in power electronics technology, many new applications are emerging. One of these new applications is the transformerless UPS. Unlike the conventional transformer-based UPS systems, these systems have higher efficiency, smaller dimensions, and economical devices. Although they have many other advantages, these devices are affected by transient and spikes where occur on the power grid. Additionally, to obtain the high DC link voltage, battery unit is consisted of many batteries. This situation leads to increase the battery cost and decrease the reliability of the ups system (Park et al.,2008; Daud et al.,2013).

3.1.2.3.(1). Transformerless UPS with Four Leg Type Converter

As can be seen from the Figure 3.12; four leg type converter behaves as battery charger/discharger unit, rectifier, and an inverter. The common leg of the system is switched at the line frequency, on the other hand battery charger/discharger unit and inverter is switched at the specific PWM signals. Battery unit is charged at the normal mode means that in the presence of grid supply and discharged the absence of the grid power supply (Park et al., 2008).

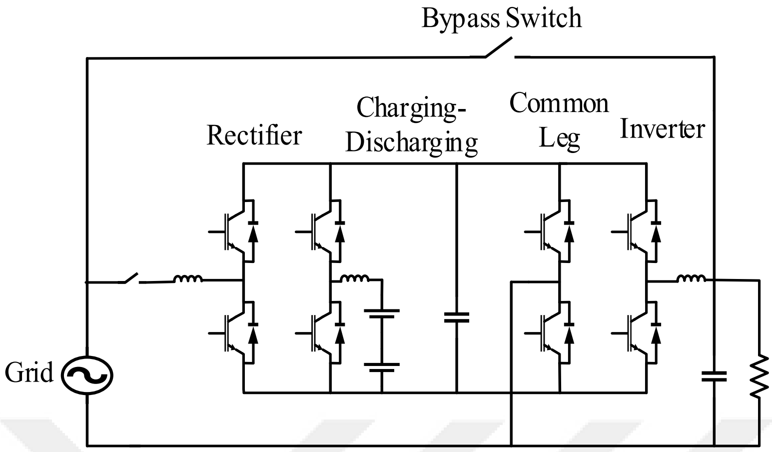

Figure 3.12. Circuit diagram of four leg type converter based transformerless UPS (Aamir et al., 2016)

3.1.2.3.(2). Non-isolated UPS topology with 110/220 V input–output voltage

Non-isolated UPS system comprises a battery charger, three level boost rectifier, and a double half bridge inverter. This UPS system can operate two different voltage level, and it provides two 110V outputs.Basic circuit diagram of non-isolated UPS is depicted in Figure 3.13. (Branco et al.,2006).

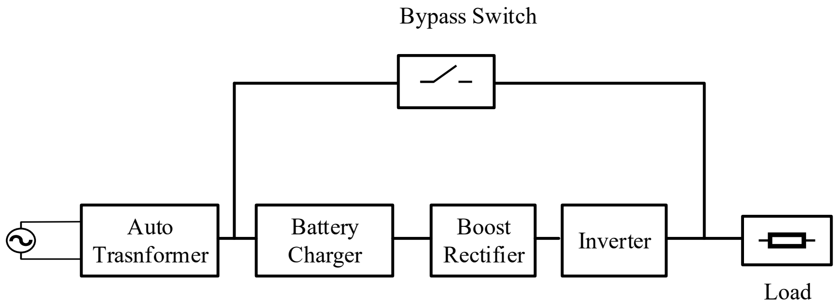

Figure 3.13. Circuit diagram of non-isolated UPS system (Aamir et al.,2016)

3.1.2.3.(3). Z-Source Inverter Based Transformerless UPS System

In Z source inverter-based topology, two power conversion stage is combined. It means that DC-DC step up conversion and DC-AC conversion is achieved in Z source inverter. There is no boost converter to step up the battery voltage level. Basic circuit diagram of Z-source Inverter based transformerless UPS system is shown in Figure 3.14.

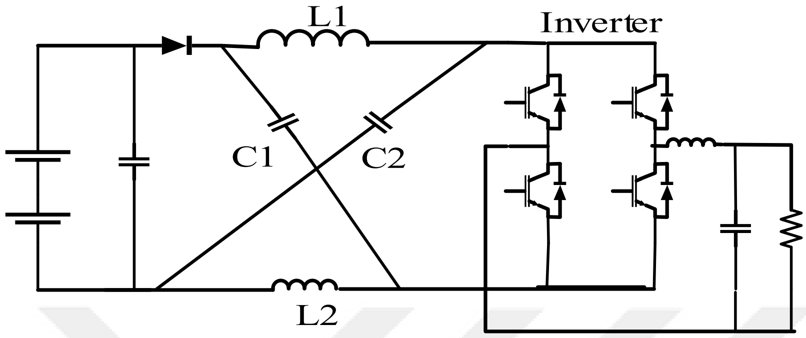

Figure 3.14. Basic circuit diagram of Z-source inverter-based transformerless UPS system (Aamir et al.,2016)

To improve the transient response of the system, dual loop control topology is used. Moreover, AC voltage distortion at the output is reduced significantly with the help of this topology. Z-Source inverter based transformerless UPS topology is particularly appropriate for usage in high power applications (Zhou et al., 2008; Peng 2003).

3.1.2.3.(4). Off-line Transformer-less UPS System

As it is known, UPS systems are basically divided into two basic groups as off-line and on-line. Transformerless topologies are also available in off-line UPS systems. The basic circuit diagram of off-line transformer-less UPS system is illustrated in Figure 3.15.

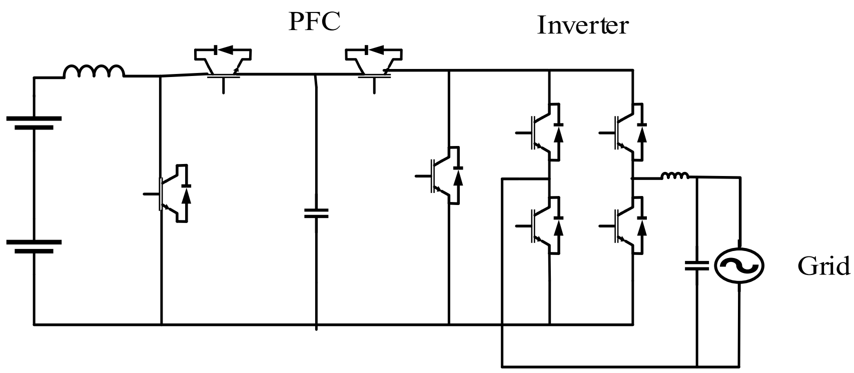

Figure 3.15. Off-line Transformer-less UPS (Aamir et al.,2016)

When the system supply is in the presence, uncontrolled rectifier converts the AC voltage to DC voltage and transmits the DC link. Simultaneously, power factor is corrected at the boost converter. Finally, voltage is stepped down by the buck converter to charge the battery unit. When the absence of the system supply, battery bank voltages step up at the boost converter and inverter converters this DC voltage to the AC voltage and supply the output loads (Marei et al., 2011).

Thanks to power electronics-based circuit elements and positive developments in this field, new technologies have begun to emerge in addition to existing technologies. With the usage of these new technologies, developments have occurred in many products. One of these products is transformerless UPS systems. Unlike traditional transformer UPS systems, transformerless UPS systems provide a smaller size and more economical solution, thanks to the absence of large and heavy transformers. Conventional transformer UPS systems can isolate the loads from faults occured in the mains. The transformer in the system prevents the transmission of transient currents and spikes where occur in the main supply to the DC bus. The opposite of this situation is also true. Not using transformers, which is one of the biggest elements in the system, ensures that transformerless UPS systems are more economical (around 30%). In addition, approximately 50% reduction in sizing can be achieved (Al Dubaikel,2011; Gunes et al.,2009).

3.1.3. Hybrid Energy Storage System for Uninterruptible Power Supplies

UPS systems are designed to provide the necessary energy to the system for a certain period, in the absence of the mains, thanks to the batteries unit. In fact, the most important indicator of the performance of an UPS system can be measured by how much it feeds the loads at the output of the system when there is no power supply in the grid. The inability of the battery units to feed the system for a long time and the chemicals they contain have allowed the emergence of new and advanced technologies. Alternatives of new energy storage applications such as s fuel cells, super-capacitor, and combinations of these are investigated and studied to integrate to the UPS systems. In this section, different energy storage systems and their combination to improve the UPS backup time are analyzed.

3.1.3.1. The Combination of Batteries/Super Capacitor Powered UPS Systems

In cases where the system needs to be fed for a long time, supercapacitors can be preferred due to their long-term energy supply feature. To provide long backup time and high-power, batteries and supercapacitors are combined nowadays. In case of temporary power demand, supercapacitors supply the system, while in cases where more stable power is needed, the batteries are on state. This situation decreases the stress on the battery unit. The installation cost of the supercapacitor-based UPS system is high and to improve the performance of the system, more research is needed (Koohi-Kamali et al., 2013; Kollimalla et al., 2014).

3.1.3.2. The Combination of Batteries/Fuel Cell Powered UPS Systems

The system consists of the fuel cell and battery unit to supply the backup power when the absence of the mains. In this system, when a power failure occurs in the grid, hydrogen gas is directed to the fuel cell. According to the working principle of fuel cells, time is needed to obtain the required voltage. To mitigate the adverse effect of the fuel cell and obtain the required voltage quickly, rechargeable battery or super-capacitor are combined (Tao et al.,2008). This system is named as hybrid UPS systems. The block diagram of the hybrid UPS systems is illustrated in Figure 3.16 and the circuit diagram of hybrid UPS is shown in Figure 3.17 respectively.

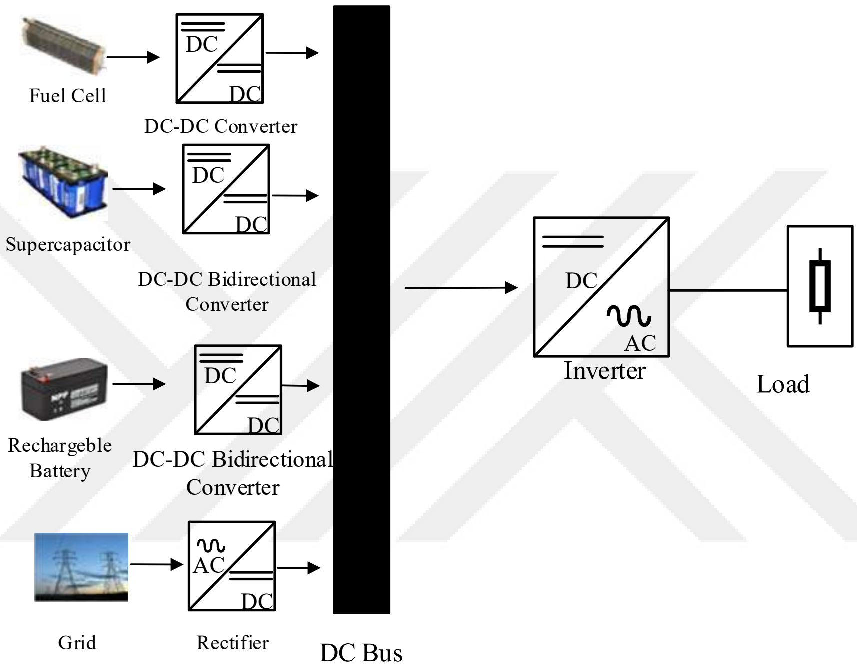

Figure 3.16. Block diagram of hybrid UPS system (Aamir et al.,2016)

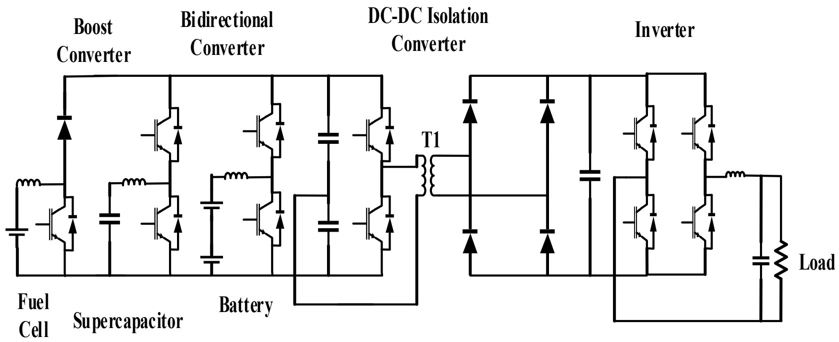

Figure 3.17. The circuit diagram of hybrid UPS system (Aamir et al.,2016)

Fuel cell voltage is stepped up via boost converter. To obtain stable DC bus voltage bidirectional converter behaves as a battery/supercapacitor charger at grid mode and when the mains absence it behaves like a discharger of battery/supercapacitor. Notwithstanding, hybrid UPS systems will find a wide place for themselves soon thanks to their positive aspects. The main disadvantages of the fuel cell system are, high installation cost and vulnerable to frequency ripple. (Aamir et al.,2016)..

3.2. Unified Power Quality Conditioner (UPQC)

As it is well known, the most important APF types used in solving power quality problems are shunt and series active power filters. Shunt APF can cope with current-based power quality problems, while series APF is one of the most appropriate solutions of voltage-based power quality problems. With the development of technology and increased sensitivity of the equipments used to power quality problems have led to an increase in the demand for a higher quality supply voltage and current drawn from the power system grid. APFs are the one of the most effective and suitable solution to these power quality problems. For the solution of current and voltage related power quality problems, the installation of individually power filters into the power system is not a cost-effective solution. To obtain cost-effective solution and mitigate the installation cost of the power quality investment new devices are developed. One of the developed devices are named as the Unified Power Quality Conditioner (UPQC). UPQC consists of shunt and series active power filters that is combined to provide a more effective solution to several power quality problems simultaneously. In this part, UPQC is investigated comprehensively.

A combination of series and shunt APF connected back-to-back with a common DC reactor was created and it was named as line voltage regulator/conditioner. Accuracy of the practical applications of this topology is proved in experimental studies (Fujita et al.,1998). Then, they named this configuration as Unified Power Quality Conditioner (UPQC) and this nomenclature began to be used frequently. The basic circuit diagram of UPQC is illustrated in Figure 3.18.

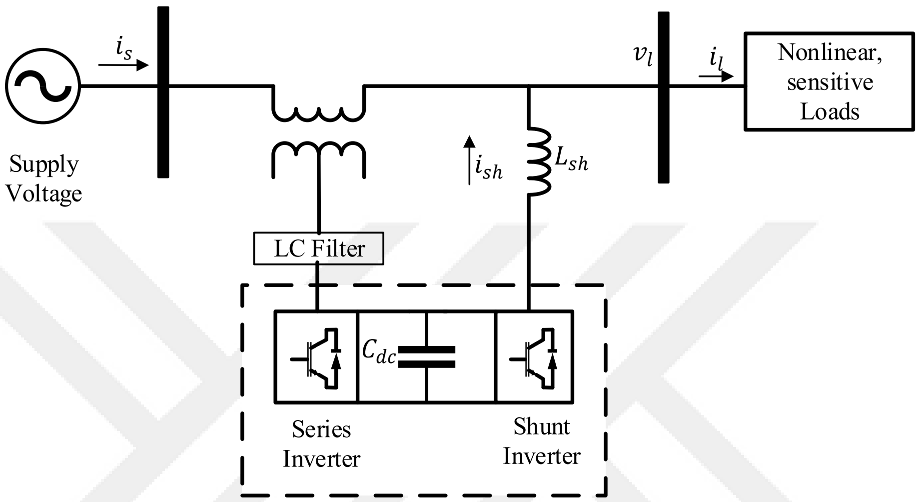

Figure 3.18. Basic circuit diagram of UPQC (Khadkikar,2012).

In terms of its designed structure UPQC has similarity to UPFC in many points. Although both devices have two voltage source inverters that is connected to the energy storage unit, UPFC is applied in power transmission systems, while UPQC is used in power distribution systems to mitigate the adverse effects of power quality problems. Since power transmission systems are generally balanced and harmonic-free, the UPFC only needs to provide balance shunt and/or series compensation. On the contrary, sometimes, power distribution systems contain DC component, harmonic distortion, unbalance, and other power quality issues such as sags, swells, flickers etc. Because of the limited ability to solve power quality problems of UPFC, usage of UPQC is more effective solution to overcome these problems (Khadkikar,2012).

As mentioned earlier, UPQC can solve power quality problems such as sags, swells, imbalances, flicker, harmonics that is experienced in voltage and power quality problems related with current such as current harmonics, imbalances, reactive currents, and excessive neutral currents, simultaneously. As can be seen from Figure 3.18. the main components of the UPQC and their intended usage are explained below.

- ***Series and shunt inverter*** as the name suggest that one of the inverters is connected to the load that act as a shunt APF and the other inverter is connected to the series to the line act as a series APF.
- ***Shunt coupling inductor*** L_{Sh} is used to connect the shunt inverter to the power grid. Additionally, current waveform is smoothed by the shunt coupling inductor.
- ***Common DC link is*** comprised of either capacitor or inductor. As can be seen from Figure 3.18. DC link is consisted of capacitor that is used to connect two inverters and maintain constant DC bus voltage.
- ***LC filter is*** used to eliminate the switching ripple that occur on the inverter output voltage.
- ***Injection transformer*** is used to provide connection between series inverter and electrical power grid. In addition, it provides isolation between the inverter and the electrical power grid.

3.2.1. Classification of UPQC

3.2.1.1. Physical Structure

UPQC, which is planned to be used to cope with power quality problems can be divided into various groups according to their physical structures in relation with certain parameters. The parameters used to decompose the physical structures of UPQCs into groups are as follows, type of equipment used in the energy storage unit, phase number and location of inverters, respectively.

3.2.1.1.(1). Converter Topology

Due to the system design, shunt, and series inverters in the UPQC share the common DC bus. Each inverter in the system has its own specific responsibility. For example, shunt inverter is in charge to set the self-supporting DC link according to the reference value. The UPQC can be improved with using PWM based current source inverter. To form the DC link on the common energy storage unit same inductor (L_{dc}) is used (Singh et al.,1999). The basic circuit diagram of current source based UPQC is illustrated in Figure 3.19.

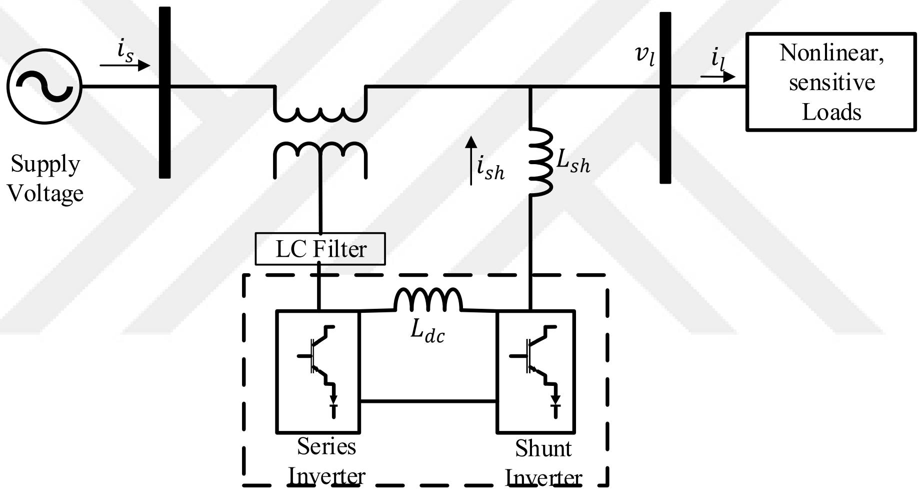

Figure 3.19. The basic circuit diagram of current source based UPQC (Khadkikar,2012).

Because of the high system losses, cost, and inability to use in multi-level configurations CSI based UPQC topology is not preferable in practical application. On the other hand, the UPQC can be improved with using PWM based VSI. To form the DC link on the common energy storage unit same capacitor (C_{dc}) is used. Nearly all the related studies about to the UPQC, VSI based inverter topology is preferred because of the decreased weight, low system cost and ability to be used in multi-level operations (Khadkikar et al.,2011).

3.2.1.1.(2). Supply System

Loads and used equipments in power systems are divided into two main categories, 1P2W and 3P3W or 3P4W according to their supply voltages. To improve the power quality, different UPQC topologies are available and able to be classified according to the supply system feature. There is a similarity between voltage-related power quality problems at single and three-phase power systems. The most common power quality problems in single-phase systems, which have a negative effect on the system, are reactive current and current harmonics. In three-phase systems, except from the ones as mentioned in single-phase systems, the unbalance in the current is a common problem. Additionally, neutral current compensation must be considered when improving power quality in three-phase four-wire systems.

The UPQC topology, which is the most preferred type for power quality improvements in single-phase systems, created using two H-bridge inverters, is given in Figure 3.20. (Chakraborty et al.,2007; Rong et al., 2009; Kolhatkar et al.,2007).

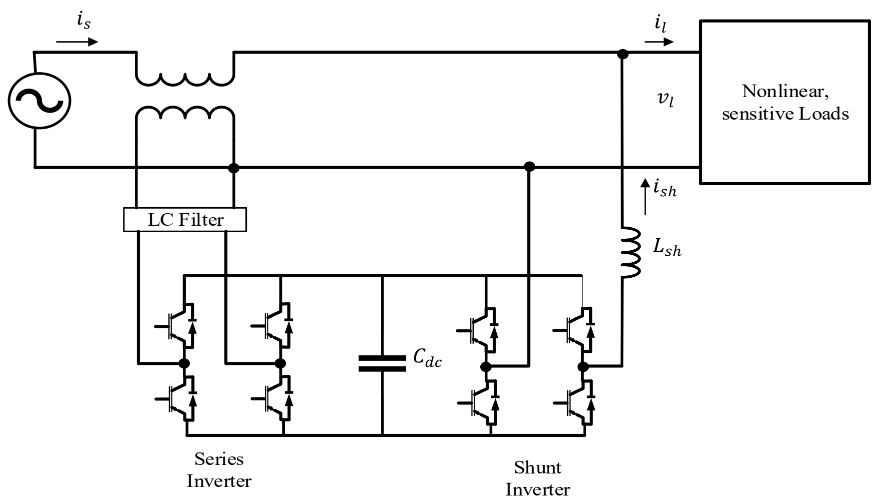

Figure 3.20. 1P2W UPQC: two H-bridge configurations (Khadkikar,2012)

According to the physical structure and voltage sag compensation method UPQC is divided into two main groups as illustrated in Figure 3.21.

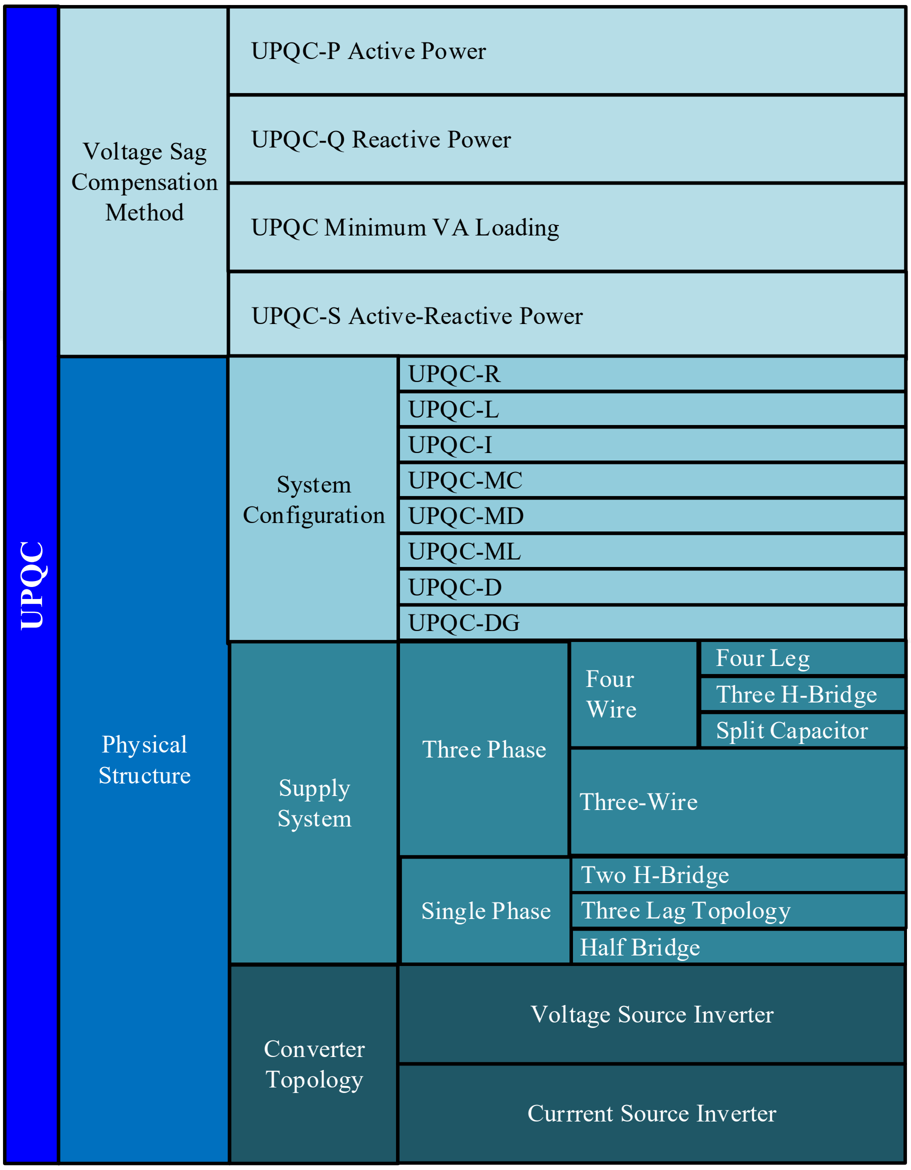

Figure 3.21. Classification of UPQC

To improve the system design and increase its efficiency, different alternatives are studied. The same topology using less equipment is implemented. This topology realized with a total of six semiconductor switches and a total of four semiconductor switches are shown in Figure 3.22 (Nasiri and Emadi, 2003).

In three leg topology, series inverter comprises of two switches named as S1 and S2 and take part on the first leg, on the other hand shunt inverter forms two switch named as S3 and S4 and take part on the second leg.

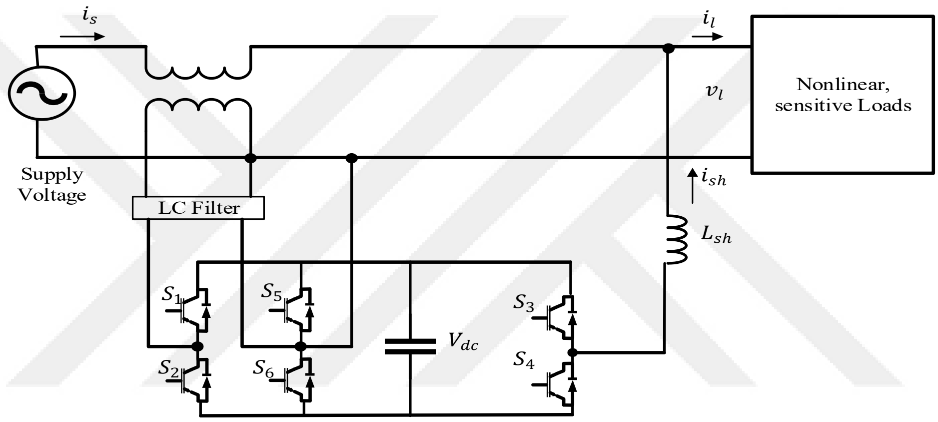

Figure 3.22. 1P2W UPQC: three-leg configuration (six switches) (Khadkikar,2012)

Another topology is used in single-phase systems at UPQC by realized half bridge configuration. In this topology, there is only one leg for two inverters as shown in Figure 3.23. Reducing the number of switches used in the circuit has an impact on the performance of the UPQC. These topologies can be implemented in low power applications with low cost. As can be seen from the Figure 3.23, S5 and S6 switches take part on the third leg that is a common leg and shared by the series and shunt inverters (Khadkikar,2012)..

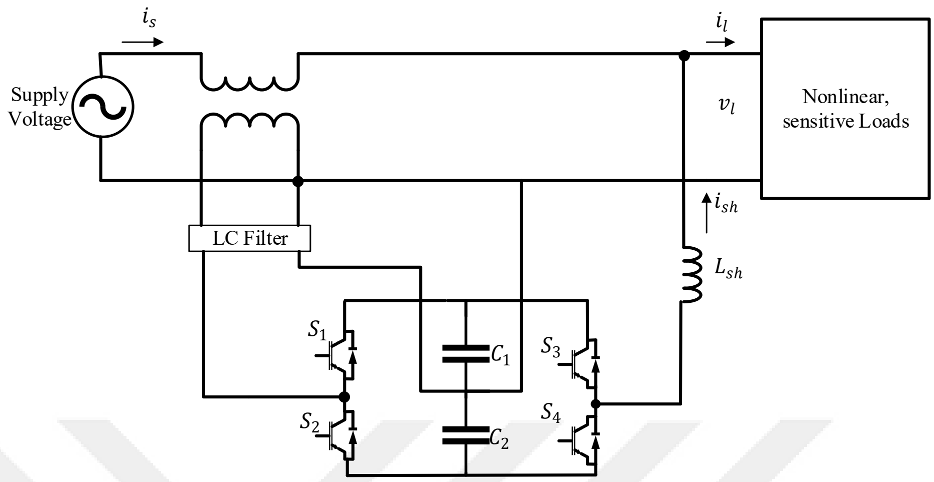

Figure 3.23. 1P2W UPQC: half-bridge configuration (four switches) (Khadkikar,2012).

In 3P3W, the load characteristics can be variable and this situation may cause negative effects on the system. For example; variable speed drives, welding machines are known as nonlinear loads in three-phase systems. As mentioned before, these loads cause situations with serious negative effects such as harmonic current drawn from the power system. To mitigate the negative effects of power quality problem in the 3P3W, UPQC that has a VSI topology is depicted in Figure 3.24. is used (Lee et al., 2010).

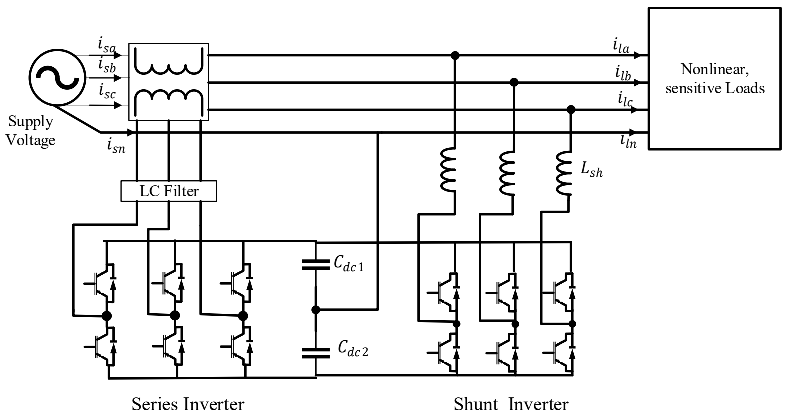

Figure 3.24. 3P3W UPQC on 2C shunt inverter topology (Khadkikar,2012)

Some load profiles can be consisted of combination of single and three phase supplied by the three-phase four wire source. In three-phase four-wire systems, the fourth wire is named as a neutral conductor and causes the excessive neutral current flow. This excessive neutral current cause the heating and isolation failure on the electrical equipment. Because of the negative impacts of neutral currents, compensation of neutral current must be required. To decrease the impact of neutral currents, different shunt inverter topology is developed, 2C and 4L and 3HB, respectively. Three-phase four-wire UPQC topology based on 2C is depicted in Figure 3.24. As the name suggest that, on the DC side of 2C topology, there is a two-split capacitor. The fourth wire is connected to the midpoint of the DC side. At this point where the fourth wire is connected zero voltage is expected. In this topology, to prevent the flow of circulating current, it must be maintained the same voltage on both capacitors. This situation needs additional control to regulate the DC bus voltage (Khadkikar,2012).

Another topology used in three-phase four-wire systems is the 4L topology. An additional leg has been added and the neutral of the load can be compensated by this leg. Thanks to the fourth leg, a more effective neutral current compensation can be achieved. Basic circuit diagram of 4L based topology is depicted in Figure 3.25. (Khadkikar,2012).

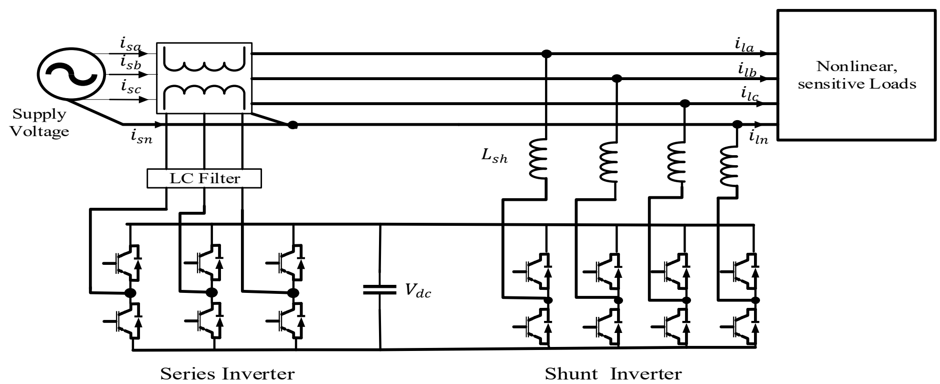

Figure 3.25. 3P3W UPQC on 4L shunt inverter topology (Khadkikar,2012)

The last topology developed for three-phase four-wire systems is the 3HB topology. As the name suggests, this topology consists of three single-phase H-bridge inverters connected to the common DC bus of UPQC. Basic circuit diagram of 3HB based topology is depicted in Figure 3.26.

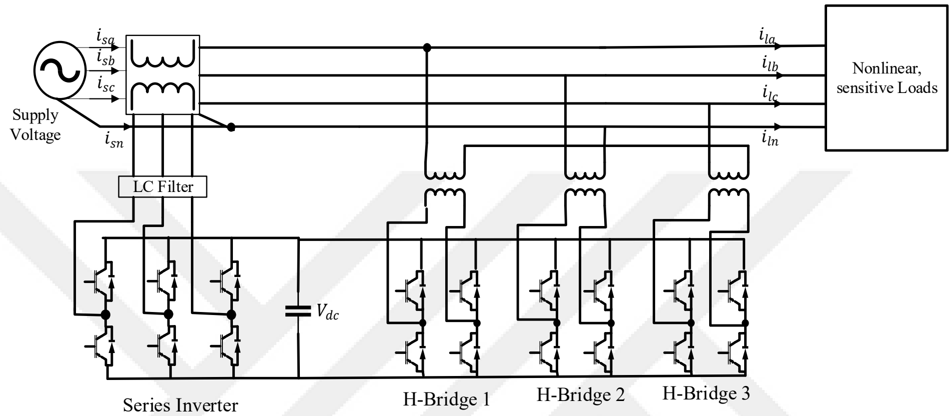

Figure 3.26. 3P4W UPQC on 3HB shunt inverter topology (Khadkikar,2012)

The main drawback of the system is the high number of semiconductors required for this topology. This situation increases the system losses, size, and installation cost. The common purpose of these three topologies is to perform the current compensation on the fourth conductor, namely the neutral. (Khadkikar,2012).

3.2.1.1.(3). System Configuration

3.2.1.1.3.a. Right and Left Shunt UPQC (UPQC-R and UPQC-L)

UPQC consists of two inverters that is connected back-to-back and can be classified according to the placement of the shunt inverter relative to the series inverter in this topology. If the shunt inverter is located to the right of the series inverter, it is called right shunt or UPQC-R, if it is located to the left of the series inverter, it is called left shunt or UPQC-L. Basic circuit diagram of UPQC-R and UPQC-L are depicted in Figure 3.27. (Karanki et al.,2010).

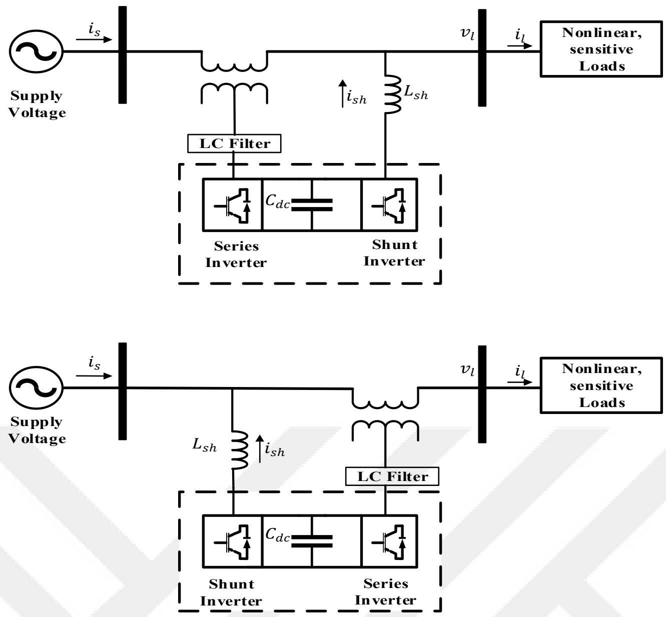

Figure 3.27.Basic circuit diagram of UPQC-R and UPQC-L(Khadkikar,2012)

In power systems applications where UPQC-R is used, characteristics of the currents passing through the series transformer are irrelevant from the characteristics of the load current. These currents are generally sinusoidal. Because of this situation, UPQC-R has higher performance compared to the UPQC-L. On the other hand, UPQC-L is used in some specific situation such as, to prevent interference between shunt inverter and passive filter. (Khadkikar,2012).

3.2.1.1.3.b. Interline UPQC (UPQC-I)

The UPQC interline topology is formed by connecting two inverters between two distribution feeders. Whilst one of the inverters is connected in series to the distribution feeder, the other is shunt connected to the second distribution feeder. By means of this configuration, voltage regulation of feeders can be achieved at the same time. Besides, UPQC-I can control the power flow between two feeders. With using the UPQC-I configuration, current related power quality problems (harmonics, unbalance etc.) are mitigated efficaciously only on the feeder in which the inverter is connected in shunt. On the other hand, voltage harmonics are enough mitigated only on the feeder in which the inverter is connected in series (Jindal et al., 2007). Basic circuit diagram of UPQC-I is depicted in Figure 3.28.

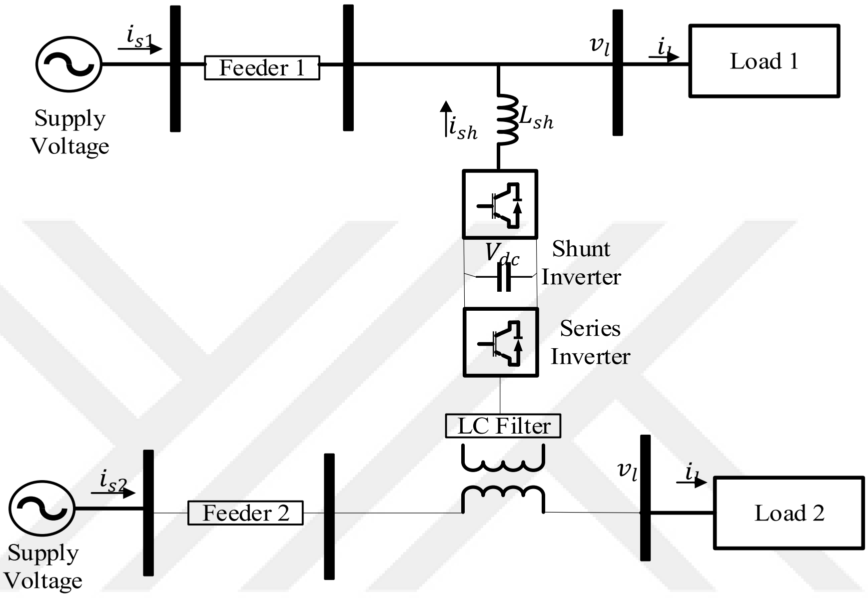

Figure 3.28. Basic circuit diagram of UPQC-I (Khadkikar,2012)

3.2.1.1.3.c. Multiconverter UPQC (UPQC-MC)

To increase the system performance, it was considered that to support the DC bus by including a third converter in the UPQC configuration. Moreover, to augment the overall system performance, usage of battery or supercapacitor as a storage unit also considered (Groavac et al.,2000) Third converter can connect to the system either series or parallel. Just like in the UPQC-I configuration, UPQC-MC can connect to the between different feeders. Basic circuit diagram of UPQC-MC is depicted in Figure 3.29.

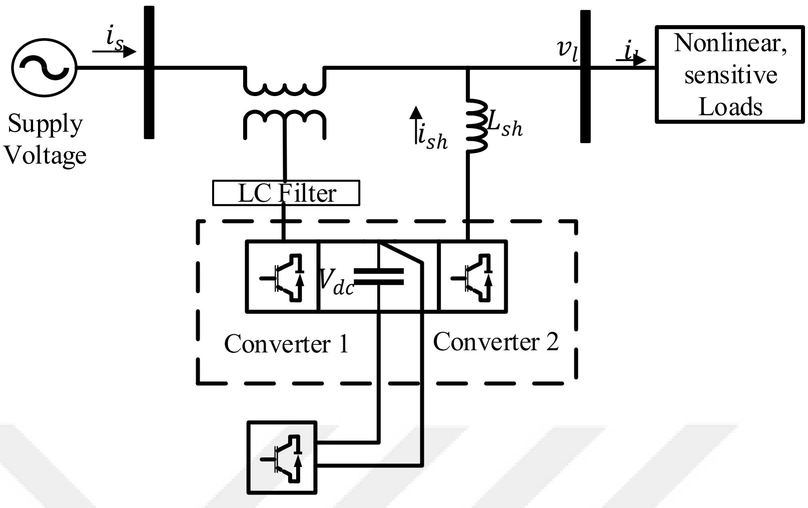

Figure 3.29. Basic circuit diagram of UPQC-MC (Khadkikar,2012)

3.2.1.1.3.d. Modular UPQC (UPQC-MD)

Modular UPQC topology is formed by combining multiple single-phase UPQCs using an H-bridge inverter in each phase. H-bridge converters on the shunt inverter side of UPQC are connected to the distribution line in series by means of a multi-winding transformer on the other hand, the H-bridge converters that take part on the series inverter side are connected in series with the distribution line without using any transformer (Han et al., 2006).

H-bridge converters on the series inverter side are connected in parallel to the line via transformer. Modular UPQC topology is appropriate for the medium voltage application to obtain high power level (Munoz et al.,2009). Basic circuit diagram of Modular UPQC is shown in Figure 3.30.

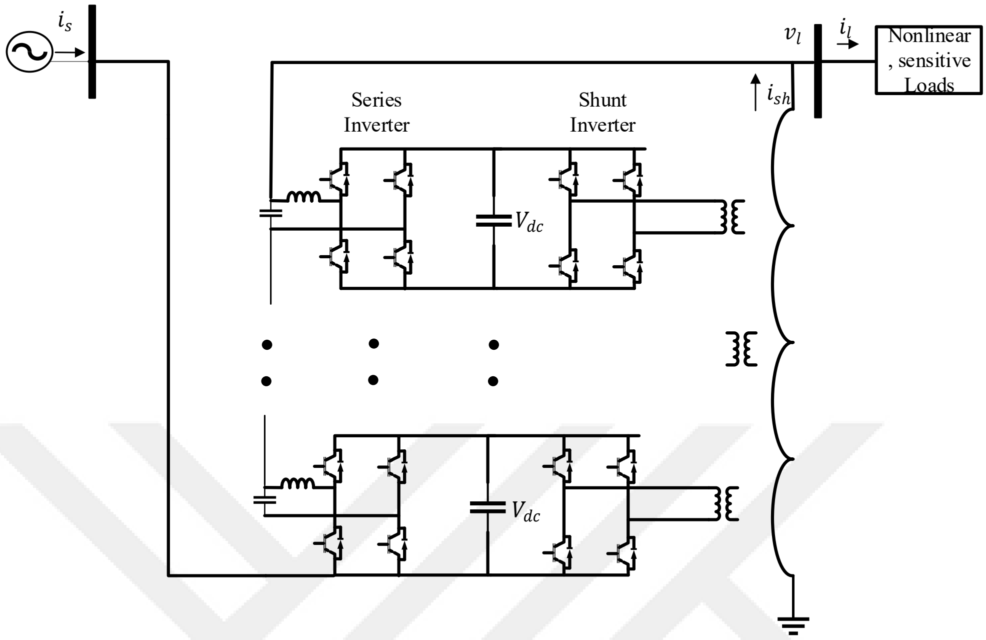

Figure 3.30. Basic circuit diagram of UPQC-MD (Khadkikar,2012)

3.2.1.1.3.e. Multilevel UPQC (UPQC-ML)

Multilevel UPQC topology is relied on three-level neutral point clamped (NPC) topology. Double semiconductor devices (24) are needed in UPQC-ML applications like the two-level UPQC applications. As with UPQC-MD applications, the UPQC-ML is appropriate for the usage in high power applications (Khadkikar,2012). Basic circuit diagram of multilevel UPQC (UPQC-ML) is depicted in Figure 3.31.

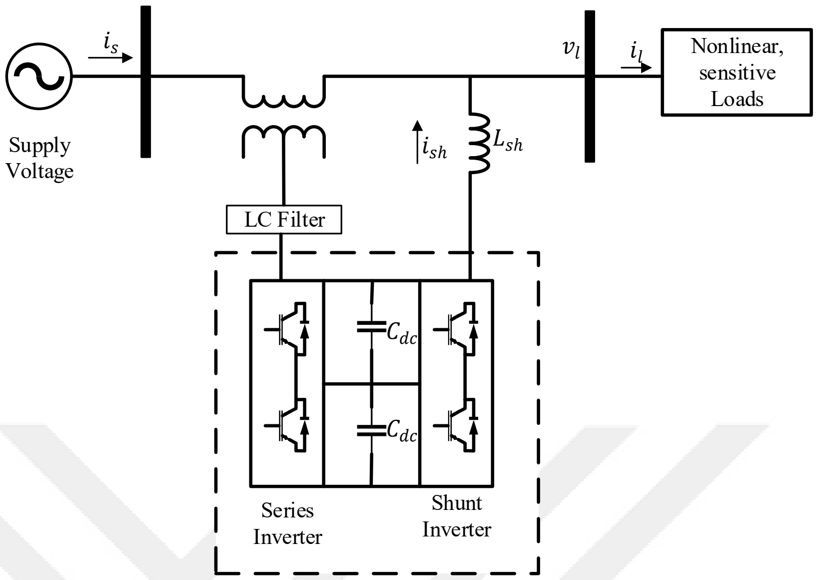

Figure 3.31. Basic circuit diagram of UPQC-ML (Khadkikar,2012).

3.2.1.1.3.f. 3P3W-to-3P4W Distributed UPQC (UPQC-D)

As it is well known, three-phase four-wire distribution systems consist of three power line phases and neutral conductor. Thanks to the new topology proposed for three-phase four-wire systems, UPQCs, which are widely used in three-phase three-wire applications, can be extended to the application called UPQC-D, which is used in three-phase four-wire systems (Khadkikar and Chandra,2011).

Basic circuit diagram of UPQC-D is illustrated in Figure 3.32. The neutral of the transformer, which is on the series side of the UPQC and provides the connection with the ac mains, can be accepted as the neutral point of the three-phase four-wire system. Although the ac mains supply is three phases, with this application it can be converted to a three phase four wire system. In this application, fourth leg is added to compensate the neutral current which flows to the transformers neutral point (Khadkikar,2012).

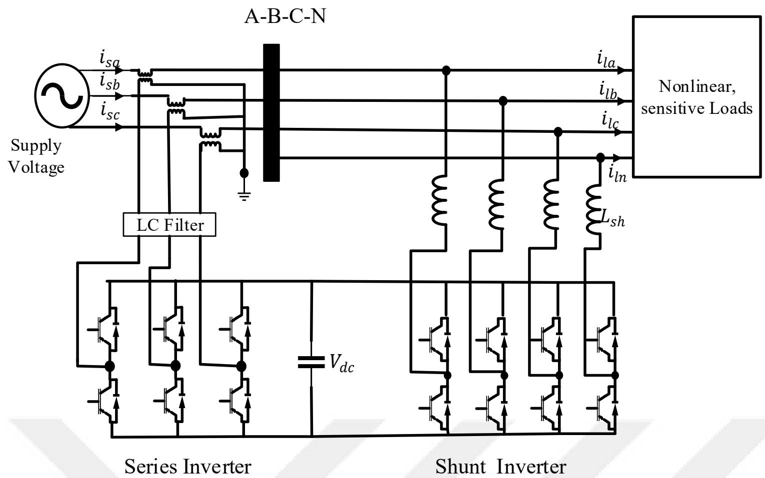

Figure 3.32. Basic circuit diagram of UPQC-D (Khadkikar,2012)

3.2.1.1.3.g. Distributed Generators Integrated with UPQC (UPQC-DG)

To meet the increasing energy demand, the orientation to various alternative energy sources such as solar, wind, has increased. In this context, the installed power of renewable energy sources is increasing. With the increase in electricity production based on renewable energy sources, the power quality in the system may also be affected by this situation. To mitigate the adverse impacts of this situation, UPQC can be coupled with distributed generation.

DC bus of UPQC and output of the distributed generation system is connected to each other. Additionally, also the battery of the distributed generation system is connected to the DC bus, by this means, excess power can be stored as a backup power. By means of energy storage unit, when a voltage interruption occurs, the UPQC-DG configuration can provide energy to the output loads uninterruptedly, as it produces energy based on renewable sources. Also, it is possible to operate the UPQC-DG configuration in islanding mode (Khadkikar,2012). Basic circuit diagram of UPQC-DG is illustrated in Figure 3.33.

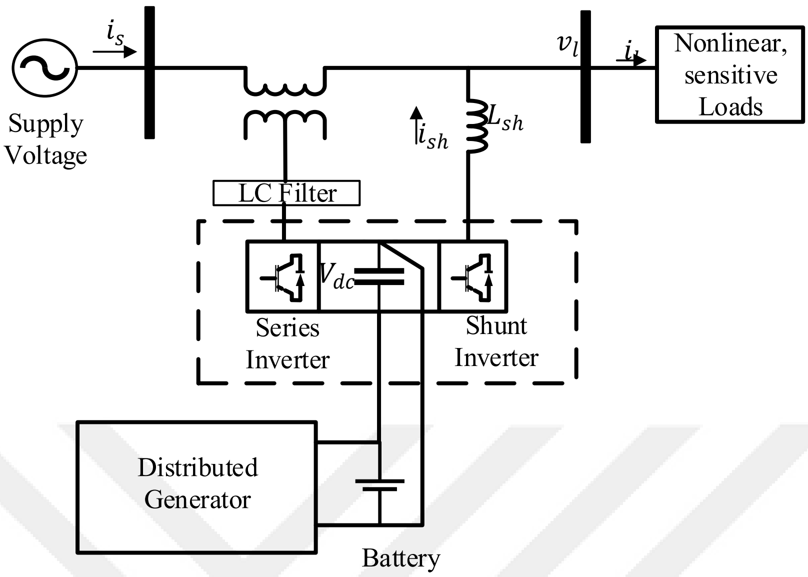

Figure 3.33. Basic circuit diagram of UPQC-DG (Khadkikar,2012)

3.2.1.2. Classification Based on the Voltage Sag Compensation Approach

Power quality problems occurring in electrical power systems are basically divided into two basic groups as current and voltage related power quality problems. One of the most important power quality problems is voltage sag events. Voltage sags events can cause serious problems on the equipment such as tripping, malfunctioning of the device and halt of production. There are various methods to compensate for voltage sag events, which have serious negative effects on devices and the system. In this part, UPQC-based voltage sags compensation methods are evaluated.

3.2.1.2.(1). Active Power Control Methods (UPQC-P)

To alleviate the effect of voltage sag on the systems and equipments, active power is used in this method. To achieve effective voltage sag, in-phase missing voltage is injected in series by means of series inverter. During the compensation phase, needed active power is drawn by the shunt inverter that is required by the series inverter. This situation may cause the magnitude of the supply current to increase in the event of a voltage sag (Rajasree and Premalatha, 2011).

3.2.1.2.(2). Reactive Power Control Methods (UPQC-Q)

Voltage sags events can be eliminated reactive power injection by means of inverter of UPQC (Lee et al., 2010). The main idea of this method based on the injection of quadrature voltage by means of series inverter of UPQC. It means that vector sum of supply voltage and injected voltage equal to the required rated voltage at the load bus. Unity power factor is provided by the shunt inverter of the UPQC at the supply side. Thus, there is no need for active power used to compensate for the voltage sag in the system. But, obtained voltage has a phase shift with respect to the supply voltage. To compensate for a voltage sag event of the same magnitude, this method requires more series injection voltage than the active power injection method. Naturally, power rating of inverter is increased in this method. UPQC-Q cannot reduce the voltage swell events on the power system. When two different methods (UPQC-P and UPQC-Q) are examined, UPQC-P is a more popular method for voltage sag compensation in UPQC based power quality improvements.

3.2.1.2.(3). Minimum Volt-Ampere (VA) Loading (UPQC-VAmin)

In this method, the series voltage is injected into the system at the most appropriate phase angle, taking the current of the supply source as a reference. Thus, while compensating for the voltage sag, the loading rate of the UPQC in VA can be reduced. There are two main parameters to consider when determining the VA loading of the UPQC are the current drawn by the shunt inverter and the series voltage injection, respectively (Lee et al., 2010).

3.2.1.2.(4). Simultaneous Active and Reactive Power Control (UPQC-S)

In this method, while the voltage sag event is compensated, the series inverter of UPQC provides active and reactive power. The series inverter that takes part of UPQC is controlled to compensate voltage sag and swell events contemporaneous and to realize reactive power sharing of load together with the shunt inverter. The control system of UPQC-S is more complicated than the other method that is used to compensate the power quality problem due to the involve many different control loops (Khadkikar and Chandra,2011).

3.3. Distribution Static Compensator (D-STATCOM)

Current-related problems such as low power factor, poor voltage regulation, unbalanced loading and increased neutral currents in distribution systems can cause serious problems. Classical technologies that have been developed so far can be effective up to a certain point in eliminating these current related power quality problems. D-STATCOM technology, which was developed to mitigate the current-related problems, is more effective in solving these problems compared to classical methods. In systems with unbalanced and nonlinear load characteristics, D-STATCOM is connected to the system as shown in the Figure 3.34. One of the main functions of D-STATCOM is to supply the reactive power to the system to obtain the regulated voltage at the point of common coupling (Mahela and Shaik,2015).

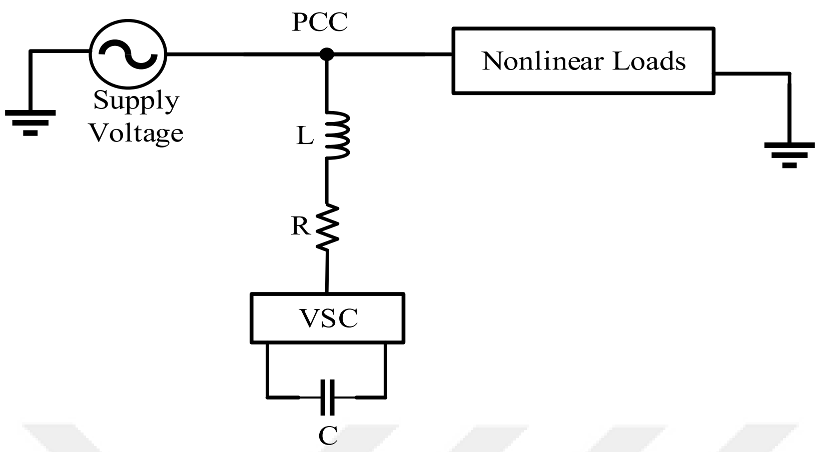

Figure 3.34. Basic circuit diagram of D-STATCOM(Mahela and Shaik,2015).

D-STATCOM consists of VSC, DC bus capacitor, transformer and filter as illustrated in Figure 3.34. The VSC is used to convert the DC voltage to the AC voltage, by the way converter output is matched to the line voltage by means of transformer. The important components of D-STATCOM are explained in the follows.

- ***Voltage Source Converter (VSC)*** The bidirectional power flow is provided by VSC by using of IGBT and MOSFET technology. VSC performs the switching function by using the PWM method, which is a traditional switching method. Together with the switching elements VSC has also DC link capacitor and inductor (Singh et al., 2014a).
- ***Transformer*** Unbalanced and nonlinear loads in distribution systems are the biggest causes of increased neutral current. Transformers can compensate the increased neutral current. The increased neutral current compensation is related with the location of the compensator and system impedance. Transformers are used in two ways in the D-STATCOM system. Either they are used to only compensate the neutral current in non-

isolated condition or providing isolation to the VSC together with the neutral current compensation (Mahela and Shaik,2015).

- ***Ripple filter*** To filter the noise from the PCC voltage, a first-order high-pass filter that tuned at half the switching frequency is used. A first order high pass filter constitutes of the resistor and capacitor that is connected in series each other (Yang et al.,2014).
- ***AC Inductor*** In order to decrease the ripple in the compensating currents, inductor is used at the at the output of the VSC. The inductance value of the VSC is calculated by using the current ripple, switching frequency and DC bus voltage (Singh et al., 2005).

3.3.1. Classification of D-STATCOM

According to the usage of transformer for isolation, number of switching devices, increased neutral current compensation, classification of D-STATCOM can be extended. Topological classification of D-STATCOM is shown in Figure 3.35.

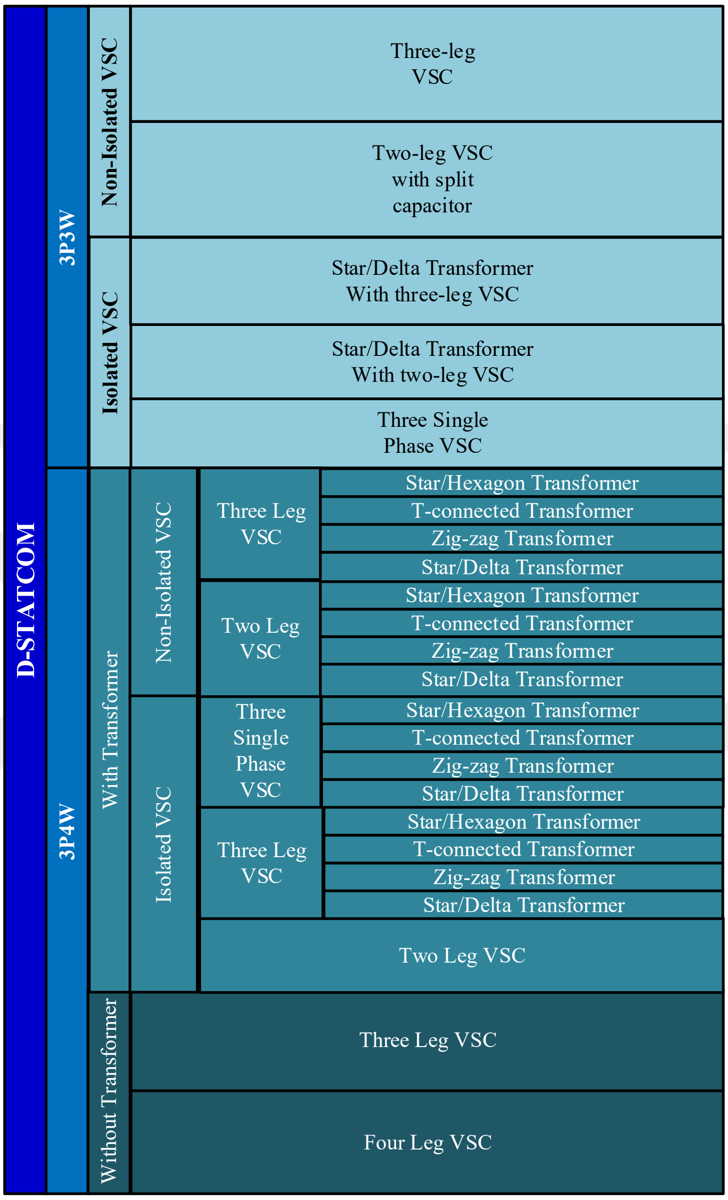

Figure 3.35. Classification of D-STATCOM

In this thesis, three-phase three wire and three phase four wire topologies of D-STATCOM is investigated and only converter topologies and transformer configurations are reviewed for the simplicity.

3.3.1.1. Three-Phase Three Wire D-Statcom Topology

Three-phase three-wire D-STATCOM topology is capable to achieve reactive power compensation, harmonic problems and improve the power quality. Three-phase three-wire D-STATCOM topology is divided into two main groups as isolated VSC-based and non-isolated VSC-based D-STATCOM (Mahela and Shaik,2015).

3.3.1.1.(1). Isolated VSC-Based D-STATCOM

In this topology VSC is separated from the supply system via transformer. The basic circuit diagram of isolated VSC-based three-phase three wire D-STATCOM is illustrated in Figure 3.36.

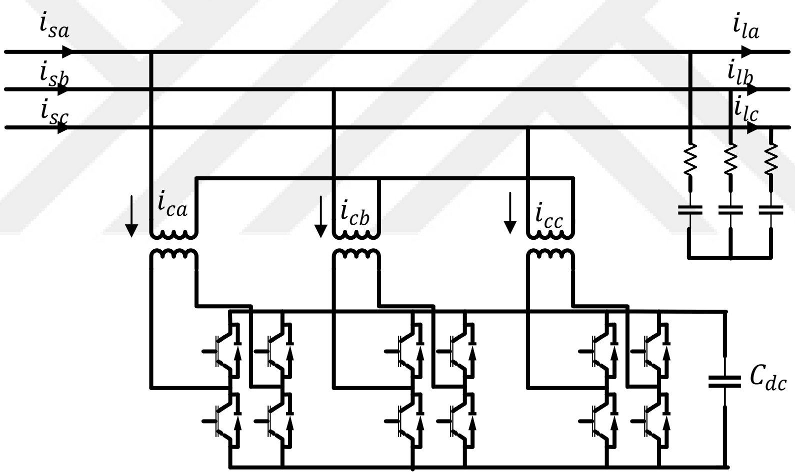

Figure 3.36. Basic circuit diagram of isolated VSC-based D-STATCOM (Mahela and Shaik,2015).

This topology consists of three single-phase VSC that shared the common DC capacitor. VSC units are connected to the line via transformer. The transformers in the circuit both provide the isolation of the converters and protect the DC capacitor unit from short circuit thanks to the controlled switches in the converter. The other transformer connections like T-connected, zigzag, and star/hexagon can also be used to the improvement of system efficiency.

3.3.1.1.(2). Non-Isolated VSC-Based DSTATCOM

In this topology VSC unit of D-STATCOM is connected to the line via inductive reactor. Non-isolated VSC-based D-STATCOM topology is divided into two main categories three-leg VSC or two-leg VSC with split capacitor respectively. Three-leg VSC based D-STATCOM topology is shown in Figure 3.37. As the name suggests, the three-leg VSC-based topology has three legs, and each leg has two IGBTs.

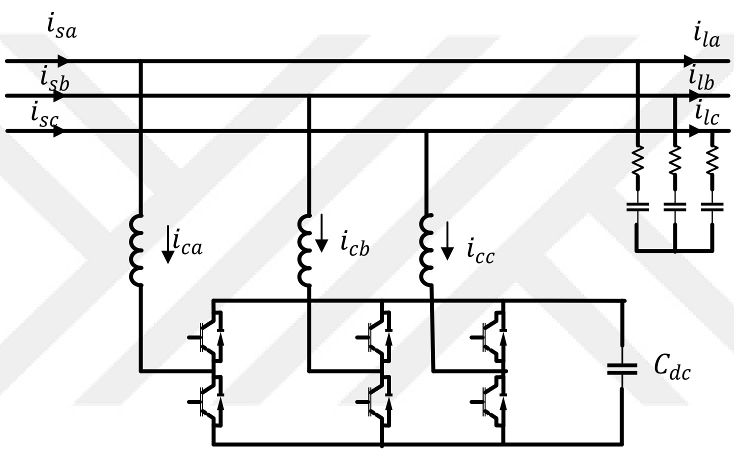

Figure 3.37. Non-isolated vsc-based 3P3W D-STATCOM (Mahela and Shaik,2015)

In the circuit of non-isolated VSC-based three-phase three wire D-Statcom, inductor is used to connect the PCC coupling and midpoint of half bridge. And three phase loads connect to the PCC. The reason for using the RC filter at the output of the circuit is to filter the ripple that occur during switching (Mahela and Shaik,2015). The circuit diagram of two-leg VSC based D-STATCOM topology with split capacitor is circuit diagram is illustrated in Figure 3.38.

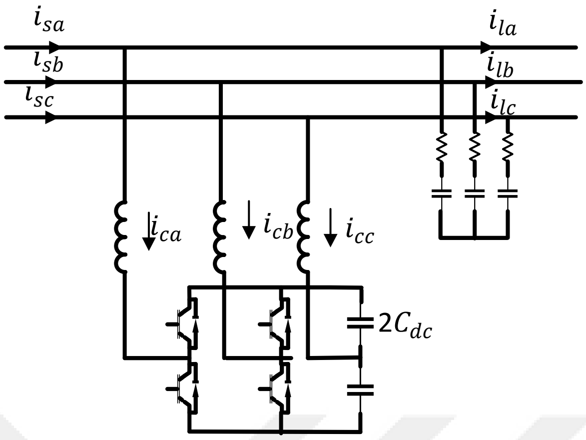

Figure 3.38. Two-leg VSC with split capacitor (Mahela and Shaik,2015)

The differences between the two types are the number of usages switching elements, the use of split capacitor groups in a two-leg topology, different transformer connection types according to the applications and DC bus voltages (Mahela and Shaik,2015).

3.3.1.2. Three-Phase Four-Wire D-STATCOM Topology

Three-phase four-wire D-STATCOM topology is used in three-phase four-wire power distribution systems to fulfill the grid connection requirements by filtering the load current. By using the three-phase four-wire D-STATCOM topology, the poor power factor is improved, and its effects are eliminated, harmonic compensation is provided, and current balance is achieved. The three-phase four-wire D-STATCOM topologies are categorized into two main groups with and without transformers (Ananth et al., 2013).

3.3.1.2.(1). Isolated Two-Leg VSC Based D-STATCOM

In isolated two-leg VSC based D-STATCOM consists of split capacitor group with transformer and isolation is provided by transformer. Star-delta, T-connected, star/zigzag and star/hexagonal connection types, which are different connection types of transformers, can be used in D-STATCOM topologies with two-legs, three-phases four-wire and are illustrated in Figure 3.39. respectively.

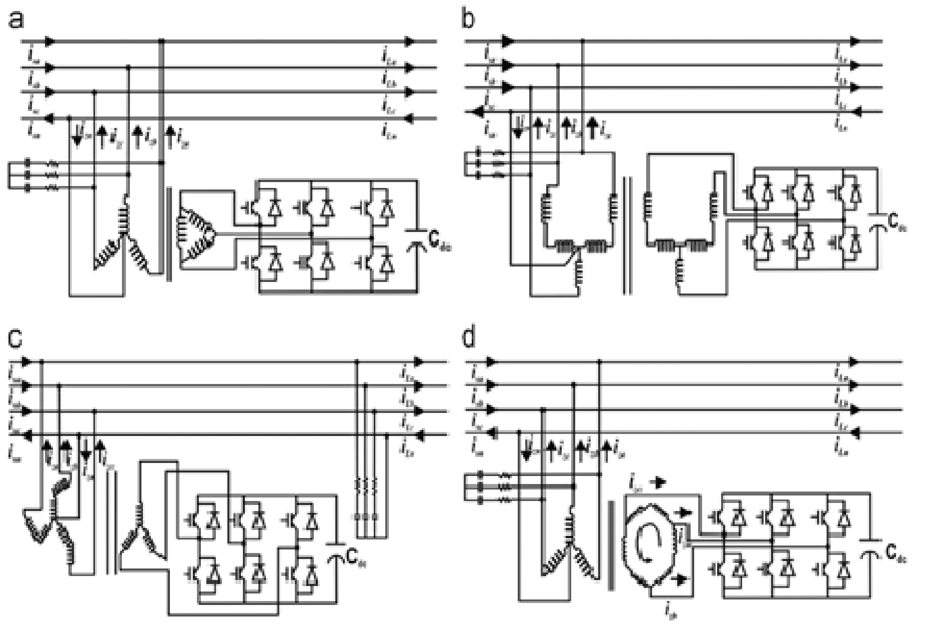

Figure 3.39. Transformer connection of two-legs, three-phases four-wire D-STATCOM topology (Mahela and Shaik,2015)

Three phases of the system power supply are connected to the three-phases of the system side windings and the neutral point of winding is connected to the neutral point of the three-phase four wire system. To control the voltage and frequency of the wind energy system that feed the three-phase four-wire loads, the transformer topology with T-connection has been used (Sharma et al., 2009).

3.3.1.2.(2). Isolated Three-Leg VSC Based D-STATCOM

Three-leg VSC that have DC bus with transformer can be used as a three-phase four-wire D-STATCOM. As mentioned before, in a similar way, isolation is provided by the transformer in this application. Star-delta, T-connected, zigzag, and star/hexagonal connection types, which are different connection types of transformers, can be used in D-STATCOM topologies with three-legs, three-phases four-wire and are illustrated in Figure 3.40. respectively.

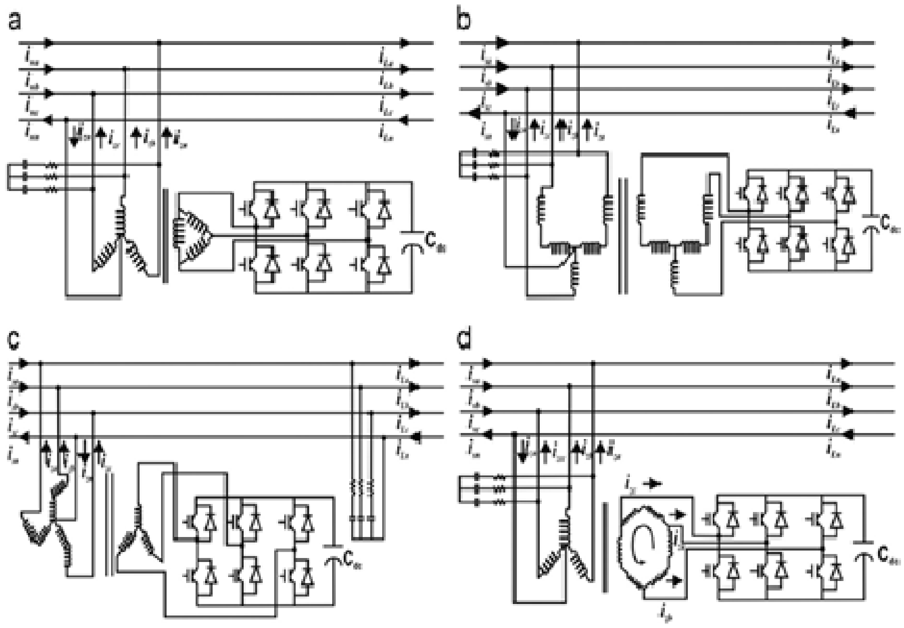

Figure 3.40. Transformer connection of three-legs, three-phase four-wire D-STATCOM topology (Mahela and Shaik,2015)

As can be seen from the Figure 3.40, the three-phase three-wire side of the transformer that is close to the VSC is connected to the three legs of the VSC. The three-phase connection of the transformer on the system side relates to the three-phase of the supply. The neutral connection of the transformer relates to the neutral point of the system. To improve the power quality in three-phase four wire distribution systems, three leg VSC type and star/ hexagon transformer connection topology is widely used. In addition, voltage regulation, harmonic elimination, neutral current compensation can also be achieved by using different transformer connections of three-legged VSC-based topology (Ananth et al., 2013).

3.3.1.2.(3). Isolated Three Single-Phase VSC Based D-STATCOM

Isolated three single-phase VSC based D-STATCOM circuit diagram is illustrated is Figure 3.41. In this topology ,three single phase VSC have common DC bus. The phases of D-STATCOM consist of the combination of H-bridge and single-phase transformer. One of the three terminal of secondary winding of transformers is connected to the phase of the system and the other terminal is connected to the neutral point of the supply system.

The main differences between of isolated two-leg, three-leg, three single-phase VSCs-based three-phase four wire D-STATCOM topologies are number of usage semiconductor devices, different transformer connection type and DC bus voltages (Mahela and Shaik,2015).

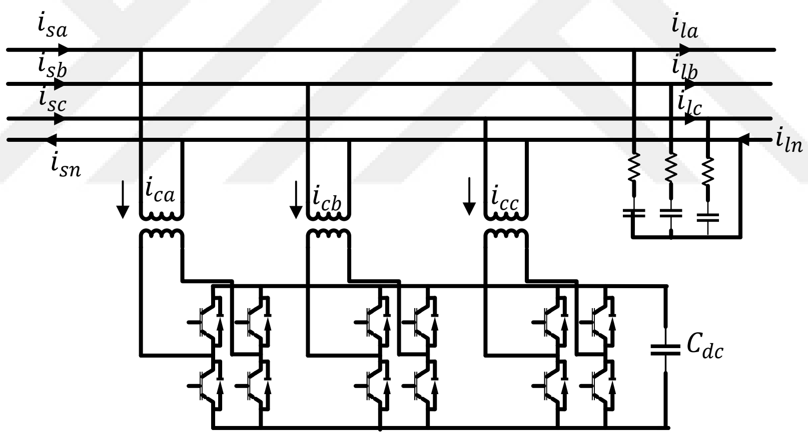

Figure 3.41. Isolated three single-phase VSC Based D-STATCOM (Mahela and Shaik,2015)

3.3.1.2.(4). Non-Isolated VSC Without Transformer Based D-STATCOM

Non-isolated VSC-based D-STATCOM topologies are divided into two main categories, four-leg, and three-leg VSC-based topology. Transformers are not used in these two groups of topologies. The basic circuit diagram of four-leg VSC based three-phase four wire topology is shown in Figure 3.42. A four-leg VSC topology with an adaptive neural network-based control algorithm was considered as an alternative to to provide compensation of linear and non-linear loads, effectively (Singh et al., 2014b).

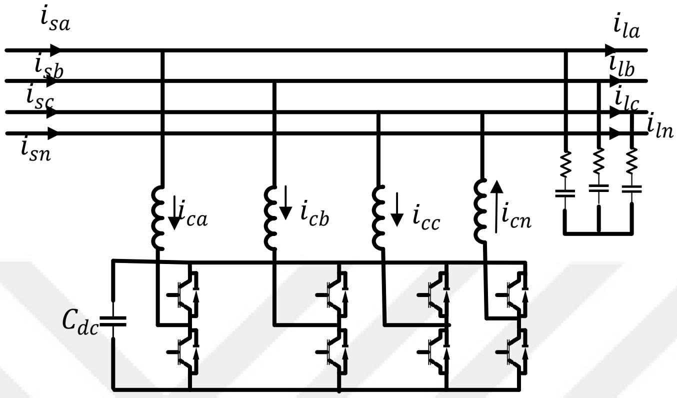

Figure 3.42. Nonisolated VSC based 3P4W D-STATCOM without transformer-based topology four-leg (Mahela and Shaik,2015)

Photovoltaic application of non-isolated VSC without transformer-based D-STATCOM is also consired as an alteranative. The aim of this study is to decrease the penetration level of low voltage distribution system and improve the power quality (Zaveri at al.,2011).

The basic circuit diagram of non-isolated three-leg VSC-based three-phase four wire D-STATCOM without transformer topology with split capacitor and three ac capacitors is shown in Figure 3.43 and 3.44, respectively.

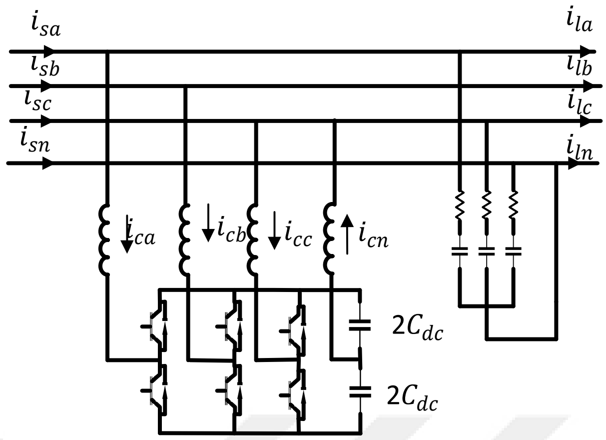

Figure 3 43. Non isolated VSC based 3P4W D-STATCOM without transformer-based topology three-leg (Mahela and Shaik,2015)

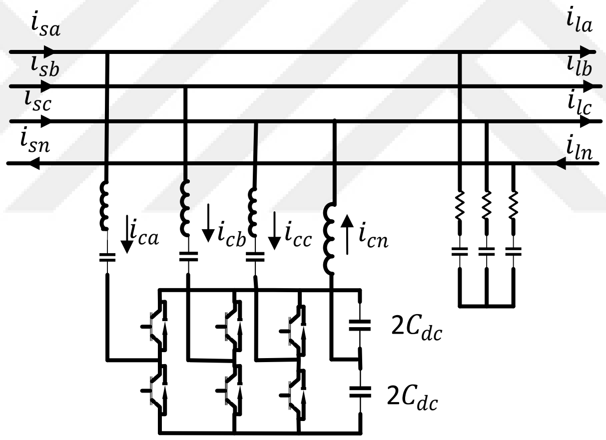

Figure 3.44. Non isolated three-leg VSC based 3P4W D-STATCOM topology with three ac capacitors and without transformer (Mahela and Shaik,2015)

Comparison between of non-isolated VSC-based three-phase four wire D-STATCOM topologies without transformer is given the Table 3.1.

Table 3.1. Comparison between of non-isolated VSC-based 3P4W D-STATCOM topologies without transformer

Four-Leg VSC	Three-Leg VSC split capacitor	Three-Leg VSC with AC capacitor
More switch is used	Capable to compensate the unbalance load in 3P4Wsystem.	Has two DC storage device.
Capable to compensate the unbalance load that contain DC component in 3P4W system	Not capable to compensate DC component of load current.	Reduced DC Link voltage and frequency
Easy to control of DC bus.	The size of capacitor is large enough to mitigate the ripple.	Capable to compensate the reactive power and harmonics at load side.
	Because of two DC bus capacitor it has big size	
	Less number of switch is used.	

3.4 Dynamic Voltage Restorer

The DVR is a series voltage compensating device that injects the missing voltages to the power system when the grid voltage decreases. The circuit of DVR is composed of a converter, a DC-link, filter, and an injection transformer as shown in Figure 3.45. The voltage needed by the system is provided by the inverter and the controller of the dynamic voltage restorer. The inverter converts DC voltage to the AC voltage and provides controllable voltage for the voltage compensation. The filter at the output of the inverter is used to prevent harmonics caused by switching while generating the AC signal. At the end of this process, the obtained voltage by the system is transferred through the injection transformer.

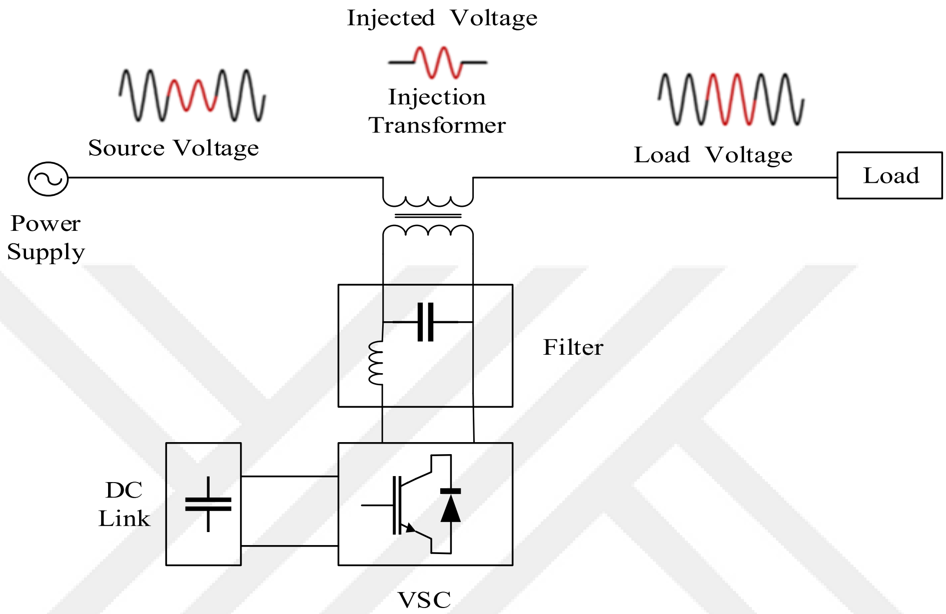

Figure 3.45. The circuit diagram of DVR

In addition, the injection transformer provides isolation between the DVR and the power grid. The DVR feeds the power system when voltage variations occur at the source. The needed power is provided by DC link capacitors to fix the load side voltages to its nominal values. The most considerable parameter affecting the compensation is the capacity of the DC link capacitor. To transfer the required energy, DC link capacitors should be selected to provide the required energy (Kangarlu et al., 2017). DVR is divided into two main categories as conventional DVR and transformerless DVR. In the following these types of dynamic voltage restorers are explained.

3.4.1. Transformerless DVR

Injection transformers have some drawbacks to inject the voltage into the system. In addition to being expensive, its main disadvantages are that it has large volume and contributes to losses during voltage restoration. Moreover, injection transformer is affected from DC magnetic flux which occurs before voltage sag and after the voltage restoration process. To overcome this situation, cross-sectional area of transformer core should be increased (Kumar and Mishra.,2014).

In some developed DVR topologies, the injection transformer and its related problems can be eliminated. These topologies are named as transformless dynamic voltage restorer. With the performed design by eliminating the injection transformer, cost and weight reduction is achieved (Kangarlu et al., 2017).

The reduced number of switches are used by multilevel inverters. Consequently, investigated dynamic voltage restorer has fewer number of switch multilevel inverter and there is no need to injection transformer anymore in this topology. That's why, lower loss is made up of and power investment cost will be reduced (Kangarlu et al.,2010).

The ability of multilevel inverters to operate at high power makes them attractive for transformerless dynamic voltage restorer applications. In addition to this situation, their low harmonic content is another positive aspect of multilevel inverter. The control methods currently applicable to the cascade multilevel inverter assume that the voltage at the output is constant (steady state) with a limited control range. For this reason, new control method is developed. According to the implemented new control methods, cascade multilevel inverter topology can effectively compensate the voltage sags under different load conditions with fast response. Also, elimination of the output filter is achieved. With this situation, injection transformer and filter equipment were eliminated and a reduction in cost and volume is achieved (Visser et al.,2002). In Table 3.2, comparison of conventional DVR and transformerless DVR is given.

Table 3.2**.** Comparison of conventional DVR and transformerless DVR

Property	**Conventional Dynamic Voltage Restorer**	**Transformless Dynamic Voltage Restorer**
Voltage Regulation	Transformer impedance may cause around %5 voltage drop	Switching element may cause voltage drop but it is ignorable.
Losses (Normal Mode)	Transformer losses can be a few percent.	Switching devices has a ignorable losses.
Losses (Sag Mode)	Transformer and inverter losses.	Only inverter losses.
Dimesion	Big	Small
Cost	Expensive	Cost effective

3.4.2. Converter Topology of DVR

The converter is one of the main components of a dynamic voltage restorer. The needed voltage required by the system during voltage disturbance is supplied by the converter. Due to this key feature, the effects of different converter topologies on the dynamic voltage restorer have been studied in the literature. There are many different converter topologies in the literature for instance; full bridge, matrix, split capacitor, half bridge, multilevel, three full-bridge, three phase three wire and four leg.

Three-phase three-wire inverter topology is used for high power / low voltage implementations. Three phase three wire inverter topology can be used for only balanced voltage sags. To overcome this negative aspect of three phase three wire inverter topology, split capacitor and four-leg inverter is used instead of it. Another converter topology is used for high power / low voltage implementation is full bridge and half bridge inverters. Meanwhile, full bridge inverters are used both single and three phase low power / high voltage application (Kangarlu et al., 2017).

The cascaded, diode clamped, and flying capacitor are multilevel inverter based dynamic voltage restorer. These topologies have low harmonic ratio compared to two level inverters (Savrun,2017).

Multilevel inverters are categorized mainly two sub-groups, single DC link and multiple DC link respectively. While diode clamp inverters and Flying capacitor inverters have a single DC source, cascaded multilevel inverters have a separate DC source (Savrun,2017).

Five-level flying capacitor based dynamic voltage restorer is investigated with repetitive control scheme. With this control structure, voltage sags, voltage imbalances, and voltage harmonics caused switching are prevented. In these studies, the control structure is divided into three categories. The first stage of control system prevents the resonance peak of the converter filter. The second stage of the repetitive control is an integer multiple of the fundamental frequency. Repetitive control provides a fast transient response and zero-tracking error in steady-state (Barros and Silva, 2010; Roncero-Sanchez and Acha 2009).

With multilevel inverter-based DVR topology voltage sag events are prevented without filter at higher voltage level. Since there is a common DC link in the system, an injection transformer is required for the H bridge in each phase of the converter. To obtain transformerless dynamic voltage restorer, separate DC-DC converter must be used for each H bridge (Babaei et al. 2013).

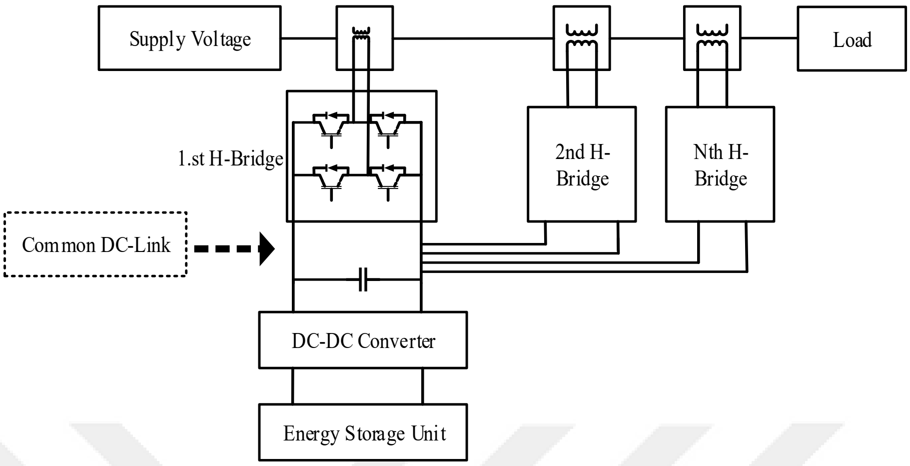

Figure 3.46. Multilevel inverter based DVR topology(Nielsen & Blaabjer, 2005)

Common DC coupling capacitors are used by conventional two-level, diode-clamped, and flying capacitor between all phases. To eliminate this situation, a lot of study has been done about multi-level inverter based dynamic voltage restorer. Due to the modular structure, high power quality, low harmonic components and low switching loss, multilevel inverter is appropriate for the high voltage level applications (Kangarlu et al., 2017). By combining modules with low voltage values, the required voltage level is obtained. By using multilevel inverter topologies injection transformer is eliminated, isolation between phases is provided by separate DC-links. (Al-Hadidi et al. 2008a, Al-Hadidi et al. 2008b, Galeshi and Iman-Eini 2016). In Table 3.3. basic specification of three-phase DVRs based on some other converter topologies are summarized in detail.

Table 3.3. Comparison of DVR according to the converter topology

Topology Name	Advantages	Disadvantages
Three-phase six-switch inverter	Basic topology, less equipment used	Not appropriate unbalanced voltage sag
Three-phase split-capacitor six-switch four-wire inverter	Basic topology, less equipment used suitable for unbalanced voltage sag	Low input/output voltage ratio
Three full-bridge	Suitable for unbalanced voltage sag	More power electronic switch
Four-leg	Suitable for unbalanced voltage sag low DC ripple	More power electronic switch high switching frequency
AC-AC converter	Eliminate energy storage unit can be used long term voltage disturbance.	Not appropriate deep voltage sag
Multilevel converter	Multilevel output voltage	Need for clamp diode
Multilevel converter	Expended more level	Charging and commisioning
Multilevel converter	Modular structure	Need multiple source
Z-source	Suitable for deeper voltage sag	Need more circuit elements
High-frequency link converters	Low weight ,cost effective	Low efficiency

3.4.3. Voltage Injection Methods of DVR

In dynamic voltage restorer applications, another important factors that affects the system performance is voltage injection methods. Voltage injection methods are divided into four main categories, In-Phase, Pre-Sag, Minimum Energy Compensation Methods (Zero Active Power Injection) and Combined Injection Methods respectively.

In In-Phase voltage injection method, the missing voltage to be injected into the load side is in phase with the remaining voltage at the system supply voltage. The most important positivity of this control method is the magnitude of the missing voltage is kept minimum value. By means of this, power rated of dynamic voltage restorer is also kept minimum. On the other hand, in phase compensation voltage injection method can reduce the demand of active power injection. But this situation cannot degrade the value of active power. It cannot repair the problems that occur in phase angles on the load side. Because of that reason, sensitive loads may affect from this situation. Vector diagram of in-phase compensation methos is shown in Figure 3.47 (Chung et al., 2003).

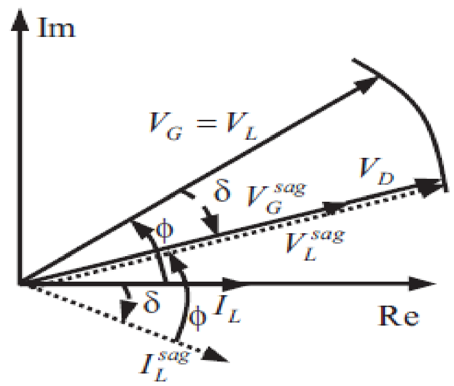

Figure 3.47. Vector diagram of in-phase compensation methods (Kangarlu et al., 2017)

In pre-sag injection method, the dynamic voltage restorer injects the voltage with the same phase angle and magnitude into the system so that the load side is not affected by the voltage disturbance. And this method can achieve to compensate the phase jump problems. In doing so, it needs more active power. Vector diagram of pre-sag compensation methos is shown in Figure 3.48. (Nielsen and Blaabjerg, 2001).

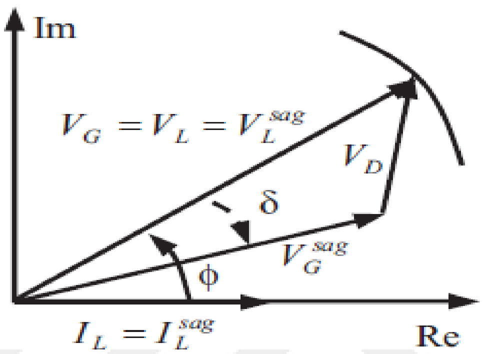

Figure 3.48. Vector diagram of pre-sag compensation method (Kangarlu et al., 2017)

In Minimum Energy Compensation Method, the voltage sag experienced on the load side is corrected by using only reactive power. Shallow voltage sags experienced in the system can be prevented by using reactive power. In this way, it has a longer compensation time. Although it seems like an advantage that it does not need active power to prevent voltage sag, this method also has disadvantages. These are respectively, the magnitude of the DVR voltage is quite high when the phase jump event occurs. As aforementioned before, only shallow voltage sags can be prevented by using reactive power. If a deeper voltage sag occurs, active power may be needed to correct this voltage sag. The vector diagram of the minimum energy compensation method is shown in Figure 3.49. (Savrun,2017).

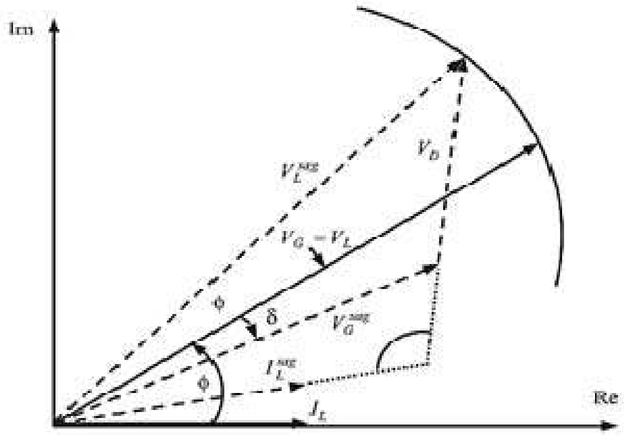

Figure 3.49. Vector diagram of minimum energy compensation method (Kangarlu et al., 2017)

Another method which is developed to use full advantage of the compensation methods and prevent the voltage sags and its adverse effects on the load side is the combined compensation strategies. If pre-sag and in-phase compensation techniques are used together, short-term voltage drops can be prevented. Another method used to prevent voltage sags on the load side is the combination of pre-sag and minimum energy compensation methods. With using this combination phase jumps problems can be prevented but, on the other hand compensation time will increase. The main purpose of this combination is to minimize the effect of a disturbance on the grid side and to design optimum system that will compensate for deeper and long voltage sags by reducing the cost (Rauf and Khadkikar, 2015). Comparison of compensation methods is given in Table 3.4.

Table 3.4. Comparison of DVR according to the voltage compensation methods

Technique	Injection Voltage Magnitude	Necessity of Energy Storage Unit	Necessity of DC link Voltage	Phase Compensation Capability
Pre-Sag	Acceptable	Major	Acceptable	✓
In-Phase	Few	Major	Minor	X
Minimum Energy	Small to Large	Minor	Major	X
Combined	Small to Acceptable	Minor	Acceptable	✓

3.4.4. Energy Storage Unit for Dynamic Voltage Restorer

The basic working principle of the dynamic voltage restorer is based on the power injected into the system to restore the voltage distortion when a voltage sag occurs in the power system. To do this, required power is provided by a power source. In this manner, dynamic voltage restorer topology is categorized two groups with and without energy storage unit. Required compensation power is given to the system via capacitor supported DC links or with different energy storage techniques such as flywheel, supercapacitors etc. When capacitor-based topologies are used obtained DC link is variable. The performance of the dynamic voltage restorer is directly affected by this situation. This is a disadvantage for the long-term voltage drops. It means that the variable DC link topology is not capable of compensating long-term voltage sags. The variable DC link topology is shown in Figure 3.50. To overcome the disadvantage of variable DC link topology, another different topology is improved. In improved new topologies, constant DC link is obtained by external energy storage unit that is fed by converter. On the contrary to the topology with variable DC link, this method could compensate for long-term voltage sags (Kangarlu et al., 2017). The topology of constant DC link is shown in Figure 3.50.

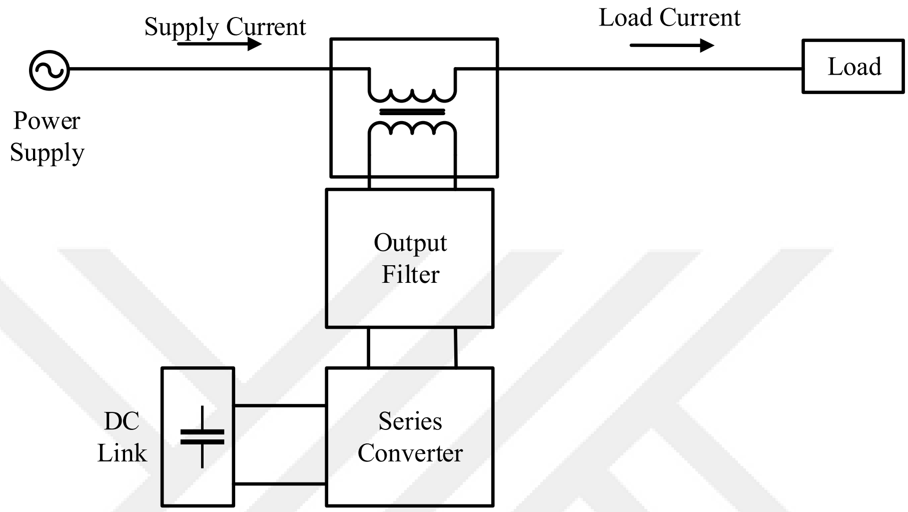

Figure 3.50. Capacitor supported variable DC Link based DVR (Nielsen & Blaabjer, 2005)

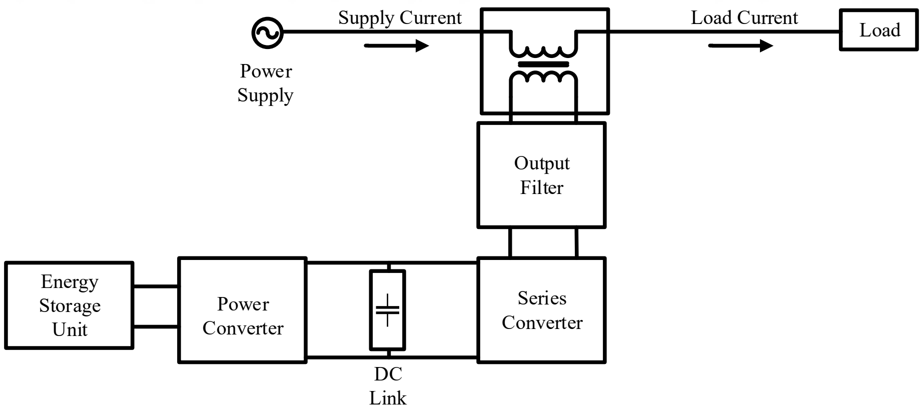

Figure 3.51. DVR with supported energy storage unit (Nielsen and Blaabjer, 2005)

In Figure 3.51, power that is used to mitigate the impact of the voltage sags on the load is provided by the energy storage units. Thanks to the developments in battery technology, voltage sags that last longer and have a deeper characteristic and their effects on the load side can be prevented. There are many studies in the literature about topologies that have an energy storage unit. A new compensation method has been proposed in a system consisting of an energy storage unit to increase the compensation capability of the dynamic voltage restorer. To minimize the energy storage unit, compensation technique is developed to calculate the value of injected power. The topology in which the energy required during the voltage sag is provided in the grid itself has also been examined. To compensate the voltage disturbance, supply voltage is used by the topologies which do not have the energy storage unit. The active power is supplied by DC link capacitor that is fed by a converter. However, this method has a negative feature, such as increasing the source current during voltage disturbance. The topology that does not have an energy storage unit is basically divided into two main subcategories, supply side connected converter and load side connected converter respectively. The operating principle of this two-converter topology is different from each other. Supply side converter consists of diode rectifier, because of that reason is not able to control the DC link voltage. The supply side inverter topology is shown in Figure 3.52.

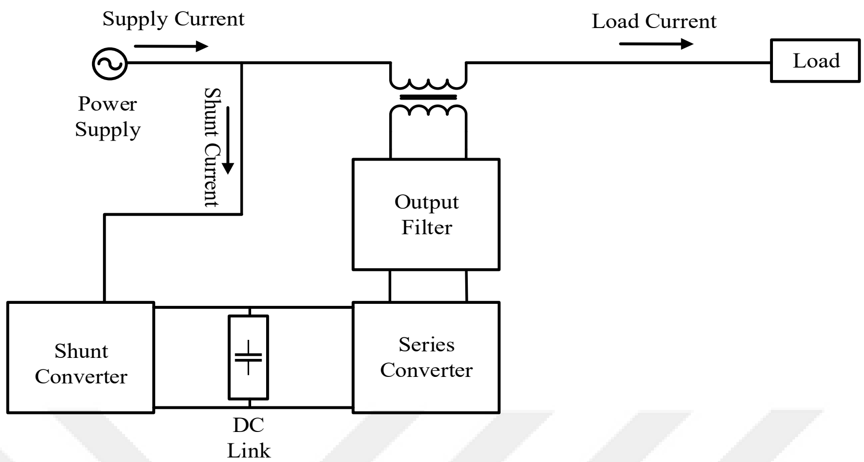

Figure 3.52. DVR with no energy storage unit and supply side connected shunt converter (Nielsen and Blaabjer, 2005)

The converter charges the DC link to the actual state of supply voltage. Because of that reason, DC link voltage is nearly equal to the peak value of phase-to phase voltage of supply voltage. DVR with no energy storage unit and load side connected shunt converter topology is shown Figure 3.53. In this topology series converters can control the DC link voltage (Nielsen and Blaabjer, 2005; Kangarlu et al., 2017).

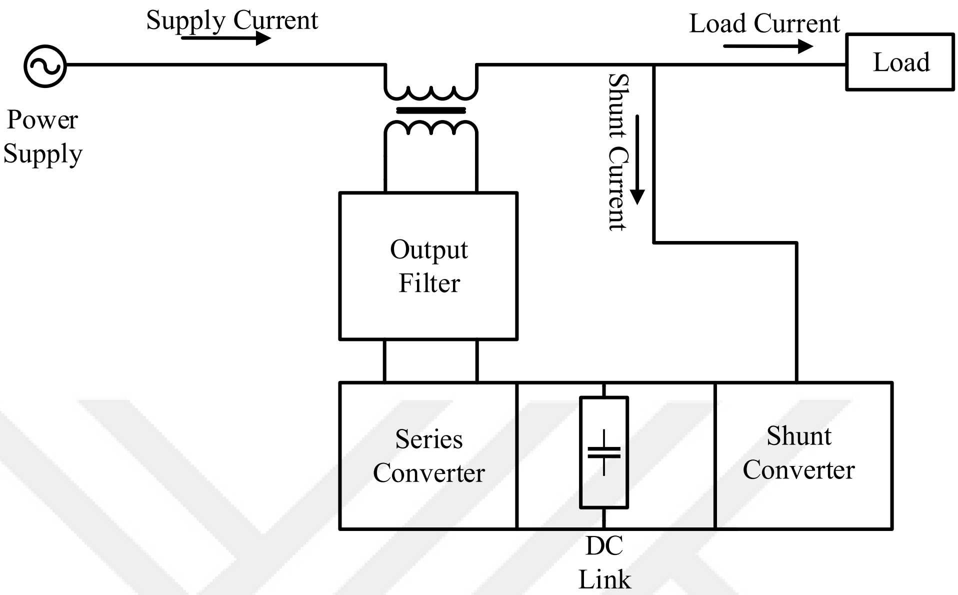

Figure 3.53. DVR with no energy storage and load side connected shunt converter (Nielsen and Blaabjer, 2005)

4. HARMONICS TERMS & ANALYSIS

Electric power systems contain different load groups and circuit elements thanks to the development of technology, the change in consumer needs and the new solutions brought to them. Electrical loads and their effects are generally divided into two groups as linear and nonlinear. Linear loads show a constant impedance characteristic against the system supply voltage, while non-linear loads show a variable impedance characteristic. Using this expression, nonlinear loads can be defined as, drawn current from the system does not have the same waveform as the supply system voltage. Nonlinear loads and their effects have increased with the development of semiconductor switching technology and the widespread usage of this switching technology in rectifiers, inverters, and many newly developed electronic circuits. The operating characteristics of linear and nonlinear elements in power systems have important effects on power quality. Especially nonlinear elements and loads have a serious detrimental effect on power quality.

Although the waveforms of current and voltage are periodic, they consist of the sum of the waves with sinusoidal properties, which have different frequency and amplitude. Periodic waves other than the fundamental wave are called harmonics. For example, the waveform formed by the combination of the fundamental wave and third, fifth and seventh harmonics is illustrated in Figure 4.1.

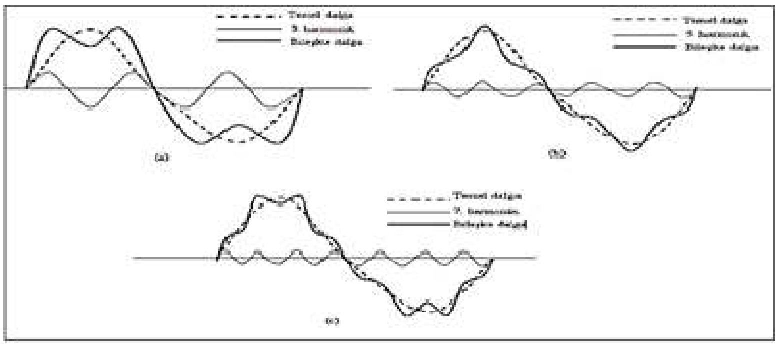

Figure 4.1.Harmonic Waveform

4.1. Fourier Series

French physicist and mathematician J.Fourier was revealed the non-sinusoidal periodic wave consists of the sum of many sinusoidal waves with different amplitude and frequency values. The series that can be expressed in this way is called the' 'Fourier Series'', and the components of this series are called the' 'Fourier Components'' (Das J.C., 2015).

Periodic wave must fulfill some conditions to be expressed with Fourier series, that is called Dirichlet conditions. An F(t) function must have the following features to satisfy the Dirichlet conditions (Sucu,1993).

- contains a finite number of discontinuities
- has finite number of minimum and maximum point
- average of the function takes a finite value

A function that satisfies the Dirichlet conditions mentioned above can be expressed as follows with the help of the Fourier Series.

$$f(t) = A_0 + A_1 cost + A_2 cos2t + \cdots + A_n cosnt + A_0 + B_1 sint + B_2 sin2t + \cdots + B_n sinnt \quad (4.1)$$

If we rewrite the above equation; it can be expressed as

$$f(t) = A_0 + \sum_{n=1}^{\infty}(A_n.cosnt + B_n.sinnt) \quad (4.2)$$

Where;

t= independent variable

A_0= constant term

A_1= fundamental component

The components represented by the index 2, 3, 4, ..., n are called harmonics.

$A_1, A_2, A_3 \ldots . A_n, B_1, B_2, B_3 \ldots . B_n$ are the Fourier coefficient of the $f(t)$.

Since the $''wt''$ variable is used instead of the $''t''$ variable in electrical power systems, the equations can be written in the below forms.

$$f(wt) = A_0 + A_1 coswt + A_2 cos2wt + \cdots + A_n cosnwt + A_0 + B_1 sinwt + B_2 sin2wt + \cdots B_n sinwt$$

or $f(wt) = A_0 + \sum_{n=1}^{\infty}(A_n cosnwt + B_n sinwt)$ (4.3)

The Fourier coefficients of $f(t)$ can be found using the following formulas.

$$A_0 = \frac{a_0}{2} = \frac{1}{2\pi}\int_0^{2\pi} f(t)dt \quad (4.4)$$

$$A_n = \frac{1}{\pi}\int_0^{2\pi} f(t)cosnwtdt = \sqrt{{a_n}^2 + {b_n}^2} \quad (4.5)$$

$$B_n = \frac{1}{\pi}\int_0^{2\pi} f(t)sinnwtdt \quad (4.6)$$

$$\varphi_n = \arctan(\frac{b_n}{a_n}) \quad (4.7)$$

4.1.1. Symmetry and Expressions in Non-sinusoidal Waves

According to the symmetry feature of waves, Fourier series expressions may differ from each other. Depending on the characteristic of the wave to be analyzed, not all terms in the Fourier series may be found. When the graph of this periodic function is examined, it is possible to identify which terms the series consists of. In the light of the obtained data, it can prevent unnecessary calculations (Kocatepe et al.,2003)

The symmetry feature of the waveform is basically categorized into three groups.

- Even function symmetry
- Odd function symmetry
- Half wave symmetry

4.1.1.1. Even Function Symmetry

If a function satisfies the condition that $f(-t) = f(t)$ is called as even function. This means that the function is the same for the positive x-axis and the negative x-axis, or graphically, symmetric about the y-axis. The graph of even function is illustrated in Figure 4.2.

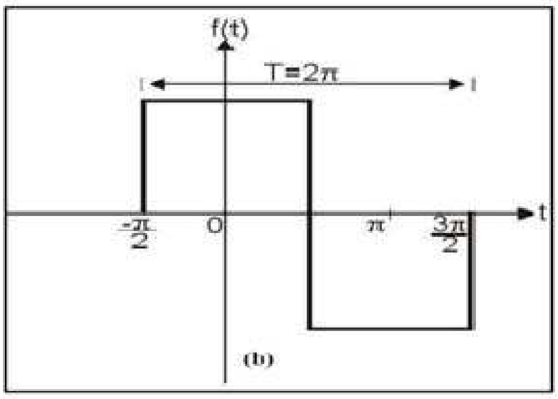

Figure 4.2. The graph of even function

Even functions consist of only cosine terms. That is, the coefficients of $B_1, B_2, B_3 \dots B_n$ which are sine terms coefficients are equal to zero. The Fourier transform for the even functions are expressed as follows:

$$f(wt) = A_0 + A_1 coswt + A_2 cos2wt + \cdots + A_n cosnwt \qquad (4.8)$$

4.1.1.2. Odd Function Symmetry

If a function satisfies the condition that $f(-t) = -f(t)$ is called as odd function. This means that, the graph of an odd function is symmetric with respect to the origin. In other words, the graph of an odd function is at the same distance from the origin but in opposite directions. For any two opposite input values of x, the function has opposite y values. The graph of odd function is illustrated in Figure 4.3.

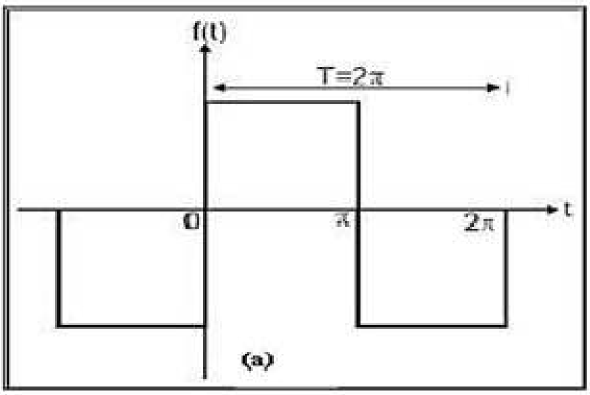

Figure 4.3. The graph of odd function

The odd function consists of only sine terms. That is, the coefficients of $A_1, A_2, A_3 \dots A_n$ which are cosine terms coefficients are equal to zero. The Fourier transform for the odd functions are expressed as follows:

$$f(wt) = A_0 + B_1 sinwt + B_2 sin2wt + \cdots + B_n sinnwt \quad (4.9)$$

4.1.1.3. Half-Wave Symmetry

If a function satisfies the condition that f(t+π) =-f(t) is called as half-wave symmetry. Half-period segment of a periodic function is shifted by π to the right or left along the horizontal axis, and if two curve segments overlap by folding around this axis, this function has half-wave symmetry. The area inside the curve of such a function on the horizontal axis is equal to the area inside the curve under the horizontal axis, and such a function is equal. There is no constant term in the Fourier series of the function, and the series consists of only odd-harmonic components (Uzan, 2013).

If a function has odd-function and half-wave symmetry, it can be expressed as:

$$f(wt) = B_1 sint + B_3 sin3t + B_5 sin5t \ldots + B_n sinnwt \quad (4.10)$$

If a function has even-function and half-wave symmetry, it can be expressed as:

$$f(wt) = A_0 + A_1 coswt + A_3 cos3wt + A_5 cos5wt + \cdots A_n cosnwt \quad (4.11)$$

If the areas (positive and negative areas) within the curves above and below the horizontal axis of a periodic function during a period are equal, constant term is equal to zero (Sucu,1993).

4.2. Harmonic Terms and Definitions

4.2.1. Distortion

The changes in the waveform of the current and voltage, which have a sinusoidal waveform in the fundamental frequency value, are called distortion.

4.2.2. Total Harmonic Distortion (THD)

Total harmonic distortion is the ratio of equivalent root mean square (RMS) voltage of all the harmonic frequencies (starting from the 2nd) over the RMS voltage of the fundamental frequency. THD is the indication of the how much distortion the wave has. It can be calculated by means of the Equation 4.12 and 4.13 for the voltage and current waveforms, respectively.

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^{\,2}}}{V_1} \tag{4.12}$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^{\,2}}}{I_1} \tag{4.13}$$

Where;

THD_V = Voltage total harmonic distortion.

THD_I = Current total harmonic distortion.

V_n = The effective value of the nth order harmonic of the voltage that is applied to the circuit.

I_n = The effective value of the nth order harmonic of the current that is applied to the circuit.

V_1 = The effective value of the voltage that is applied to the circuit at the fundamental frequency.

I_1 = The effective value of the current that is applied to the circuit at the fundamental frequency.

Various standards have been developed to keep harmonics under control in electrical power systems and to reduce their damage. One of the most important of this standard is the IEEE-519 Recomended Practice and Requirements for

Harmonic Control in Electrical Power Systems Standard developed by IEEE. According to the this standard voltage and current harmonic limits are shown in Figure 4.4.

Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
Below 69 kV	3.0	5.0
69 kV to 161 kV	1.5	2.5
161 kV and above	1.0	1.5

NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Current Distortion Limits for General Distribution Systems (120 V Through 69000 V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc}/I_L	<11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g. half-wave converters, are not allowed.

* All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

Where

I_{sc} = maximum short-circuit current at PCC.

I_L = maximum demand load current (fundamental frequency component) at PCC.

TDD = Total demand distortion (RSS), harmonic current distortion in % of maximum demand load current (15 or 30 min demand).

PCC = Point of common coupling.

Figure 4.4. IEEE Std 519-1992 Harmonic Limits

4.2.3. Total Demand Distortion (TDD)

Total demand distortion is the total harmonic current distortion defined by means of the ratio of the RMS value of the sum of the individual harmonic amplitudes to the maximum or rated demand load current. It can be calculated with the Equation 4.13.

$$TDD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n{}^2}}{I_L} \tag{4.13}$$

Where;

TDD= It is the total distortion ratio in the current depending on the demand load.

I_n = nth current harmonic component.

I_L = fundamental frequency demand current at Point of Common Coupling (PCC).

4.2.4. Form Factor

The form factor is the ratio of the effective value of the signal to the mean value. It is the indication of gives measure of the distortion of distorted sinusoidal wave.

$$k_f = \frac{Effective\ Value}{Mean\ Value} \tag{4.14}$$

4.2.5. Crest Factor

Crest factor can be defined as the ratio between the instantaneous peak amplitude of a waveform and the root mean square RMS value of the waveform.

$$Crest\ Factor = \frac{\text{Instantaneous peak amplitude}}{\text{RMS value of the waveform.}} \tag{4.15}$$

4.3. Source of Harmonics in Electrical Power Systems

4.3.1. Transformer

In electrical power systems, coils that has a core, causes harmonics on the system when their core reaches saturation. Transformers, which are frequently used in power transmission and distribution stages and have great importance, can also be considered as important harmonic manufacturer due to this feature. The main reason of transformers produce harmonics is that the magnetization property of their cores is non-linear. That is, since the magnetization feature of the transformer core is not linear after certain region, sinusoidal voltage and flux do not occur even if sinusoidal current is applied to the transformer winding. The magnetization curve of transformer is illustrated in Figure 4.5.

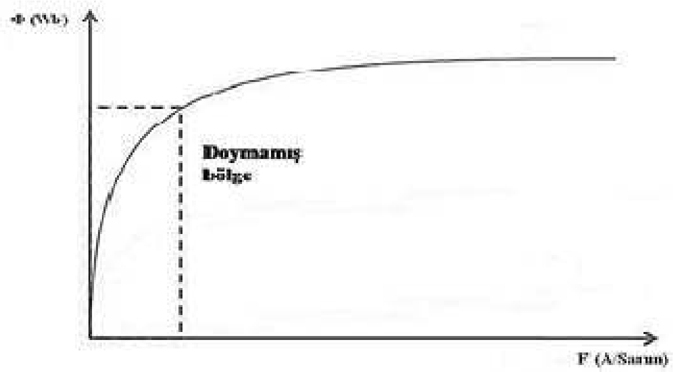

Figure 4.5. Magnetization curve of transformer (Kocatepe et al.,2003)

According to the magnetization curve of the transformer, the operation of the transformer in a region that is different from its rated values causes the core to reach saturation faster and the harmonic currents increase. Despite this negative feature, transformers do not produce very high amounts of harmonics. However, since electrical power systems consist of many transformers, the total harmonics produced can reach serious levels. For example, increases in third harmonic currents during the hours when the load in the system is low and voltage is high, usually in the morning, can be considered as a serious situation. (Uzan, 2013).

4.3.2. Uninterruptible Power Supply

Large industrial plants, hospitals, airports, etc. are systems that cannot tolerate situations where the mains voltage drops below certain limits, or the mains are completely cut off due to the sensitive loads they have and the critical operations they perform. Voltage drops and interruptions can cause many situations such as halt of production, data loss, disruption in the process and so on. To mitigate the adverse impact of these situations, uninterruptible power supplies are used. The basic circuit diagram of UPS is shown in Figure 4.6.

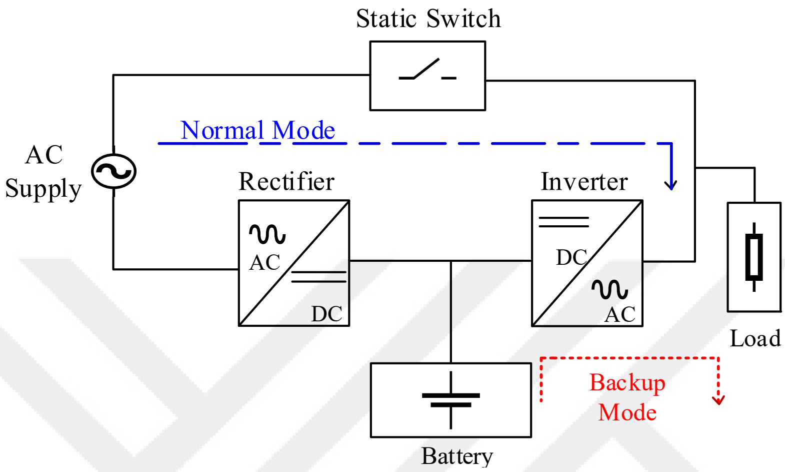

Figure 4.6. Basic circuit diagram of UPS (Aamir et al.,2016)

The AC voltage is converted to DC voltage by means of rectifier and stored in the battery unit. When the mains completely cut off, the energy stored in the batteries is converted back to the AC voltage via inverters and feeds the loads in the system. Since full sinusoidal voltage cannot be obtained in these transformations, harmonics occur on the electrical power systems.

4.3.3. HVDC Transmission Systems

As it is well known, in AC transmission system, the direction of alternating current and voltage changes every millisecond. These changes of directions cause losses in the form of heat energy. On the contrary of AC transmission systems, voltage and current do not need to the direction change in the DC transmission systems. So, to increase the transmission efficiency and decrease the system losses power is transferred by means of HVDC systems. Another reason of DC transmission systems is preferred is that two points with different frequency values can be connected to each other. The basic circuit diagram of HVDC transmission system is illustrated in Figure 4.7.

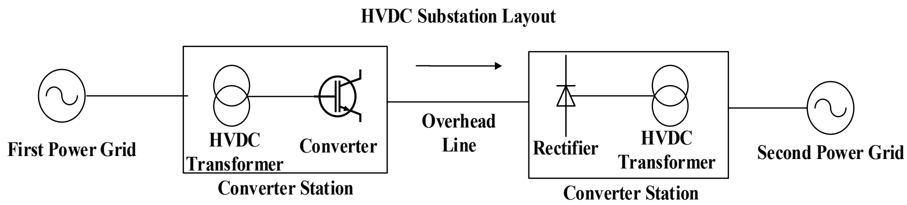

Figure 4.7. HVDC transmission system

In this system, AC is converted to the DC with rectifier and feeds the transmission line, and then converted back to AC via inverter at the end of the line. Power converters and inverters that is located at the beginning and end of the transmission line are sources of harmonics, because of their switching feature. Due to this reason HVDC transmission system is one of the main sources of harmonics.

4.3.4. Photovoltaic Systems

The technology that converts solar energy into electric current is called photovoltaic technology. Photovoltaic solar cells are that receive sunlight and consist of semiconductor materials that convert sunlight directly into DC electrical energy. Photovoltaic power system is used to feed some small loads that work directly with alternating current, as well as it can be connected to the electrical power grid in high-power applications.

Power electronics-based devices such as converters and inverters are used to transform the generated DC voltage to AC voltage. Since these devices are consisted of semiconductor elements and power conversion, they can cause harmonic problems. The basic stages of photovoltaic power conversion system are illustrated in Figure 4.8.

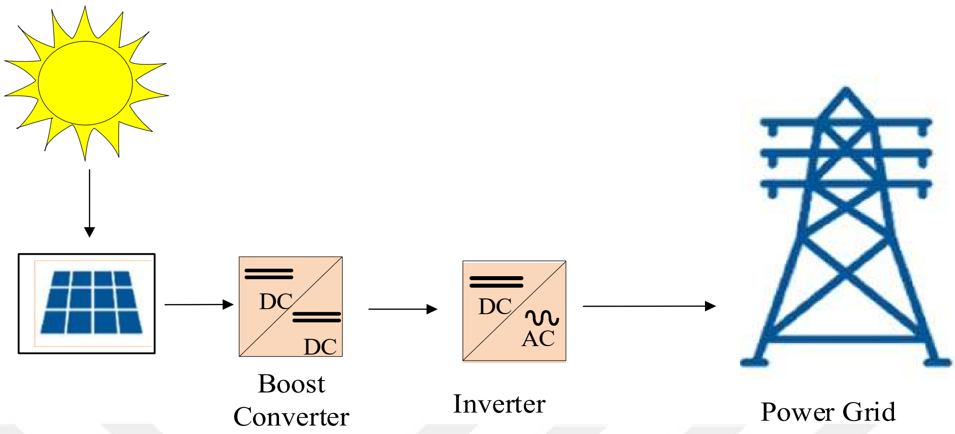

Figure 4.8. Photovoltaic power conversion system

4.3.5. Variable Frequency Drive

AC motors that are used in industry and various other applications may need to operate at different speeds depending on the process needs. The speed of the AC motor depends on the number of poles and frequency. Since it is a difficult process to change the number of poles of the motor in practice, the speed of the motors can be controlled by changing the frequency. The equipment used to adjust the speed by changing the frequency in AC motor circuits is called VFD or ASD. The working principle of VFD is explained as follows. Firstly, rectifier unit rectify the AC applied to its inputs and then DC voltage is obtained. Then, by means of the inverter units, obtained DC voltage is transformed to the AC voltage with variable frequency. Thanks to this alternating voltage with variable frequency, AC motors can operate at variable speeds. Since power conversion devices are consisted of semiconductor elements in drive circuit, they may cause serious harmonic problems.

4.3.6. IT and Office Equipments

The IT and office equipment such as printers, computers cause the third, fifth and seventh harmonics to increase due to the SMPS that contain. The increase in the third harmonics in the system causes an increase in the current passing through the neutral conductor. These equipment's also very sensitive to the harmonics in the system. Harmonic spectrum of the computer and printer is shown in Figure 4.9.

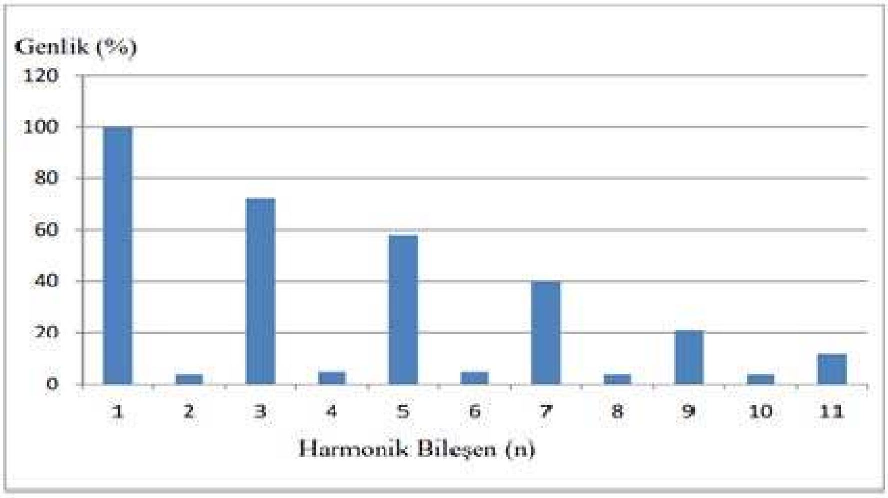

Figure 4.9. Harmonic spectrum of office equipments

4.3.7. Switch Mode Power Supply

Devices such as computers and printers, which are used in almost every home and workplace, have become an indispensable element of technological life. These devices can produce harmonics thanks to the switched power supply device that they contain.

Unlike traditional power supplies switch mode power supplies have positive features such as transformerless operation and compact structure. However, the main drawbacks of the switch mode power supplies are that it generates third harmonics. The increase in the third harmonics in the system causes an increase in the current passing through the neutral conductor and overheating. Current waveform and harmonic content of switch mode power supply is illustrated in Figure 4.10.

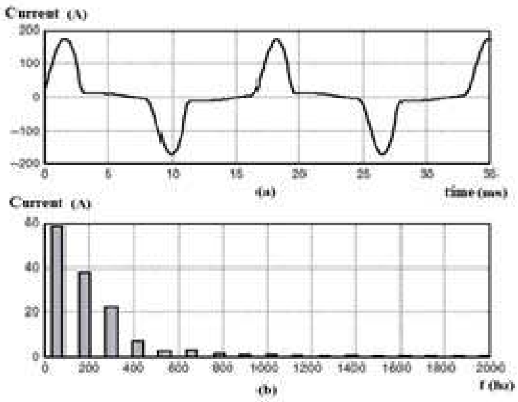

Figure 4.10. Harmonic spectrum of switch mode power supply

4.3.8. Grid Connected Wind Energy Turbine

The variable speed control method is used to minimize the fluctuations that will occur in the generator torque during wind speed fluctuations in new wind turbines developed in recent years. Minimum mechanical stress, maximum power tracking, maximum energy efficiency from wind and reduced noise are the main advantages of the variable speed system. In modern wind turbine power electronic based converters are widely used. As it is well known, the major drawbacks of this converters are their non-linear structure and switching feature. Due to these reasons, they are major source of harmonics and effect the power quality in bad ways (Hoseinpour et al., 2012; Li et al.,2008).

4.3.9. Static Var Compensator (SVC)

Static VAR Compensation (SVC) is one of the solutions of reactive power compensation and voltage regulation that is comprised of semiconductor devices, switching elements and capacitors. TCR and TSC are the commonly used SVC systems. Prevention of voltage sags, balanced load distribution, increasing efficiency of transmission and distribution systems are some benefits of TCR. SVC systems are extremely suitable for systems that reactive power needs change rapidly. Circuit elements used in less developed compensation systems are not capable to respond to this rapidly changing reactive power demand at the desired speed. To diminish this negative situation, semiconductor-based switching elements with high current carrying capacity such as IGBT or Thyristor are used in these situations. These systems, which are used for reactive power compensation, cause harmonics due to the non-linear structure of the semiconductor devices they have (Kocatepe et al.,2003).

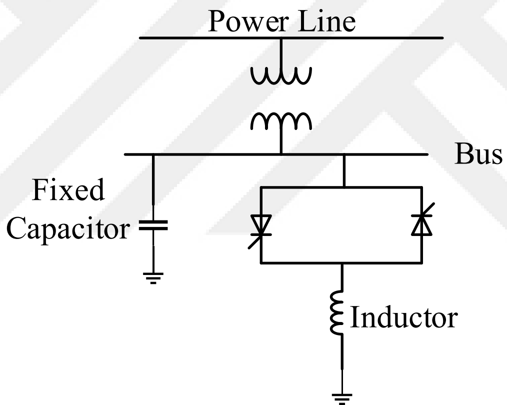

Figure 4.11. Basic circuit diagram of SVC system

4.4. Effects of Harmonics on Equipments and Systems

With the increase in the number of non-linear equipment in electrical power systems, serious increases have occurred in the harmonics produced by this equipment and injected into the grid. These injected harmonics not only disrupt the waveform of the loads, but also cause negative effects on other equipment in the system. For reasons such as increasing the power quality, eliminating the negative effects caused by harmonics, increasing the lifetime of the equipment, technical analyzes of harmonics should be carried out and necessary precautions should be taken against them. Since the devices in the system have different resistance to harmonics, they have different effects on each device. This leads to the emergence of different harmonic solutions. In this part of the thesis, the effects of harmonics on systems, equipment, and the precautions to be taken are examined in detail. The general effects of harmonics can be briefly listed as follows and then details about harmonics effects are given.

- Decreases the efficiency of energy in the production, transmission, and distribution stages.
- Causes additional losses on equipment and loads.
- Waveform distortion of generator and power grid.
- Increases the voltage drops
- Overloading and insulation damage of capacitors in reactive power compensation systems.
- Resonance problems
- Overloading of uninterruptible power supplies
- Malfunction of protection systems
- Shortening of the usage life of the equipment due to the insulation problems
- Loss of efficiency, overheating and noisy operation in electric motors
- Interference problem on communication systems

4.4.1. Effects of Harmonics on the Resistance

The order of the harmonics and their frequency values are directly proportional to each other. This means that higher order harmonics have larger frequency values. E.g., third harmonics have a 150 Hz frequency, and fifth harmonics have 250 Hz frequency value. As a natural result of the increase in the order of harmonics, the frequency values will increase, and this will cause the situation that is called ’’skin effect’’ on the resistance. Skin effect is the non-uniform distribution of electric current over the surface or skin of the conductor. As a result of the skin effect, the usable cross-section area of the conductor decreases with the increase in frequency. In this case, the resistance value due to harmonics R_H is added to the ohmic resistance value of the conductor in direct current R_{DC}. The new ohmic resistance value against the harmonic current becomes $R = R_{DC}+R_H$

Resistance value is calculated by using Equation 4.16. and 4.17.

$$x = 1.585.10^{-4}.\sqrt{\frac{f}{R_{DC}}} \qquad \text{where } 0 \le x \le 3 \quad R = R_{DC}.K_1 \qquad (4.16)$$

$$x > 3 \qquad R = R_{DC}.K_2$$

K_1 and K_2 are equal to the

$$K_1 = \frac{1}{2}\left[\sqrt{1+\frac{x^4}{48}}+1\right] \quad \text{and } K_2 = \frac{x}{2{,}828} + 0{,}26 \qquad (4.17)$$

Where ;

x is the constant that is depended on the R_{DC} and frequency of the conductor.

f is the frequency

R_{DC} is the ohmic resistance of DC

R is the new resistance value that is included skin effect

R_H is the resistance value that is caused by harmonics

K_1 and K_2 are the constant

In most of the analysis studies carried out, the new resistance value due to harmonics can be neglected, but this value should be considered when detailed analysis is required for the critical power systems (Circuitglobe Web Page).

4.4.2. Effects of Harmonics on the Inductive Reactance

Inductive reactance is a frequently used in equipment of electrical systems. They are mainly used for modelling of cables, motors, and transformers. In a system without harmonics, the inductive reactance value is calculated by means of Equation 4.18 and 4.19.

$$X_L = w.L = 2.\pi.f.L \tag{4.18}$$

This value is calculated by using below equations that includes n.th order harmonics.

$$X_{Ln} = n.X_L \tag{4.19}$$

Where;

X_L is the inductive reactance at fundamental frequency

w is the angular velocity (Rad/sec)

L is the inductance

f is the frequency

X_{Ln} is the inductive reantance value at n.th order harmonics

n is the harmonic order

Consequently, harmonic order and inductive reactance value is proportional each other.

4.4.3. Effects of Harmonics on the Capacitive Reactance

Just as inductive reactance is used for modeling electrical equipment, capacitive reactances are also frequently used in modeling studies. In a system without harmonics, the capacitive reactance value is calculated by means of Equation 4.20 and 4.21.

$$X_C = \frac{1}{wC} = \frac{1}{2.\pi.f.C} \tag{4.20}$$

This value is calculated by using below equations that includes n.th order harmonics.

$$X_{Cn} = \frac{X_C}{n} \tag{4.21}$$

Where ;

X_C is the inductive reactance at fundamental frequency

w is the angular velocity (Rad/sec)

C is the capacitance

f is the frequency

X_{Cn} is the capacitive reantance value at n.th order harmonics

n is the harmonic order

Consequently, harmonic order and capacitive reactance value is inversely proportional each other.

4.4.4. Effects of Harmonics on the Transformer

One of the most important elements of electrical power systems is the transformers that is used for the transmission of energy by increasing or decreasing the voltage and current values without changing the frequency value of the system.

As mentioned before, transformers, which have an important role in power systems, are harmonic generators due to their nonlinear magnetization feature. At the same time, they are seriously affected by harmonics that is created by other equipment in the power system. Transformers are affected by harmonics in the system basically in two ways. Voltage source harmonics and current source harmonics have different effects on transformers. While current harmonics cause an increase in copper (I^2R) and leakage flux losses, voltage harmonics cause an increase in iron losses and insulation stress due to foucault and hysteresis currents. In addition to these negative effects, harmonics also cause sound and noise increase in the transformers.

If the inductive reactance of the transformer and the capacitive reactance value of the system that is fed by the transformer are equal, the resonance phenomenon, which is an important effect created by the harmonics in the systems, may occur. The negativities caused by current and voltage harmonics on the transformer are closely related to the frequency value. As a natural consequence of increasing the order of harmonics, the frequency value will also increase. Increasing the frequency causes the hysteresis losses to increase. Finally, harmonic components with high frequency values cause overheating of transformers and contribute to the increase in losses. In this regard, high-frequency harmonics have a more critical importance than low-frequency components. That is, the increase in frequency causes the losses on the transformer to increase (Uzan, 2013; Kocatepe et al.,2003).

4.4.5. Effects of Harmonics on the Electric Motors

The biggest effect of current and voltage harmonics in rotating machines is the decrease in efficiency and noisy operation of equipment by increasing copper losses and heating. The harmonic related heating problem occurs in the electric motor in the form of high rotor temperature. Heating problems caused by harmonics damage the insulation of the motor and shorten the usage life of the equipment. The efficiency of motor is mitigated by the harmonics nearly %5-10 (Arrillaga et al.,2003).

4.4.6. Effects of Harmonics on the Circuit Breakers and Fuses

In electrical power systems, harmonics can cause serious problems by affecting the current breaking properties of circuit breakers and fuses used to protect equipment and people. The electromagnetic induction coil used in circuit breakers will not operate correctly when there are harmonics in the system and this circumstance will cause situations such as incorrect opening and closing operation of the breaker. As it is known, harmonic currents cause heating on the system. Each of the fuses has a certain current carrying capacity according to the designed values. The increase in heating causes changes the current carrying characteristics of the fuses and damage the insulation material. As a natural consequence of this, untimely and incorrect tripping may occur in fuses (Uzan, 2013).

4.4.7. Effect of Harmonics on the Protection Elements

In cases, where the necessary precautions are taken to reduce the effect of harmonics in the system or when these harmonics are at a negligible level, the effect of harmonics will not be perceivable level in applications such as overcurrent protection. On the other hand, third harmonics that is occurred in the distance protection relay applications can cause faulty measurements and operations (Sucu,1993).

The main adverse effects of harmonics on the protection relays are changing the operating characteristics of overcurrent and overvoltage relays, sensitivity, and response time of protection and as a result of these, faulty operation. Recent studies have shown that harmonic distortion between 10%- 20% may cause adverse effects on the operation of protection relays. (Uzan, 2013; Arrillaga et al.,2003).

4.4.8. Effect of Harmonics on the Conductors

The biggest effect of harmonics on the conductors is the overheating. This overheating can occur in two ways. As mentioned in the previous section, the first cause of the overheating is the phenomenon called "skin effect". The skin effect is the accumulation of this current on the outer surface of the conductor while the current is transmitted on the conductor and result of this the increase in the resistance of the conductor. As explained before, the resistance value is proportional to the frequency. Loads, which are in three-phase four-wire systems and have a nonlinear structure, where single-phase loads are fed, cause unbalanced loading of the system and high currents flow on the neutral conductor. This situation is the second reason of the overheating on the conductor. To overcome this negative situation, the cross-section of the neutral conductor should be chosen large, and attention should be paid to the distribution of the loads to the phases (Uzan, 2013).

4.4.9. Effect of Harmonics on Capacitor Groups

Capacitors, which are the main elements of the systems designed for reactive power compensation and power factor correction in low voltage distribution systems, are among the elements most damaged by the adverse effects of the harmonics. The main adverse effects of harmonics on capacitor groups are that they are exposed to overcurrent and therefore their insulation can be damaged. As mentioned before in previous section, since the capacitive reactance is inversely proportional to the frequency, the current drawn by the capacitors will increase as the order of the harmonics increases. As a natural consequence of this situation, effects such as overloading, insulation stress and overheating may occur on the capacitors at harmonic frequency. The current drawn by the capacitor groups at the nth harmonic can be calculated by using Equation 4.22.

$$I_n = n.w.C.U_n \tag{4.22}$$

The effective value of the voltage and current at the capacitor is calculated by using Equation 4.23 and 4.24.

$$U_C = \sqrt{\sum_{n=1}^{\infty} U_n^{\ 2}} \tag{4.23}$$

$$I_C = \sqrt{\sum_{n=1}^{\infty} I_n^{\ 2}} \tag{4.24}$$

There is an important issue that should be considered during the design phase of compensation systems. The presence of voltage harmonics in the system causes an increase in the power of capacitor groups. For this reason, total reactive power including fundamental components and harmonics should be considered while designing the compensation system. In this case, total reactive power must not exceed the rated value of the reactive power. The total reactive power that is explained in this case can be calculated using Equation 4.25.

$$Q = \sum_{n=1}^{\infty} Q_n \tag{4.25}$$

Since capacitor groups are one of the equipment where the effect of harmonics can be noticed early, when capacitor groups affected by harmonics are detected in the power system, detailed power quality analyzes should be performed. According to the obtained results, necessary measures should be taken to mitigate the adverse effects of harmonics both capacitor groups and whole system (Uzan, 2013).

4.4.10. Effects of Harmonics on Communication Systems

As the degree of harmonics increases, their effect decreases. For example, the effect of the 3rd harmonic in an electrical power system is higher than the 11th harmonic. Although the effect of high harmonics in electrical power systems is weak, the same situation is not valid for communication systems. High order harmonics pass over the neutral line to the communication lines, causing interference with the communication line. To overcome and mitigate the effect of interference between power and communication lines shielding should be done (Eberhard,2011).

4.5. Resonance Phenomena

While inductive reactance changes in directly proportional with harmonic frequency, capacitive reactance varies inversely proportional with harmonic frequency. The resonance phenomena can be defined as the capacitive reactance value equals to the inductive reactance value. The frequency value when these two values are equal is called the resonance frequency. One of the most important situations that will affect the harmonic orders that will occur in the system is the resonance phenomenon and it is categorized into two basic groups as series resonance and parallel resonance.

4.5.1. Parallel Resonance

Parallel resonance phenomenon is a frequently encountered power quality problem. As mentioned in the previous section, resonance phenomenon occurs when the capacitive reactance value equals to the inductive reactance value. Parallel resonance can occur because of the capacitor banks in filters and reactive power compensation circuits. When the resonance event occurs, although the admittance value of the circuit is small, small resonance currents occur at high voltage values. This means that in the resonance event, the impedance value is at its maximum value and even if a low amplitude current passes through the circuit, high resonance voltages occur on the circuit elements. This resonance voltage that is applied to the equipment can affect the performance in bad ways. The basic circuit diagram of parallel resonance circuit and variation of current and impedance with frequency are depicted in the Figure 4.12 and 4.13.

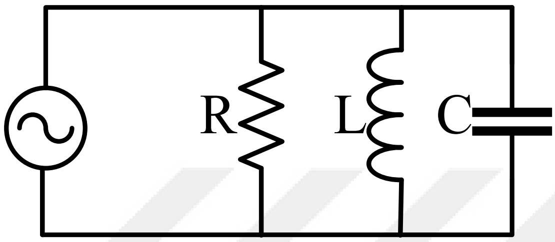

Figure 4.12. Parallel resonance circuit

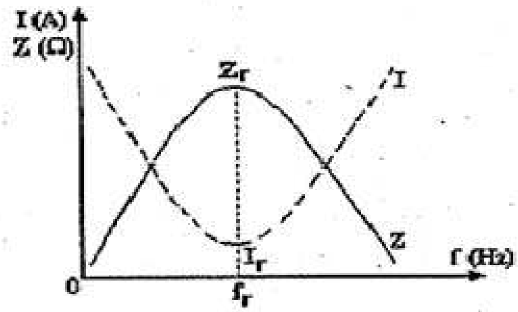

Figure 4.13. Variation of current and impedance with frequency

When the circuit diagram of parallel resonance is examined, the circuit impedance is equal to the Equation 4.26.

$$Z = \frac{-j.R.X_L.X_C}{R.(X_L - X_C).j.X_L.X_C} \tag{4.26}$$

Since X_L and X_C will be equal in the resonance event, resonance frequency is equal to the Equation 4.27.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (4.27)$$

In this case, the current passes through the circuit and capacitor are equal to the Equation 4.28 and 4.29, respectively.

$$I_r = \frac{V}{R} \quad (4.28)$$

$$I_{Cr} = \frac{V}{X_{Cr}} = I_r.\frac{R}{X_{Cr}} \quad (4.29)$$

4.5.2. Series Resonance

As with the parallel resonance event, the series resonance event occurs when the capacitive reactance is equal to the inductive reactance. When series resonance occurs, the impedance of the circuit is low. This means that even if a low amplitude voltage is applied to the circuit, a high amplitude resonance current will flow through the circuit elements. The basic circuit diagram of series resonance circuit and variation of current and impedance with frequency are depicted in Figure 4.14.

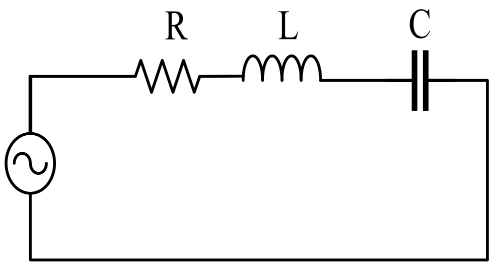

Figure 4.14. Series resonance circuit

Variation of current and impedance with frequency is given in Figure 4.15

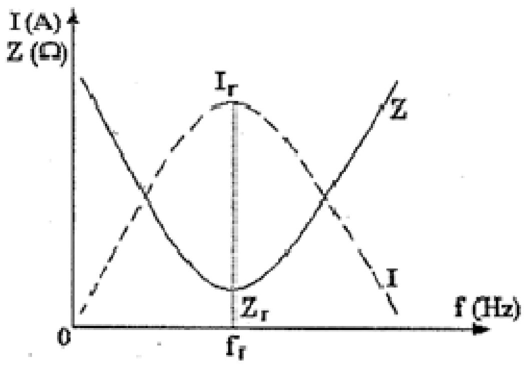

Figure 4.15. Variation of current and impedance with frequency

When the circuit diagram of series resonance is examined, the circuit impedance is equal to the Equation 4.30.

$$Z = R + jwL + \frac{1}{jwC} = R + j(X_L - X_C) \tag{4.30}$$

Since X_L and X_C will be equal in the resonance event resonance frequency is equal to the Equation 4.31.

$$f_r = \frac{1}{2\pi\sqrt{LC}} = \frac{f}{w\sqrt{LC}} = f\sqrt{\frac{X_C}{X_L}} \tag{4.31}$$

In this case, the current passes through the circuit and inductance voltage equals to Equation 4.32 and 4.33, respectively.

$$I_r = \frac{V}{R} \tag{4.32}$$

$$V_r = I_r . X_r = V . \frac{X_L}{R} \tag{4.33}$$

Moreover, capacitor voltage is calculated by using Equation 4.34.

$$V_{Cr} = I_r . X_c = V . \frac{X_C}{R} \tag{4.34}$$

High currents passing through the series resonance event cause overheating problem on equipment's such as contactors, connection elements and capacitor groups. Overheating in capacitors causes shortening of the service life and inability to fulfill its duty (Kocatepe et al.,2003; Uzan, 2013).

4.6. Harmonic Filtering in Electrical Power Systems

There are some precautions that can be taken to reduce the adverse effects of harmonics on the electrical power systems and its components. These precautions can be taken at the design stage of the equipment that is used in the electrical power system, or they can be provided by some studies to be carried out on the established system. The basis of the studies in the design phase is based on the selection of equipment that will create the least total harmonic distortion on the system. For example, uninterruptible power supplies, speed control devices and the selection of the transformer connection type according to the total harmonic distortion are issues that should be carefully evaluated during the design phase. However, harmonics and their effects show their effects more clearly in installed systems.

4.6.1. Zigzag Connection Type of Transformer

The low impedance value of the zigzag-connected transformer allows zero-sequence currents to flow over the neutral conductor and this creates a harmonic filter effect. Since the current will choose the path with a lower impedance value, the currents flowing to the neutral conductor to the transformer will decrease. This situation is illustrated in the Figure 4.16.

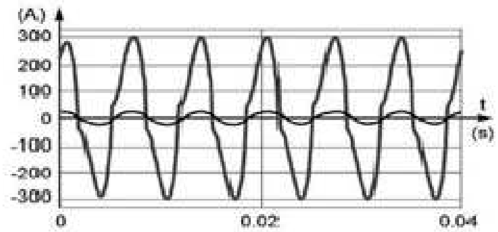

Figure 4.16. Neutral curret flow (Arrillaga et al.,2003)

The high current flowing in the neutral line is the main cause of heating problems in the electrical power system. This is especially true when the loads are unevenly distributed at the phases and commercial buildings. To solve this problem, a zigzag connection is used in the secondary side of the transformer. Zigzag transformers are used third harmonics problems, heating in the neutral line and problems at the star points of the transformers. Because of these features, zigzag transformers are generally used to eliminate zero sequence harmonic components in commercial buildings where single-phase loads are used heavily, such as lighting and computers. According to the studies carried out, transformers with zigzag connection can filter the third harmonic currents by 50% (Dugan R.C., Mcgranaghan M.F., 2012; Uzan, 2013).

4.6.2. Harmonic Filters

Even if precautions are taken to reduce the effects of harmonics during the design phase of the system, these precautions can often be insufficient against the developing system needs. Against these situations, it may be necessary to add new equipment to the existing system to reduce the effects of harmonics. Harmonic filters are elements that can be integrated into the system according to the developing needs and are widely used to prevent harmonics.

The main task of harmonic filters is to mitigate the effect of harmonic currents and voltages at different frequencies. They are divided into two main groups as active and passive filters according to their working characteristics. Classification of harmonic filters are shown in Figure 4.17.

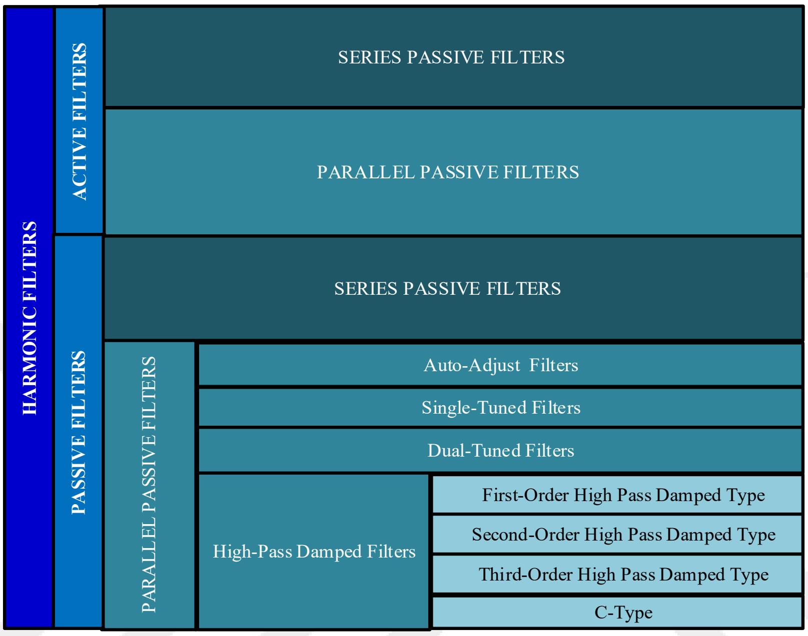

Figure 4.17. Classification of harmonic filters

4.6.2.1. Passive Filters

Passive filters are created by using passive circuit elements. It has a low or high impedance value according to the designed filter type at a certain frequency value. It can be connected to the circuit in series or parallel.

4.6.2.1.(1). Series Passive Filters

Series passive filters consist of an inductance (L) element and are connected in series between the system source and the harmonic generating element. While this filter exhibits low impedance at the fundamental frequency, it provides high impedance at harmonic frequencies to filter harmonics. Series passive filter circuit diagram is shown in Figure 4.18.

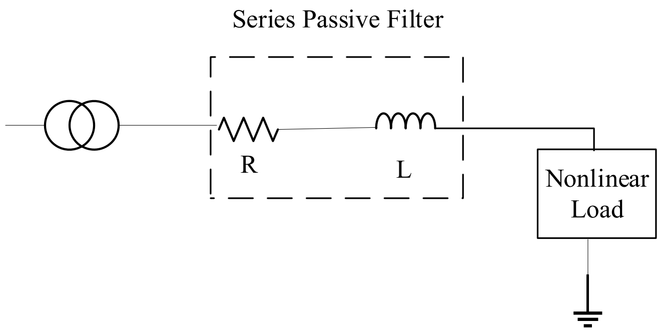

Figure 4.18. Circuit diagram of series passive filters

Series filters are generally used for filtering loads such as variable frequency drives that have nonlinear load characteristics. Series passive filters do not cause resonance when compared to parallel passive filters. In addition to this positive feature, it has some disadvantages such as the fact that the entire load current passes through the filter and this situation increases the cost and size of the filter to be designed. Another important disadvantage of series passive filter is that it causes voltage drop (Uzan, 2013).

4.6.2.1.(2). Parallel Passive Filters

The working principle of the parallel passive filters is based on the resonance phenomenon. That is, the values of the inductance (L) and capacitance (C) elements that will create resonance at the frequency of the harmonic component to be filtered are calculated and their connection with the system is ensured. Parallel passive filter circuit diagram is shown in Figure 4.19.

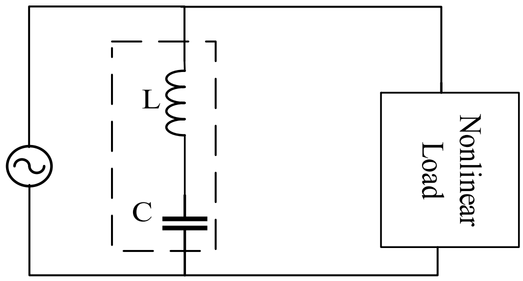

Figure 4.19. Parallel passive filters

In parallel passive filters, filtering operation can be performed by means of creating resonance for each harmonic frequency by using the resonance feature. However, since creating resonance for each harmonic component will not be a suitable solution for system design, it is necessary to create a resonance for the component with the highest amplitude value and to create a single resonance for the remaining small amplitude components. Compared to series passive filters, ıt has low cost and size. Because only currents belonging to tuned harmonic components flow in parallel passive filters. This situation directly affects the costs and sizes of the equipment to be used in filter design. In addition to these positive features, it can be used reactive power compensation with the capacitor used in its circuit. However, despite these positive aspects, it can cause dangerous resonance problems in electrical power systems. According to their design, it can be categorized four main groups as, single-tuned (band-pass) filters, dual-tuned filters, auto-adjust filters and high pass damped filters.

4.6.2.2. Active Filters

One of the most important power quality problems occurring in electrical power systems is undoubtedly harmonics. If necessary, precautions are not taken against harmonics, serious effects may occur on the equipment and the electrical power systems. The most common precautions to be taken to eliminate the effect of harmonics is various filtering methods. As mentioned before, harmonic filters are basically divided into two main groups as passive and active filters. To mitigate the adverse effects of harmonics, Passive filters are commonly used, due to their low cost. However, passive filters may be insufficient in eliminating the negativities caused by harmonics due to some of the reasons stated below.

- Due to the deviations in the values of the used circuit elements, the adjustment frequency of the filter may change over time. This causes a decrease in the performance of the filter.
- After the filter system is installed, the performance of the filter decreases due to the increase in the amount of nonlinear load.
- Resonance phenomenon

To overcome the above negativities of passive filters, active filters are developed. Active power filters consist of a control unit and an inverter operating with pulse width modulation. Thanks to the control unit, they analyze the harmonics drawn by the load and eliminate the harmonics by injecting the same harmonics in a suitable phase into the system in reverse phase. In addition to reducing the effect of harmonics of active power filters, it can also perform different functions such as reactive power compensation, voltage regulation, neutral current compensation, and current and voltage imbalances. In addition to these positive features, high installation cost is an important disadvantage.

4.6.2.2.(1). Parallel Active Filter

As the name indicates, they are connected to the system in parallel and filter the harmonics. Parallel active filters inject currents of the same amplitude but opposite phase with the harmonic currents drawn by the load into the system. The basic connection diagram of parallel active filter is illustrated in Figure 4.20.

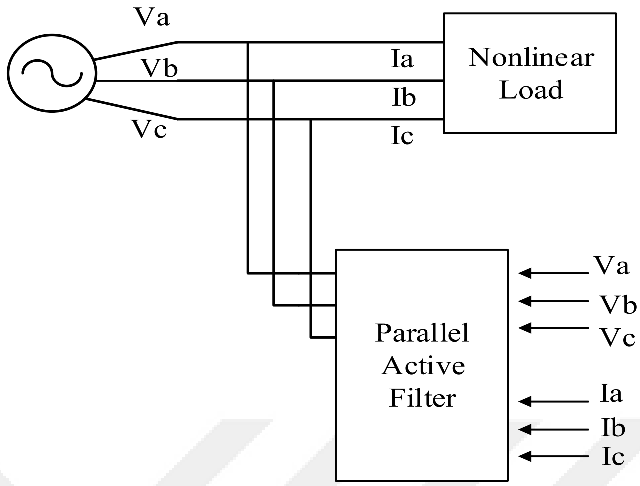

Figure 4.20. Circuit diagram of parallel passive filters

4.6.2.2.(2). Series Active Filter

Series active filters are connected to the power systems by means of transformers. By using series active filters, voltage unbalances and fluctuations can be prevented. Comparison of the passive and active filters are given in Table 4.1.

Table 4.1. Comparison of passive and actie filters

Parameter	Active Filters	Passive Filters
Components	Consist of active elements (transistor,op-amp)	Consist of passive elements (resistor,capacitor,inductance)
Cost	High	Low
Complexity	Complex	Less complex
Weigt	Low	Bulky
Q factor	High	Low
Power Supply	Needed	Not needed
Sensitivity	High	Low
Resonance Phenomenon	Low	High
Maintenance	Difficult	Easy
Response to the load variation	Fast	Slow
Installation option	Indoor	Indoor & Outdoor
Target harmonics	2nd to 50th	Only single harmonics

Series active filters are used to eliminate the voltage harmonics. Basic connection diagram to the power system of series active filter is illustrated in Figure 4.21.

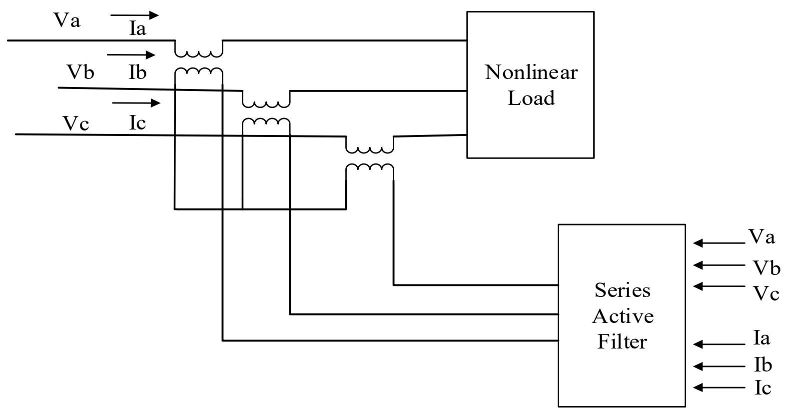

Figure 4.21. Circuit diagram of series active filter

5. EFFECTS OF PQ PROBLEM ON FACILITIES

Thanks to the development of technology in recent years, new products have emerged in many fields, especially in the field of power electronics. The rapid development of technology and industry has significantly increased the amount of consumed energy in the industrial facilities in all over the world. The industrial continuous production systems which are integrated with the developing technology and contain highly sensitive processes stages and equipment's, are closely associated with the reliability of the electrical power supplied. This situation makes essential the emergence and evaluation of the concept of electrical power quality. The interpretation of the concept of "electrical power quality'' by the energy supplier point of view and the end user point of view may differ from each other. From the point of view of the energy supplier, the concept of electrical power quality can be defined as a voltage of constant magnitude and frequency for 24/7. Due to the various faults, natural events and load characteristics in the electrical power system, deterioration in electrical power quality may occur. The end-user side is the party that uses the power provided by the energy supplier and is most affected by this situation. The deviation of the electrical power provided by the supplier from the ideal situation can cause serious economic and technical problems at the end user side. According to the end user, power quality term can be defined as any power problem manifested in voltage, current, or frequency deviations that result in failure or misoperation of customer equipment. As can be understood from the definitions, power quality has a different definition according to various perspectives. Because of this situation, there is no clear agreed definition of electrical power quality (Bollen, 2001).

As aforementioned before, important developments have been experienced in the field of electronics-based equipment thanks to the technological developments. Products designed with these technological developments such as VFD, advanced microprocessors, PLC are more vulnerable to changes in power quality and these equipment's are frequently used in as pharmaceutical industry, chemistry, paper, and semiconductor sectors. Considering that these facilities have continuous production features and consist of many different production stages that are very closely related to each other by design, power quality problems can result in serious problems. To mitigate the adverse aspect of power quality problems some measures should be taken.

In the first part of this chapter, the main power quality problems, and the effects of these problems on industrial facilities are evaluated. In the second part, variable frequency drives which are affected by the changes in electrical power quality, and the measures that can be taken against the effects of power quality problems on these devices are examined.

5.1. Common Power Quality Problems of Industrial Facilities

Power quality problems manifest themselves in the simplest form with the changes in current, voltage and frequency. The most common power quality problems that occur on the industrial facilities and their definition is given below.

Surges or Transients: It can be defined as a short-term but high-energy electrical pulse that is induced on an electrical circuit or equipment. The main reasons of transients are mainly divided into two subcategories as internal and external sources. The main internal sources of transients are capacitor, circuit breaker and power semiconductor switching, electrostatic discharge and arcing respectively. On the other hand, external sources can be listed as follows; Lightning, short circuits caused by animals, bad weather conditions and loose connections etc. The effects of surges or transients on the equipment and electric circuits are loss of data, chronic degradation of equipment's etc (Resources Web Page).

Interruptions: It occurs when the supply voltage or load current drops below 0.1 pu for a period not exceeding one minute. Power system faults, equipment failures and control malfunctions are the main reasons of the interruptions. Interruptions may cause data and production loss, tripping of equipment and stoppage of production etc. (IEEE 1159-2019)

Voltage Sags: It can be defined as a reduction of voltage or current in rms value at rated frequency to the range between 0.1pu and 0.9 pu and lasting 0.5 cycle to the 1 minute. The main reasons of voltage sags are lightning, commissioning of large asynchronous motors, inrush currents of transformers, switching of large loads, SLG (IEEE 1159-2019).

5.2. Effects of Power Quality Problems to The Industrial Facilities

Power quality problems can show their effects on industrial facilities in many ways. These negative effects can manifest themselves directly or indirectly. Main adverse effects and their explanations are given below.

Loss of Production: These are the losses caused by power quality problems that are not produced and therefore cannot be sold when production is interrupted because of the power quality problem.

Production Interruption: There are many related processes in continuous production facilities. If any of these related processes is affected by power quality problems, it will adversely affect the next process stage. In such a case, the final product will not be able to meet some predefined quality parameters. To obtain a final product with the desired qualifications, production may be interrupted and the whole process may need to be started again.

Loss of Income: A power quality problem will directly affect the sales and cause disruptions in production plans. Various penalty actions may be applied due to delays in production plans. In all these situations can cause serious income losses.

Wasted Energy: An electrical problem in the production process will cause serious energy wastage in the time that pass until the entire process is restarted and the final product meets certain quality parameters. In fact, the energy in the time until the desired quality product is produced will be wasted.

Decreased Equipment Life: Voltage sags and short-term transients with high energy may cause high currents in electrical circuits. This situation can have serious adverse effects especially on electronic cards, controller unit and cause malfunctions on these equipment's. In addition, harmonics, which are another important power quality problems as explained before, and imbalances between phases cause overloading and heating problems of equipment such as transformers and motors and effects their internal structure. Thus, the useful life of these equipment is shortened.

Reduction in Competitiveness: Power quality problems will result in poor quality final products and, naturally this final product decreases the customer satisfaction. Due to these problems experienced, company miss the deadline of orders. Naturally, this situation effects the prestige of company in bad ways and reduce the chance of competition in the market.

Increased Cost of Labor: Since it will take a certain time to eliminate the changes in the process conditions and to reproduce the desired quality product, extra personnel may be needed. This will result in an increase in labor costs as it will result in overtime work (Vegunta and Milanovic, 2011; Muhamad et al.,2007).

5.3. Structure of VFDs and Effects of PQ Problem on VFDs

Electric motors are used in a wide variety of implementation in the industry with different application and load characteristic such as fan, pump, compressor, elevator etc. applications. According to the recent research, electric motor load constitutes approximately 70% of the electricity consumption of the industrial sector all over the world (De Souza et al.,2022)

The wide usage area of the motor's appearance various speed needs for different applications. The speed of three-phase asynchronous motors is directly proportional to the supply voltage frequency and inversely proportional to the number of poles. There are two ways to change the speed of three-phase asynchronous motors. These are changing the frequency of the voltage applied to the motor or changing the number of poles of the stator windings, respectively. Since it is practically not possible to change the number of poles in the windings of asynchronous motor, the speed of a asynchronous motor can only be changed using the relationship between the frequency of the supplied voltage and itself. Devices that are designed to change the speed of asynchronous motors are called variable frequency drives or variable frequency drives (Von Juanne et al., 1999).

Variable frequency drives basically compromise of four main units. These are AC/DC rectifier unit, DC bus and filter unit, DC/AC inverter unit and control unit, respectively. The basic circuit diagram of the variable frequency drives is shown in Figure 5.1.

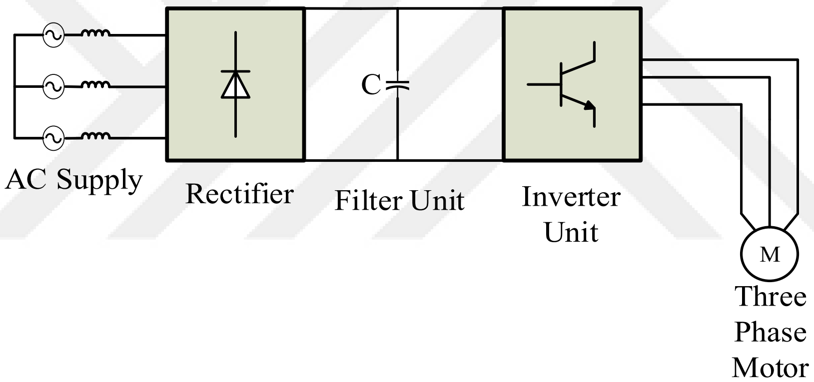

Figure 5.1. Structure of Variable Frequency Drives

The explanation of the main unit of variable frequency drive is given below.

AC/DC Rectifier Unit: Consists of diodes or IGBT and converts the applied AC voltage to DC voltage.

DC Bus and Filter Unit: This unit basically has two main tasks. These are to filter the ripples of the DC voltage that is coming from the AC/DC rectifier unit and to provide energy to the inverter unit when a power outage occurs, thanks to the capacitors it contains. The size of the capacitor is directly proportional to the power demanded by the inverter.

DC/AC Inverter Unit: It is the part where the speed control of the motor is provided by converting the filtered DC voltage to AC voltage of adjustable magnitude and frequency (Epperly et al.,1997).

By means of the usage of the variable frequency drives where different speed requirement of various process, provide energy savings in applications with variable torque loads and reduced motor speeds, reduction the mechanical and thermal stresses on the motor are achieved. Due to these efficacies, the usage of variable frequency drives in industrial applications has been increasing rapidly in recent years. Metal casters, paper machines, winders, extruders, fan, pumps, compressors, and crane are the main applications where variable frequency drives are used (Von Juanne and Enjeti,1997).

Variable frequency drives are vulnerable to power quality problems where occur in the electrical power grid. As the device is affected by the variations in the electrical power grid, it can also cause negative effects on the electrical power grid and electric motors. As mentioned before, variable frequency drives convert the supply voltage to DC voltage and this DC voltage is converted back to AC voltage in the inverter unit. The switching feature of power electronics elements used during these transformations is the large harmonic generator. The effects of injected harmonics into the electric power grid cause overheating of transformers, cables, motors, alternators, and capacitors; and also malfunction of relays and protection equipment. Additionally, switching feature of inverter induce current at motor shafts. If there is no equipment grounding with adequate conditions, these currents cause bearing failures (Epperly et al., 1997; Maosum et al.,2007).

Another important problem caused by variable frequency drives is EMI. EMI is the disturbances on an electrical circuit caused by electromagnetic signals that is created from an external source. Due to their high switching capacity, IGBTs are used as switching elements in variable frequency drives. Although high-speed switching provides effective frequency control, it is the biggest cause of EMI generation. EMI causes equipment malfunction and communication problem between systems. To annihilate the EMI problem, use of shielded power cable connection between motor and drive, twisted control cables and EMI filter may use (Vfds Web Page).

Variable frequency drives have effects on the electrical power grid and equipment's as described before. However, the rest of this study is about the effect of power quality events occurring in the electrical power grid on variable frequency drives, and the solution methods developed for these effects are examined in detail.

The main power quality problems that affect the variable frequency drives are voltage sags, swells, and momentary interruptions, respectively. Voltage sags, that is experienced at a rate of 10%-30% of the nominal voltage and has a duration of 3 to 30 cycles, effects variable frequency drives. This event causes either a momentary stoppage or a complete stop of the relevant process where variable frequency drives are used (Von Juanne and Enjeti,1997). Most of variable frequency drives have a voltage sensor on the DC bus unit that measures the DC voltage. When voltage sag occurs at the supply voltage of the variable frequency drive, this will cause the DC link voltage to drop. A 15% to 30% decrease in DC voltage will cause the inverter to not output. In this case, the speed of the motor will gradually decrease, and may cause to stop relevant process. This reduction in DC bus voltage may vary depending on the magnitude and duration of the distortion, imbalances between phases, the current capacity of the DC bus and the power demanded on the load side (David et al., 1993).

As explained in the previous of the study, variable frequency drives are highly sensitive devices to the variations in power quality disturbances, especially oltage variations. Voltage tolerance of variable frequency drive is shown in Figure 5.2. Variable frequency drives can operate up to a value equal to 85% of the nominal value of the supply voltage. In other words, variable frequency drives with

400 V_{ac} supply voltage can also work with 340 V_{ac} supply. According to the IEEE 1346 Recommended Practice for Evaluating Electric Power System Compatibility With Electronic Process Equipment standard, variable frequency drives will fail at all points outside the operating curve that is specified in the standard and will not be able to continue its operation (IEEE 1346-1998).

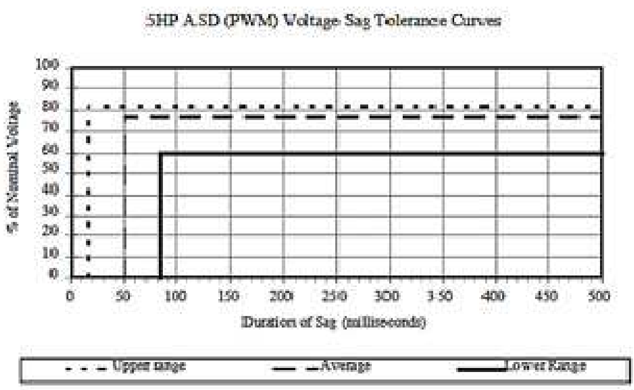

Figure 5.2. Voltage tolerance of variable frequency drives (IEEE Std 1346)

5.3.1. Solution Alternatives for Voltage Sag Issue of VFD

Various methods have been developed to prevent the variable frequency drives used in production facilities that have continuous process feature and have production stages closely related to each other, from being affected by power quality problems. Endurance capability against to the voltage sag issue of variable frequency drive is considered as an extremely important issue when considering the critical roles of these devices and their sensitivity to the changes in the power quality. There are several methods to increase the endurance level of variable frequency drives to the power quality problems. These methods can be divided into three main categories as drive-based solutions, hardware-based and energy storage-based techniques. Improved solutions for increasing the ride-through capability of variable frequency drives are shown in Figure 5.3.

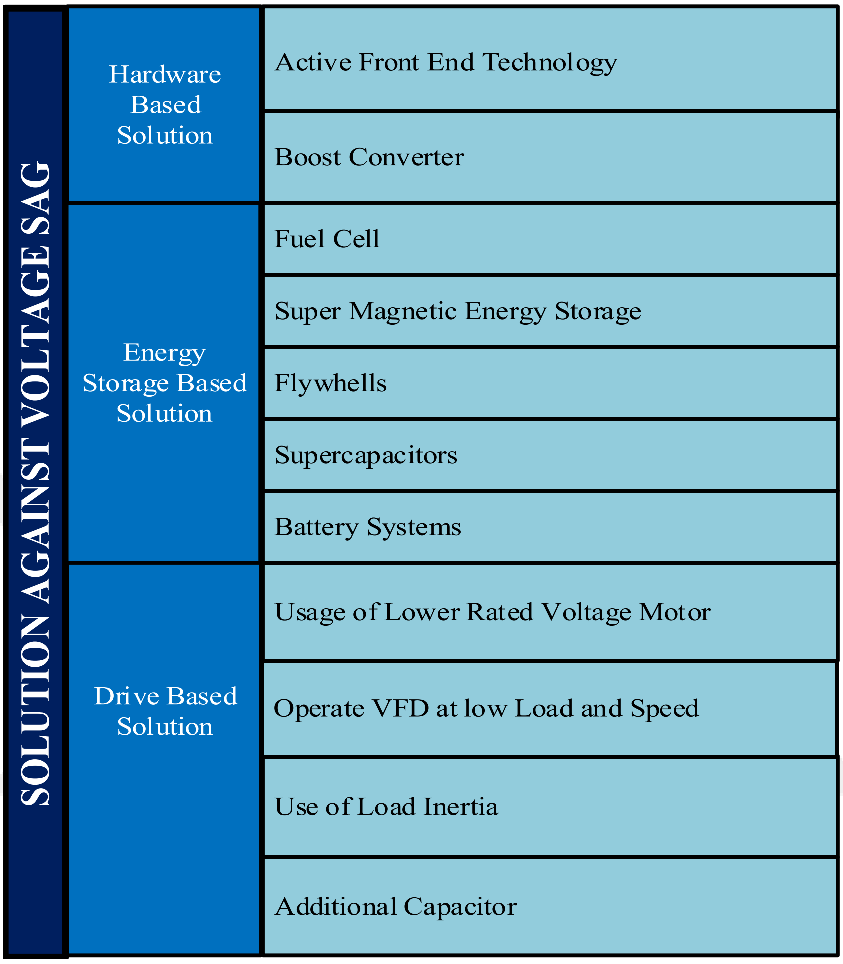

Figure 5.3. Improved solution against voltage sag

5.3.1.1. Drive-Based Solutions

When voltage disturbance occurs in the electrical power grid, this situation affects the DC bus voltage where at the output of the AC-DC rectifier section. According to the voltage sag or swell issue, this effect may be form in the form of undervoltage or overvoltage. Meanwhile, the inverter unit used to obtain adjustable AC voltage for the load is fed from the capacitor that is connected to the DC bus. The DC bus acts as a backup energy source for the loads when the voltage sag occurs. The size of DC bus capacitor is closely related with the power of the load.

If the DC bus voltage varies out of the predetermined limits, some serious problems occur in the variable frequency drives. Since the power that is transferred to the load when voltage sag occurs is constant, this decrease in the voltage will cause the current to increase. To prevent these situations, ASDs have undervoltage protection. Undervoltage protection can trip out the inverter unit when the DC bus voltage drops the predetermined limits, approximately between 85-90%. To continue for the operation of ASD normally, when voltage disturbance occurs in the electrical power grid, the DC link voltage must be maintained. In the following, the methods developed for the maintain the DC bus voltage against voltage sag problem are explained (Devval et al., 2012; Epperly et al.,1997).

5.3.1.1.(1). Additional Capacitor

One of the methods developed for the increasing endurance of the variable frequency drive is to add capacitor to the DC bus. As mentioned before, DC bus acts as a backup energy source for the loads when the voltage sag occurs. If the capacitor unit is selected adequate to feed the load during voltage sag, the load will not be affected by this voltage sag. To explain the role of the capacitor unit in this situation with an example; suppose that a motor with 460 V_{ac} supply 50 Hz, 10 Hp, has a capacitance value of 5000 µF. The nominal DC link voltage under these conditions can be calculated by means of Equation 5.1.(Von Juanne et al., 1999).

$$V_{dc,nom} = 1.35xV_{LLrms} \tag{5.1}$$

The capacitors are charged up to a maximum of 95% in the VFD. For this reason, Equation 5.1. is used to calculate the nominal voltage of the DC bus. In this formula, the nominal DC bus voltage is approximately equal to percentage of maximum charging voltage value (0.95) and root twice ($\sqrt{2}$) the phase-to-phase rms voltage (V_{LLrms}).

Variable frequency drives trips when the DC bus voltage is equal to 0.9 of its nominal value. In this case, the trip value of the DC bus voltage will be $V_{dc,trip} = 558V$ as shown in Figure 5.4.

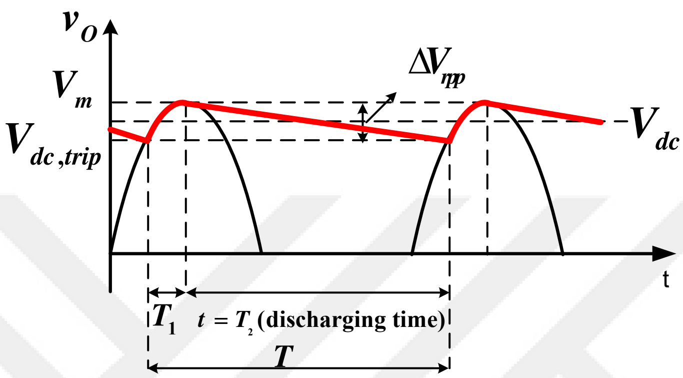

Figure 5.4. DC Bus Voltage waveform

The DC bus current of the variable frequency drive can be calculated using the Equation 5.2.

$$I_{dc} = \frac{P_0 x746}{V_{dc}} = 12A \tag{5.2}$$

Where P_0 is a power rating of motor.

The operation time of the motor (t), which is powered by capacitors, without being affected by this fault, can be calculated with the Equation 5.3.

$$i = C\frac{dv}{dt} \text{ and } I_{dc} = C\frac{\Delta v}{\Delta t} \tag{5.3}$$

$$t = \frac{C*(V_{dc} - V_{dc,trip})}{I_{dc}}$$

$$t = \frac{5000*10^{-6}x(620\text{-}558)}{12} = 25.8ms$$

25.8ms corresponds to a period of 1.55 cycles in a system with a frequency of 60 Hz. When the DC bus voltage of this device drops to 558V, it will continue to operate 25.8 ms and will not be affected by this variation of voltage during this time. When this voltage sag lasts for half a cycle (0.5), i.e., 30ms, the new capacitance value will be calculated with the Equation 5.4.

$$C = \frac{I_{dc} \times t}{V_{dc} - V_{dc,trip}} = \frac{12 \times 0.5}{620 - 558} = 0.097F \tag{5.4}$$

As understood from the Equation 5.4, twenty pieces of 5000µF capacitor will need to be added to operate at a voltage sag of 0.5 seconds for a motor with 10 Hp (Von Juanne et al., 1999).

5.3.1.1.(2). Usage of Load Inertia of Electric Motor

There is an alternative to maintain the DC Bus voltage of the variable frequency drive not to be affected by the voltage disturbance in the electrical power grid. It is possible to operate the variable frequency drive below the operating frequency of motor with software alteration of the control system of the drive. Thus, the electric motor operates in generator mode that is another mode of operation of motor. In this way, variable frequency drive tries to maintain the minimum DC bus voltage to operate system properly by absorbing some energy from the rotating load. Research shows that, DC bus voltage is not affected from the voltage sags around 20% of nominal voltage by means of this method (Von Juanne et al., 1999).

5.3.1.1.(3). Reduction of Load and Speed of Motor

The term of revolution per minute (rpm) stands for the motor’s speed. It means that rate at which the rotor is revolving, which is the number of times the rotor shafts complete full rotation each minute. Rpm is the measurement of the speed of motors,conveyors, fan etc. Rpm of equipment's are calculated by using Equation 5.5.

$$n_s = \frac{120xFrequency}{number\ of\ Poles} \tag{5.5}$$

As can be clearly seen from the equation 5.5. rpm of the motor is directly proportional to the frequency and inversely proportional to the number of poles of motors. Electrically, frequency value is an extremely important parameter that influences many different parameters. On the drive side (frequency), frequency has an effect not only on the rotational speed of the motor, but also on the DC bus current. Fan, pumps, and etc.applications in industrial facility are variable torque loads. In these types of applications, if the rotational speed of motor is decreased, frequency of this load is decreased, and DC bus current also decrease, naturally. DC bus current decreases, the endurance of the variable frequency drive to endurance capability against to voltage sag will increase (Epperly et al.,1997; Von Juanne et al., 1999).

5.3.1.1.(4). Usage of Lower Rated Voltage Motor

The DC bus voltage is equal to 1.35 times the line-to-line voltage as stated in Eq. 5.1. In other words, in the system where the line-to-line voltage is 400 V_{ac}, the DC bus voltage will be calculated as 540 V_{dc}. If a 230 V_{ac} motor is used instead of a 400 V_{ac} motor, the DC bus voltage will be calculated as 310,5 V_{dc}. Means that the DC bus voltage will decrease by 57%. The maximum AC voltage supplied to the motor by the variable frequency drive; can be calculated by means of Equation 5.6.

$$V_{acmax} = V_{dc} x\ 0{,}82 \tag{5.6}$$

For a motor with 230 V_{ac} nominal voltage, this value is calculated as 229.6 V_{ac}. In other words, even if there is a voltage sag when the variable frequency drive is working under these specifications, it will be able to provide a constant voltage of 230 V_{ac} to the motor and motor will not be affected by voltage sags. However, to provide the same power in this method, the current capacity of the motor working with 230 V_{ac} must be increased. This will cause the increasing the size of the equipment and changing the insulation feature of used material.Comparison of drive-based solution is given in Table 5.1.

Table 5.1. Comparison table of drive-based solutions

Methods	Pros	Cons	Cost(per KW)
Lower rated motor	No additional equipment	Increased equipment size High insulation feature	Equal to drive cost
Adding Capacitor	Easy to ımplement Robust	High installation cost Need large space Need additional charge circuit	$600
Reduction of load & speed	No additional equipment	Not appropriate all loads	$0
Load Inertia	No additional equipment Low delay time	Not appropriate all loads	$0

5.3.1.2. Energy Storage-Based Solution

Thanks to the emergence of new technologies and research development studies, significant developments have been made in the field of energy storage systems. With its developed features, energy storage systems are used to minimize the effects of power interruptions that may occur in many critical processes. Systems developed using battery systems, super capacitors, motor generator sets, flywheel, SMES and fuel cells are some of the alternative methods that is used to increase the endurance capability of variable frequency drives against to voltage sag. In this part of the thesis, these methods will be examined, and a comparison table will be given at the end of the chapter.

5.3.1.2.(1). Battery Systems

The basic working principle of battery systems is based on performing the same function as adding capacitor to the variable frequency drive that is described in the previous section. Although their duties are the same, the advantage of batteries is that they have higher energy density per unit volume when compared to capacitors (Schoenenung et al.,1997). Revised circuit of variable frequency drive by adding a battery unit is shown in Figure 5.5.

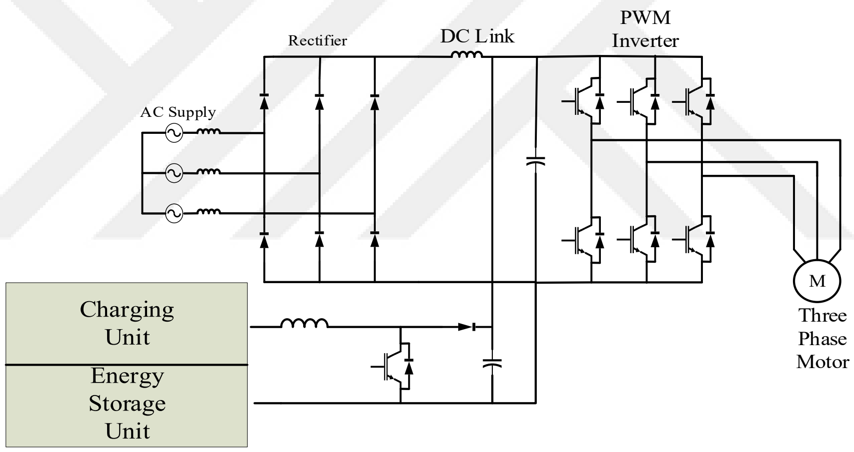

Figure 5.5. Revised circuit of variable frequency drive by adding a battery unit (Von Juanne et al., 1999)

To increase the endurance capability of variable frequency drives thus prevent the system from being affected by voltage sags, the drive circuit can be revised with an additional module.

The required operating voltage of DC bus is obtained by connecting the batteries in series each other. The current that the batteries will provide to the system is directly proportional to the load demanded by the system. When DC voltage drops the critical limit, battery unit is activated and supply the DC bus. Since the working principle of batteries is based on both electrical and chemical events, there are various limitations in their work. One of the most important of these limitations is the charge/discharge event. Frequent charging-discharging situation causes aging and the reduction of service life of battery units. In addition, since the ambient temperature and charging currents of the batteries are other important factors affecting their operation, they should be constantly monitored, and care should be taken to keep them at appropriate values. Since the number of batteries varies according to the demanded load, as the number of batteries to be used increases, the area required by the system for the installation increases, also. Batteries whose lifetime is completed are considered as chemical waste and must be disposed of according to certain criteria. This process causes high expenditures in terms of cost (Epperly et al.,1997; Von Juanne et al., 1999).

5.3.1.2.(2). Supercapacitor Based Solution

Supercapacitors can store energy in the form of an electrostatic field, just like conventional capacitors. Although the main function of conventional capacitors and supercapacitors is to store the energy, supercapacitors store more energy and have higher energy density than standard capacitors due to the difference in material that is used between their electrodes (Supertech Web Page). In order to increase the endurance capability of variable frequency drives, the DC bus of the variable speed drive and thus prevent the system from being affected by voltage sags, the drive circuit can be revised with an additional module as shown in the Figure 5.6.

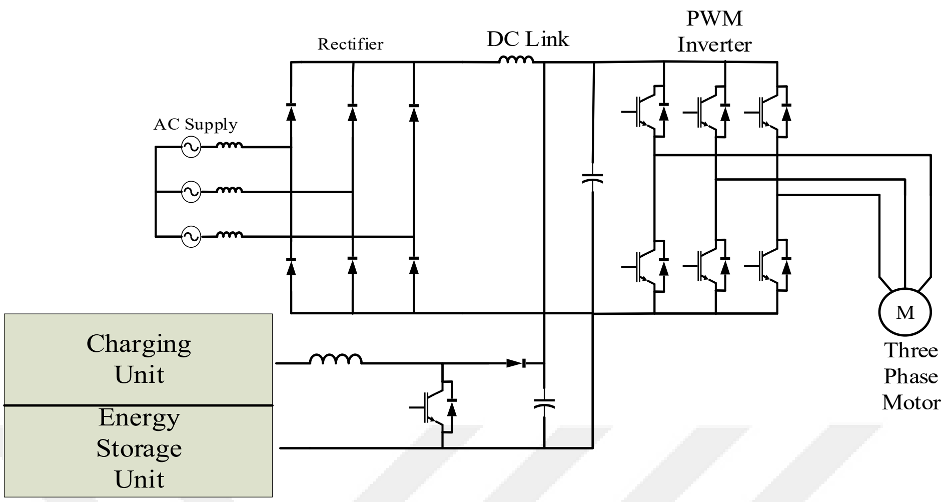

Figure 5.6. Revised circuit of variable frequency drive by adding a supercapacitor unit (Von Juanne et al., 1999)

The basic operation of the system realized by means of using capacitors is explained as follows. According to the study carried out for a load of 100 KW, commercially available capacitor modules were used. This module compromises of 8 capacitors. Each capacitor has a value of 56 Volts and a capacitance value of each capacitor is equal to 96.4F. Energy stored in one capacitor unit can be calculated by means of using Equation 5.7.

$$E_{capacitor} = \frac{C*V^2}{2} = \frac{96.4*56^2}{2} = 151.2kJ \quad (5.7)$$

The total energy that is stored in these units is equal to the $E_{total} = 8*151.2kJ = 1.2MJ$. As can be clearly seen from the Equation 5.7 the stored energy is directly related to the voltage value of the capacitor. In other words, a 30% decrease in the voltage of the capacitor means a 50% decrease in the stored energy. According to this situation, t_r, which is the endurance time of the 100 KW system in a 30% decrease in voltage, is calculated with Equation 5.8.

$$100 * 10^3 * t_r = \frac{1}{2}(C * V^2 - C * (0.7V)^2) * 8 \qquad (5.8)$$

Where C is equal to 96.4 and V is equal to 56; then t_r is obtained 6 seconds. This means that when the system is installed with the above features, if 30% sag occurs in voltage, the system can have the ability to tolerate this voltage sag for 6 seconds thanks to the supercapacitors (Maxwell ,1998).

5.3.1.2.(3). Motor-Generator Set

Motor-generator sets are formed by connecting the motor and generator (generally DC generator) on a common shaft. In this system, electrical energy is converted into the mechanical energy. Motor-generator set that has common rotor is shown in Figure 5.7.

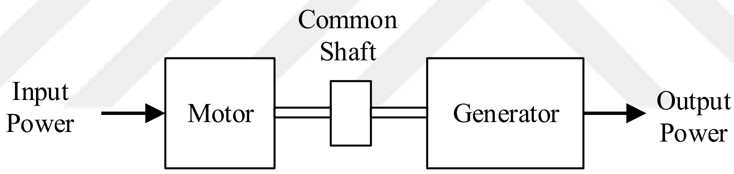

Figure 5.7. Motor-generator set

In motor-generator set, the electrical power is supplied to the motor from the outside, as a result, the motor shaft rotates the generator rotor. That is, the motor receives electrical energy from the power grid, its shaft rotates, and since the generator shaft is mechanically connected to it, the generator receives its mechanical input from this shaft. Thus, the generator also generates electrical output power, or in other words, the generator converts mechanical energy into electrical energy. Means that, while the power on both the input and output side is electrical, the power flowing between the machines is in the form of mechanical torque. Motor-generator sets use the kinetic energy of the rotating mass to provide energy so that the connected load is not affected during a voltage sag or interruption (Melhor et al.,1997).

5.3.1.2.(4). Flywheels

Flywheel technology uses the energy of rotating mass to increase endurance capability of the variable frequency drive. In this system, the AC motor drives a DC generator with the help of a flywheel and the DC generator output is directly connected to the DC bus of the drive. The basic circuit of the flywheel technique is shown in the Figure 5.8.

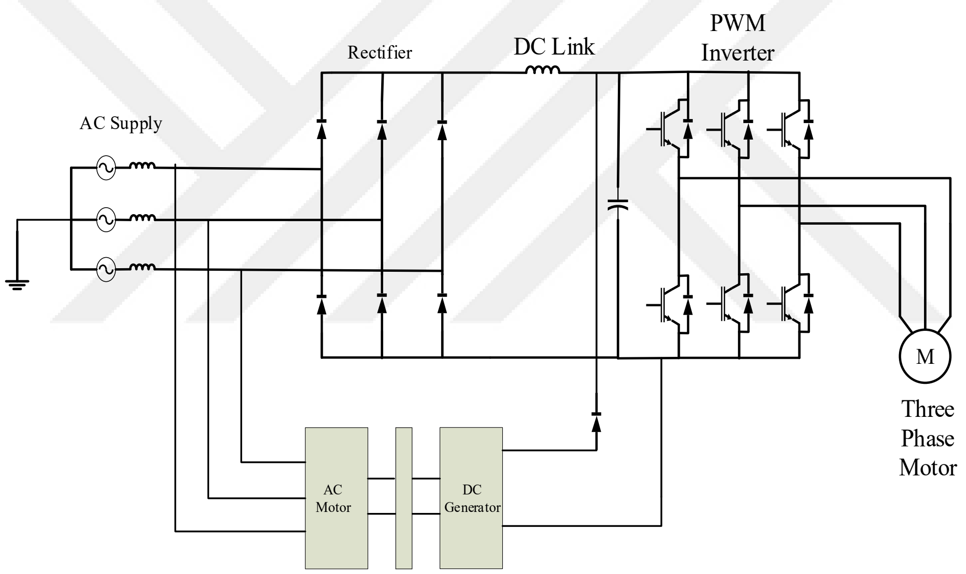

Figure 5.8. Basic circuit of variable frequency drive by using flywheel technique (Von Juanne et al., 1999)

The M-G set may have a flywheel on the same shaft to obtain great inertia and improve ride-through time. When the power grid is subjected to voltage sags or interruptions, the inertia of the machines and the flywheels continue to supply power to the loads. It has endurance performance against voltage sags nearly one hour (Melhor et al.,1997).

5.3.1.2.(5). Fuel Cells

A fuel cell uses the chemical energy of hydrogen or other available fuels to produce clean and reliable energy. Just like in battery units, energy conversion is based on electrochemical process. It is a more costly solution than the other improved methods. In addition, there is also the situation that the system cannot start quickly because of the requirement of cooling. Due to its high cost and inability to fast action, it is not preferred much in DC bus increase endurance capability of the variable frequency drives (Schoenenung et al.,1997).

5.3.1.2.(6). Superconducting Magnetic Energy Storage (SMES)

SMES is another method of storing energy and supplying when it is needed, like the other energy storage applications. SMES is a large superconducting coil that can store electrical energy in the magnetic field created by the DC current flowing through it (Breeze.,2018). The circuit that is created by means of using SMES to strengthen the DC bus of the variable frequency drive is as shown in Figure 5.9.

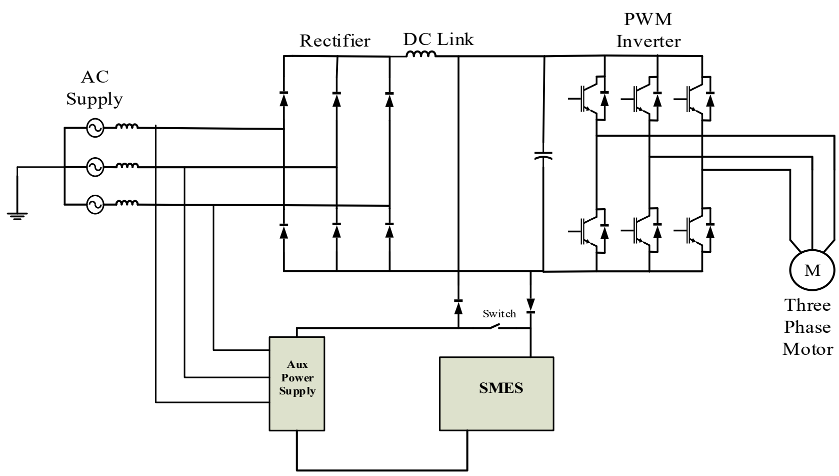

Figure 5.9. The basic circuit of variable frequency drive by using SMES (Von Juanne et al., 1999)

In the event of a voltage sag or an interruption occur, the switch in the external circuit will open and canalize the circulating current in the circuit to the filter capacitors of the driver to keep the voltage in the DC bus constant. The comparison of energy-storage based solution is given in Table 5.2.

Table 5.2. Comparison table of energy storage-based solutions

Methods	Pros	Cons	Cost(per KW)
Fuel Cell	Appropriate for deep sag& long interruption Ride through capacity up to 1hr Low maintenance	Additional hardware	$1500
SMES	Low maintenance Ride through capacity up to 5 sec	Large space Additional hardware Require cooling system	$600-$800
Supercapacitor	Appropriate for deep sag& long interruption Ride through capacity 5 sec Low maintenance Long cycle life	Large space	$300-$400
Flywheels	Appropriate for deep sag& long interruption Ride through capacity 5 sec to 1 hr	Large space Additional hardware Maintenance requirement	$200-$300
M-G Set	Appropriate for deep sag& long interruption Ride through capacity up to 5 sec	Large space Additional hardware Maintenance requirement	$200-$300
Battery	Fast transfer time Appropriate for deep sag& long interruption Ride through capacity 5 sec to 1 hr	Additional hardware Large space Maintenance requirement Low cycle life	$100-$200

5.3.1.3. Hardware Modification Based Solution

It has been explained in the previous sections that the most important parameter from an electrical point of view is the DC bus voltage for a variable frequency drive to continue its operation normally and that the DC bus voltage must be maintained within certain limits. In addition to the methods described, in this section, the methods to be performed using hardware modifications on the drive circuits is discussed and a comparison table of all methods with each other is given at the end of the section. Hardware modifications methods are divided into two main categories as boost converter technology and active front end variable frequency drive front end technology, respectively.

5.3.1.3.(1). Boost Converter Technology

As the name suggest that, boost converter increases the input DC voltage to the predetermined DC output voltage. It can be integrated between the rectifier unit and DC bus capacitors in the circuit of variable frequency drives, or it can be connected to the existing system as a separate module. The circuit diagram of the system that is realized by using the boost converter is shown in the Figure 5.10.

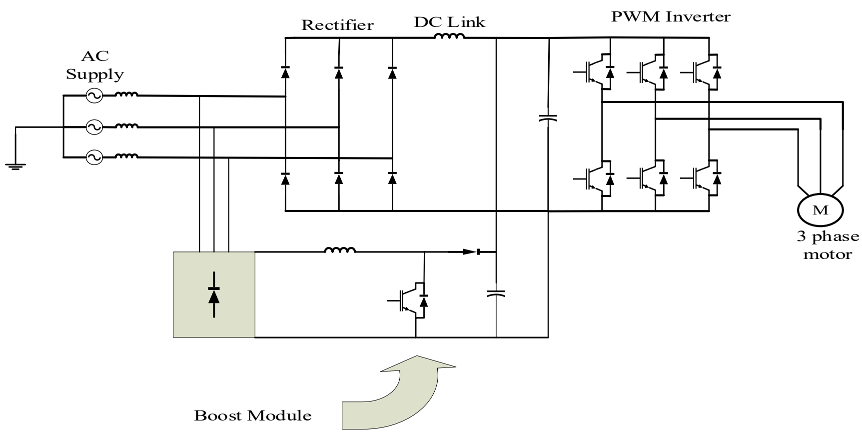

Figure 5.10. The circuit diagram of the system realized by using the boost converter (Von Juanne et al., 1999)

The applied revision can be used to increase the capacity of the variable frequency drive to withstand voltage sags or to increase the DC bus voltage of the drives in systems with a common DC bus. When voltage sag occurs in the systems, this event is detected by the boost converter and it adjusts its DC bus voltage according to the minimum DC bus voltage required for the variable frequency drive to operate (Pandya et al.,2020)

5.3.1.3.(2). Active Front End VFD Technology

In conventional variable frequency drives, three phase AC voltage is converted to DC voltage with using diode circuits. As a result of the developments in the field of power electronics, diode circuits have found the opportunity to be replaced with pulse width modulated converters. Due to the controlled structure of the power electronics equipment, which are the components in the pulse width modulated converter, DC bus voltage at the desired value can be obtained. In addition, pulse width modulated converters contribute to the improvement of power quality by providing lower input current harmonics to the system. The circuit diagram of the system that is realized by using the active front end variable frequency drive is shown in the Figure 5.11. Also, comparison of hardware modification-based solution is given in Table 5.3. (Van Zyl et al.,1997).

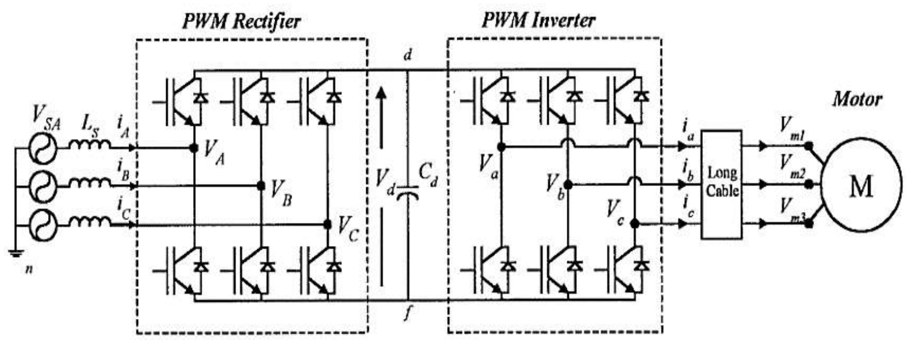

Figure 5.11. The circuit diagram of the system that is realized by using the active front end VFD technology (Von Juanne et al., 1999)

Table 5.3. Comparison table of hardware modification-based solutions

Methods	Pros	Cons	Cost(per KW)
Active Front End Rectifier	Low current harmonics High power factor Bidirectional power flow Suitability with IEEE 519 Ride-through capacity up to 5 sec	High installation cost Requirement of input filter High EMI	twice cost of variable freequency drive
Boost Converter	Suitable for up to 50% sag Adjustable DC bus voltage	Additonal hardware No operation during the mains failure	$100-$200

6. SITUATION ANALYSIS OF INDUSTRIAL PLANT

This part of the study consists of 3 sub-sections. In the first part, the methods evaluated to mitigate the negative effects caused by power quality events are analyzed. In the second part, the power quality events that occurred in the industrial facility where the investigations were carried out and the effects of these events were evaluated. In the third part, the measurements of the power quality events in the facility were taken by means of FLUKE 438 II and POWERLOGIC ION 9000 devices and these measurements were interpreted.

6.1. Evaluated Methods

It is seen that many different methods are used to eliminate the negative effects of voltage sags when the literature review studies are reviewed. Especially, three of them were selected and analyzed to eliminate the negative effects of voltage sags occurring in the facility where the study was carried out among these investigated methods. These methods are the central or individual UPS solution and super capacitor or battery solutions. In this section, the evaluated methods will be explained, and a comparison table will be given at the end of this section.

6.1.1. Central UPS Solution

In many critical systems, the continuity of electrical energy and power quality has vital importance. Data centers, hospitals, communication systems and industrial facilities that contain sensitive and critical loads, inherently need clean, conditioned, uninterrupted, and undisturbed electrical energy. These sensitive loads and equipment; significantly affected by interruptions, sags, overvoltage, undervoltage and harmonics. Uninterruptible power supplies are used in many different applications to provide uninterrupted and undisturbed power to the vital loads. When events such as voltage sag-swell, short-long term interruptions occur in the electrical power grid where critical loads are located, UPS can protect to the load from being adversely affected by this situation thanks to the battery systems (Aamir et al.,2016; Niroomand and Karshenas,2010).

Schematic diagram of central ups system is shown in the Figure 6.1. The busbar in the main distribution panel is energized by decreasing the 31500 V to 400V (phase to phase) through a step-down transformer. UPS devices are energized by 2 feeders from the main distribution panel. UPS distribution board is energized through the output of the UPS device. In addition to these feeders, there is one more feeder between the main distribution panel and the UPS distribution panel to be used when the UPS device is taken into maintenance. When interruption occurs, critical loads are fed through the battery group. The size of the battery groups to be used in the system is directly proportional to the amount of the loads (Lahyani et al.,2013).

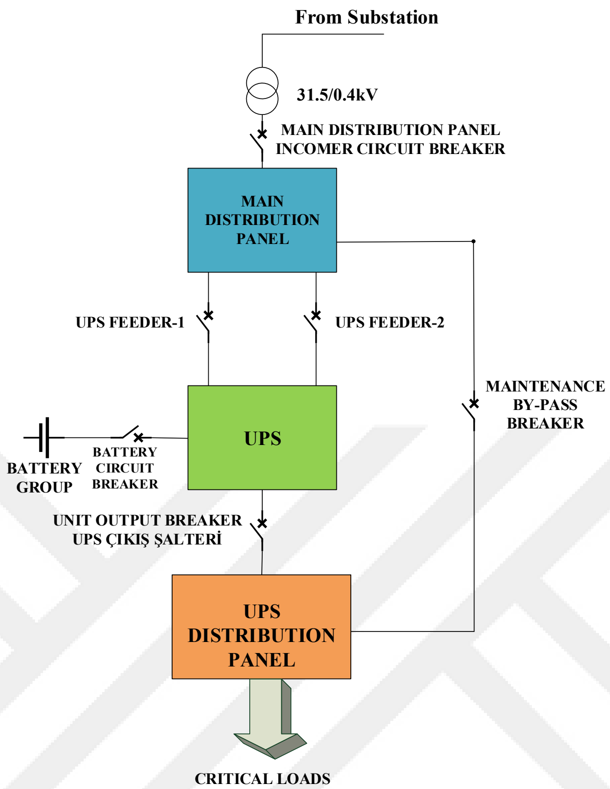

Figure 6.1. Schematic diagram of central ups system

6.1.2. Individual UPS Solution

The individual UPS solution is based on the same working principle with the central UPS system. The difference of this method from the central UPS system is to provide machine-based protection individually. Individual UPS solutions are preferred in industrial facilities where the low voltage distribution system is not suitable for installation of a central UPS system. In Figure 6.2 schematic diagram of individual ups system is shown.

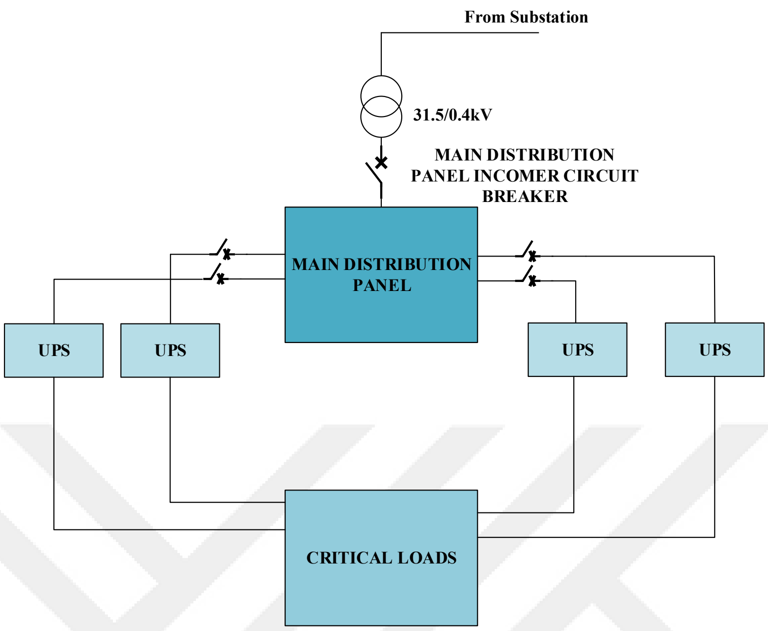

Figure 6.2. Schematic diagram of individual ups system

6.1.3. Energy Storage-Based Solutions

As explained in detail in the section 5, one of the measures that can be taken against voltage sags is to strengthen the DC bus of variable frequency drives. Two alternatives were evaluated in the facility where the study is planned to be carried out for the strengthening. These methods are energy storage-based solutions that consist of super capacitor and battery systems. The working principle of both alternatives is nearly the same. When the two systems compare with each other while supercapacitors require less maintenance costs, they have more investment cost than the batteries (Gomez et al.,2002).

Figure 6.3 shows the schematic diagram of the strengthen DC bus by means of the energy storage-based solutions.

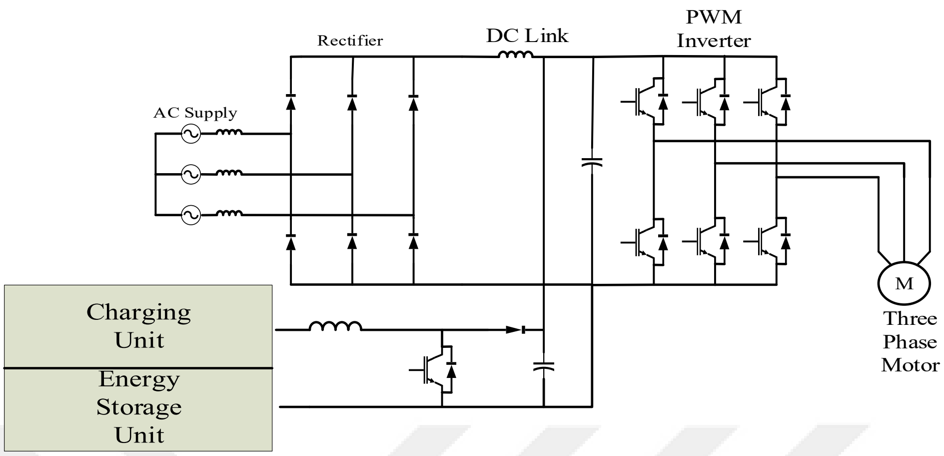

Figure 6.3. Schematic diagram of energy storage-based solution(Von Juanne et al., 1999)

In the facility where the study was carried out, the method based on the strengthen the DC bus was preferred by using the battery-based solution from the applications that is described above. The central UPS based solution was not preferred to solve the voltage sag problems due to the low voltage distribution system in the facility where the study was carried out, is not suitable for the establishment of the infrastructure shown in the Figure 6.1. Another reason is the installation and maintenance costs being relatively high compared to the other method evaluated.

Likewise, individual UPS-based solutions were not preferred due to the number of individual UPSs, space problems and a serious workload for maintenance activities. Although other methods are advantageous in many ways against battery-based solutions, factors such as low installation cost, short payback period and less maintenance cost bring this method into the forefront. The comparison of the evaluated alternatives according to various parameters is given in the Table 6.1. According to the comparison table of alternatives and losses that are occurred by the voltage sags that is shown in Table 6.2 the payback of the battery-based solution is calculated 1.58 years.

Table 6.1.The comparison of the evaluated alternatives

NAMES OF ALTERNATIVES	POWER RANGE	EFFICACY (η)	CHARGE DURATION	INSTALLATION COST ($)	MAINTENANCE COST ($)
UPS (CENTRAL)	~ 1.5MVA	98,50%	minutes	7.920.000,00	200.000,00
UPS (INDIVIDUAL)	10-200KVA	98,50%	minutes	3.450.000,00	135.000,00
BATTERY SOLUTION	5kW-10MW	70-90%	hours	3.000.000,00	94.000,00
SUPERCAPACITOR SOLUTION	5kW-10MW	90%	seconds	3.547.000,00	120.000,00

6.2. Effects of Power Quality Events on Industrial Facility

Power quality events can cause extremely serious problems in the facilities. To eliminate these problems, various measures are taken, and improvements are made. The distribution of power quality problems that have occurred in the industrial facility where the study carried out, in the last five years is shown in Figure 6.4.

Figure 6.4. Distribution of power quality problems last five years

When the distribution of power quality events by years is examined, it is seen that the most common problem is "voltage sag". As can be seen in Figure 6.4, there has been two black out in the last 5 years.

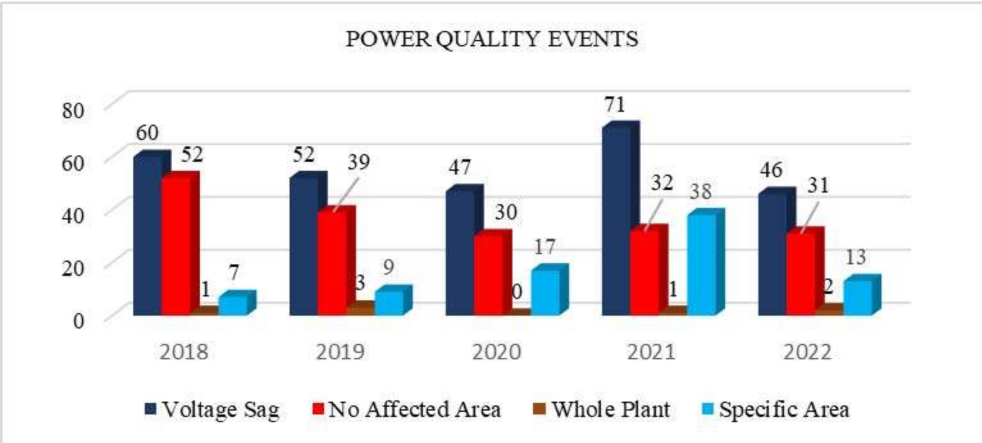

Figure 6.5. Detailed distribution of power quality problems last five years

When distribution of voltage sag events is analyzed over the years from the Figure 6.5 while some voltage sags do not affect any area of the facility, it is seen that some voltage sags affect a specific area of the facility or the whole plant. This situation is closely related to the characteristic of the voltage sag, that is, its duration and depth, as well as the characteristics of the devices in the facilities against voltage sags. As the frequency of power quality problems increases, the probability of occurrence of situations that can cause serious costs and damage, also increases. The main negative effects of these problems can be listed as follows; production losses, second quality products, increment of labor costs, and wasted product, respectively. The percentage distributions of the negative effects of voltage sags that was occurred 2020, 2021 and 2022 are shown in the Table 6.2.

Table 6.2. Percentage distribution of losses

	Plant 1 ($)	Plant 2 ($)	Total ($)	% (Percentage)
Production Losses	840.000	500.000	1.340.000	68,51
Second Quality Products	225.000	99.000	324.000	16,56
Wasted Product	185.000	75.000	260.000	13,29
Overtime Costs	22.000	10.000	32.000	1,64
			1.956.000	100

In addition, the graphical distribution of the losses in the table 6.2 is shown in the circle graph in Figure 6.6.

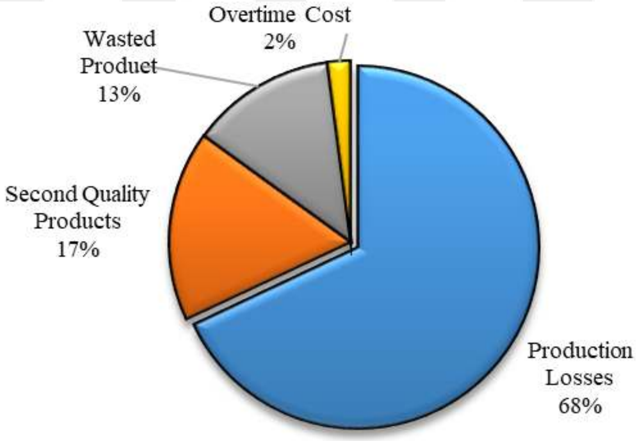

Figure 6.6. Graphical distribution of the losses

Considering the negative effects of all these effects on the facility, it is seen that they cause serious cost problems. Another point that is not shown in the tables but needs attention is wasted energy. Since the facility has a continuous production feature and the production stages are interrelated, it takes an average of 24 hours for this facility to start first quality production. The average installed power of each machine in the facility is 150 kW and consumption details of machine is given in the Table 6.3 and Table 6.4.

Table 6.3.Energy consumption details of machine

	DAY 1	**DAY2**	**DAY3**
Machine No	**Active Power (kWh)**	**Active Power (kWh)**	**Active Power (kWh)**
20	3.287.894,00	3.292.060,00	3.296.246,00
31	2.294.504,00	2.298.391,00	2.302.269,00
3	2.847.052,00	2.850.718,00	2.854.421,00

Table 6.4.Daily energy consumption and average consumption of machine

	Energy Consumption(kWh)		
Machine No	**1st 24 hour**	**2nd 24 hour**	**Average**
20	4.166,00	4.186,00	4176
31	3.887,00	3.878,00	3882,5
3	3.666,00	3.703,00	3684,5
			3914,33

Electricity bills are invoiced according to the price determined by the Energy Market Regulatory Authority. (EPDK) According to this pricing, the kilowatt hour price of electricity for industrial facilities is 3.93 ₺. In the calculations, the average of the three-day consumptions of the three machines was used. The value of the average electricity consumption of a machine for this period in terms of ₺ is equal to,

Amount of energy (₺) = Active Energy Unit Price * kWh (6.1)

Amount of energy for each machine (₺) = 3,93*3914,33
Amount of energy for each machine (₺) =15383,31

In the facility where the study will be carried out, a total of 242 machine shutdowns occurred due to voltage sag events that happened on different dates in 2022. In this case, the wasted energy in the machines is approximately equal to, 3.722.762 ₺.

6.3. The Measurements of The Power Quality Events of Facility

Power quality in industrial facilities is one of the most important parameters for the continuity of production. The POWERLOGIC ION 9000 device, which can continuously measure 24/7 from 2 busbars located at medium voltage (31.5 KV) level, is used to perform power quality analyzes effectively in the facility where the study carried out. With this device, information about transients, voltage sags and swells, interruptions, undervoltage and overvoltage events can be analyzed. Details of the last two events that is recorded by means of POWERLOGIC ION 9000 are shown in the Table 6.5. Table 6.5 shows the busbar at which the voltage sag occurs, its duration and the percentage of the main busbar voltage to the rated voltage.

Table 6.5. Details of last two power quality events

EVENT NO	***POWER QUALITY EVENT***	***MEASURING POINT***	***DURATION (sec)***	***MAGNITUDE (%)***	***IMPACT (Effected Machine)***
# 1	SAG	BUS A	0.1	65.44	38
# 1	SAG	BUS B	0.1	64.87	
# 2	SAG	BUS A	0.08	70.75	21
# 2	SAG	BUS B	0.09	70.12	

Voltage sag details of event 1 and event 2 are shown in Figure 6.7 and 6.8.

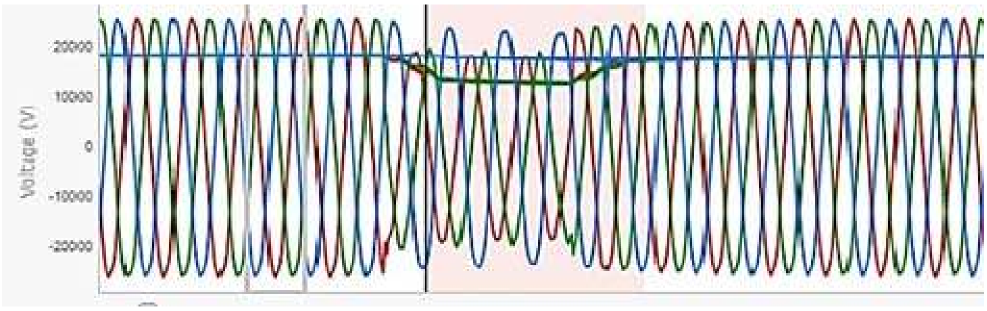

Figure 6.7. Voltage sag detail of case 1

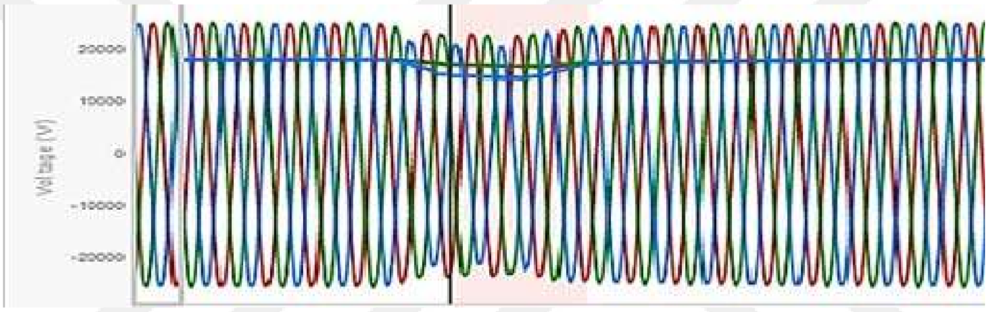

Figure 6.8. Voltage sag detail of case 2

The ITIC curve created by the Information Technology Industry Council and is used to show the tolerance limits of electronic equipment, programmable logic controllers, telecommunications equipment, and power distribution units against power quality problems. These devices, which are mentioned in the “No Interruption Region” in the figure below, are expected to continue their normal operation. At points outside of this zone, the devices will trip and may not maintain their operation properly (Openquality Web Page). ITIC curve for the first and second events are shown in Figure 6.10.

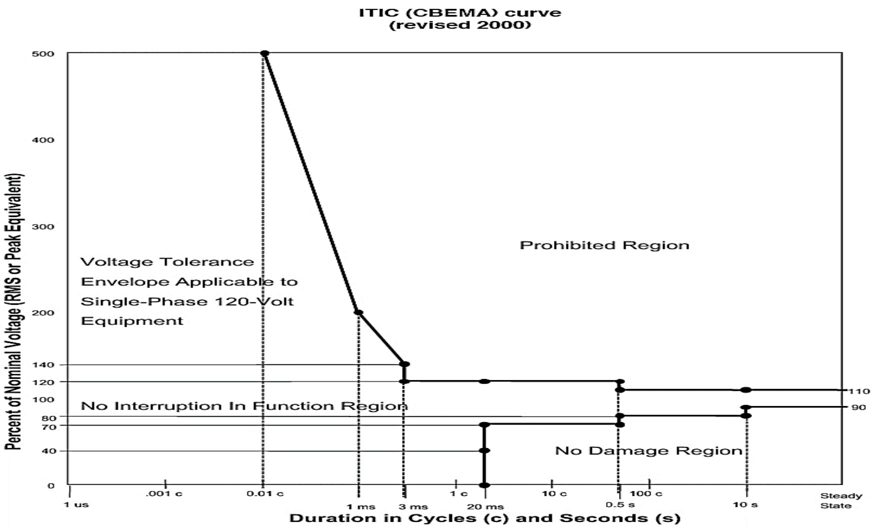

Figure 6.9. ITIC Curve

Table 6.6. Results of Fluke 430 energy analyzer

Residual Voltage u [%]	*Duration*						
	t<10	**10<=t<=200**	**200<t<=500**	**500<t<=1000**	**100<t<=5000**	**5000<t<=60000**	**60000<t**
90> u >= 80	0	2	0	0	0	0	0
80> u >= 70	0	0	0	0	0	0	0
70> u >= 40	0	1	0	0	0	0	0
40> u >= 5	0	0	0	0	0	0	0
5> u	1	0	0	0	0	0	0

According to the results that is obtained from the power quality analyzer, although it was observed that the event was within the tolerable limits, but it caused some machines to stop as stated in the section of the Table 6.3. This situation is closely related to the sensitivity of variable frequency drives to voltage sag events, which is explained in the previous sections and is the main subject of this thesis.

To understand how the voltage sag in the medium voltage level affects the devices at the low voltage level, the measurement was taken by means of the

FLUKE 430 II energy and power quality analyzer. Measurements were taken at 0.25 sec sample time. Table 6.6 shows the duration of the measured events and the rated voltage values.

According to the Table 6.6, the rated voltage dropped below 5% once for a period of less than 10 ms. Also, as can be seen from the Table 6.3, the nominal supply voltage took two values between 90-80% for a period of less than 200 ms. It also dropped to a value between 40-70% once under 200 ms.

As can be seen from the ITIC curve of this event that is shown in Figure 6.10. other power quality events recorded by the device are two voltage sags. Graphical details of these events are shown in Figure 6.11.

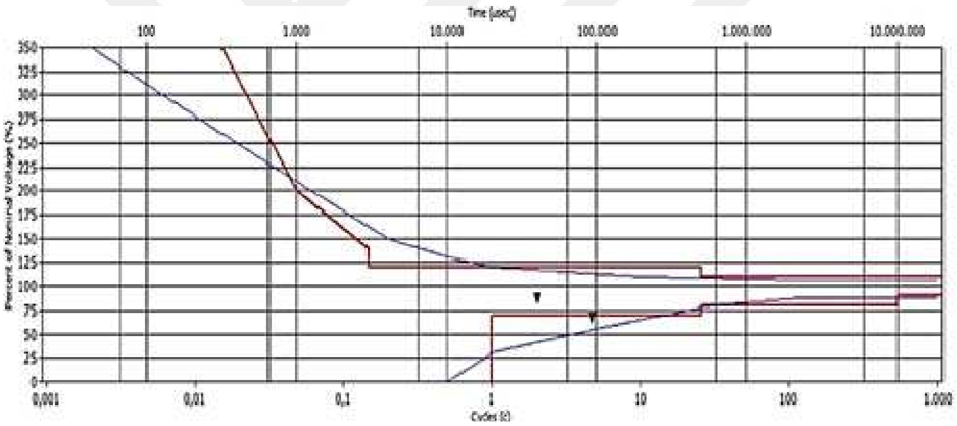

Figure 6.10. ITIC Curve of case 2

Figure 6.11. Low voltage details of case 2

7. SIMULATION STUDY & RESULTS

In this thesis, the effects of voltage sags on the plant where the study is carried out are discussed comprehensively in Chapter 6. In this section, the simulation studies of the applied method are carried out by means of MATLAB/SIMULINK program, and the acquired results are evaluated.

7.1. Simulation Model

The circuit diagram of the system to be simulated is given in Figure 7.1.

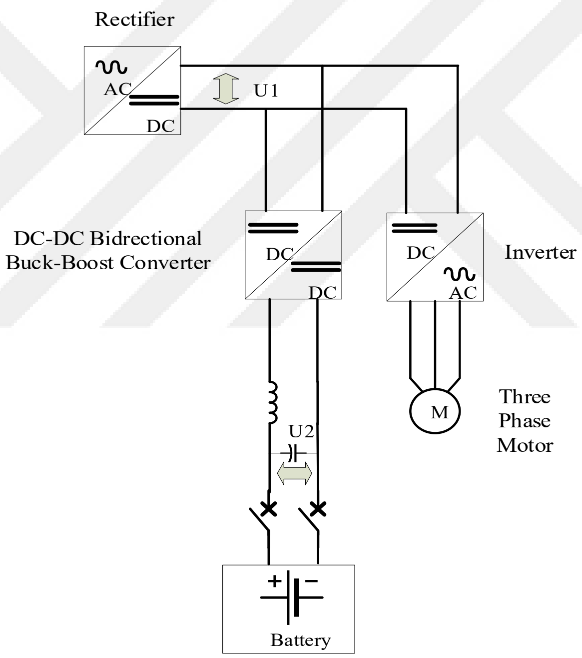

Figure 7.1. Simulation model of the system

In this part of thesis, the modelling and analysis of the applied method has been carried out with respect to the real data obtained from power quality measurement devices and given in section 6.3. The simulation study consists of three main parts. These are the active converter unit (PWM Rectifier), which consists of IGBTs, and AC/DC conversion takes place, the DC/AC conversion unit (PWM Inverter), which also consists of IGBTs, and the bidirectional DC/DC converter, respectively.

7.2. Simulation Study of AC/DC Conversion

7.2.1 Generating Gate Signals and Transformations

In this part of the study, AC/DC conversion is performed. In the performed study, the DC bus operating voltage range of the variable frequency drivers is in the range of 590-610 volts. In order to obtain controllable DC voltage, AC/DC conversion is carried out in the active converter section consisting of IGBTs.The performance of the active converter unit (PWM Rectifier) closely related to the generation of gate signals and the proper triggering of the IGBTs.

PWM is a widely used method to control the output of converters. With this technique, harmonics of output voltage can be decreased. The working principle of this method based on the comparision of the reference signal with the triangular carrier wave to get the desired output voltage. When two signals are compared, a positive or negative DC voltage is produced according to the varying magnitude of the reference signal with respect to the triangular carrier waveform (Tan, 2015). In this thesis, PWM method is used to get a gate signal applied to PWM rectifier units. Figure 7.2 shows the gate signal generation of the AC/DC unit conversion via Matlab/Simulink program.

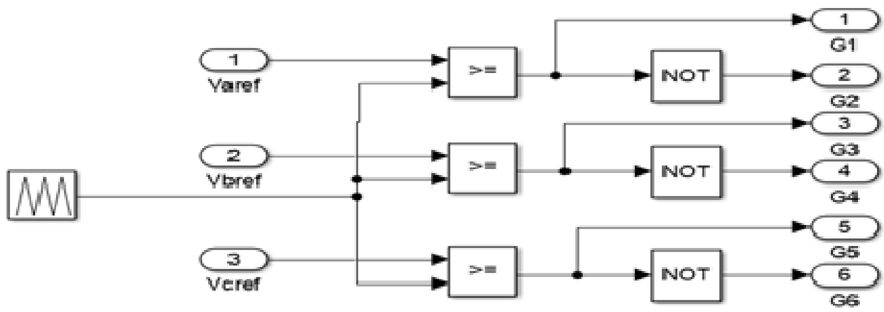

Figure 7.2. Gate signal geneation of active converter unit

Additionally, to mitigate the complexity of the system, DC values are used instead of the AC values by means of the clarke and park transformation. In clarke and park transformation, three phase AC signals can be represented as two DC quantities. In this part of the simulation clarke transformation is firstly performed. With clarke transformation, three phase AC signals are represented in complex plane and its real(α) and imaginary (β) part are obtained. Geometrical representation of clarke transformation is shown in Figure 7.3 and 7.4.

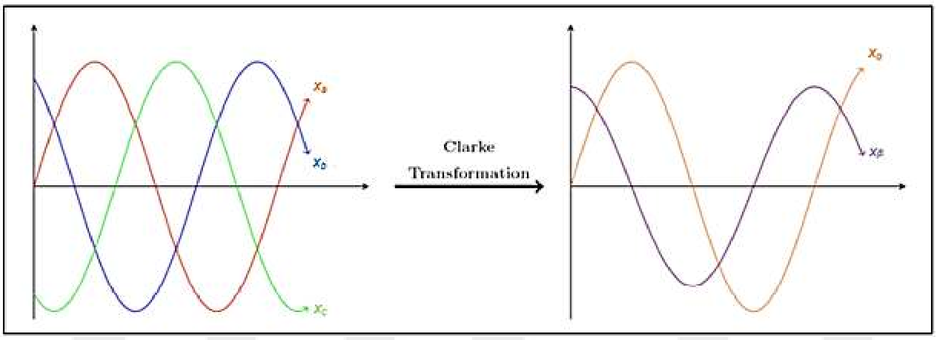

Figure 7.3. Clarke transformation(Tan, 2015)

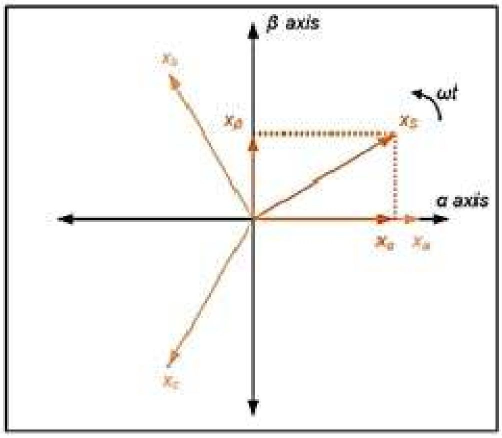

Figure 7.4. Geometrical demonstration of Clarke transformation (Tan, 2015)

In this part of simulation, phase voltages of grid and phase currents of grid are transformed to its dq components by means of Matlab/Simulink blocks. This situation is shown in Figure 7.5 and 7.6,respectively.

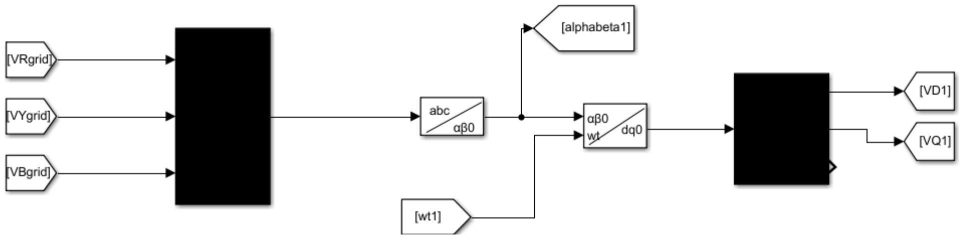

Figure 7.5. The d-q-0 transformation of the grid voltage

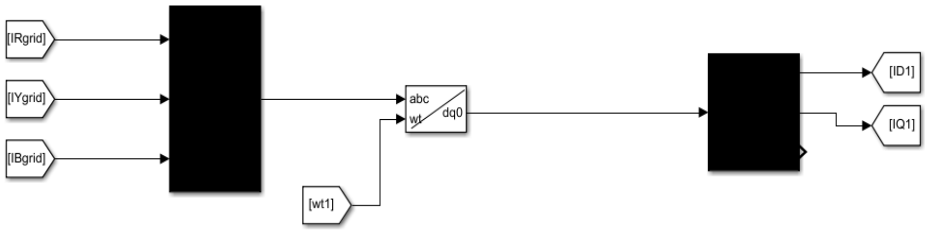

Figure 7.6. The d-q-0 transformation of the grid current

Moreover, PLL block is used in this simulation study to obtain angular velocity of AC signals. This process is named as park transformation and utilized to obtain dq rotating frame with the αβ stationary frame by means of the angular velocity of the AC signals. With this process, AC signals can be transformed into two different quantities (Tan, 2015). Geometrical representation and details of PLL are shown in Figure 7.7 and 7.8,respectively.

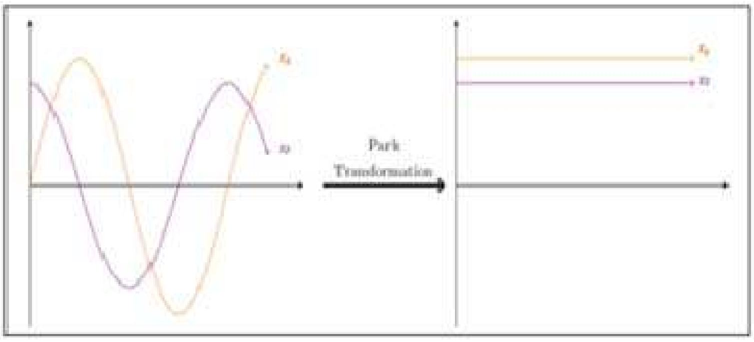

Figure 7.7. Park transformation (Tan, 2015)

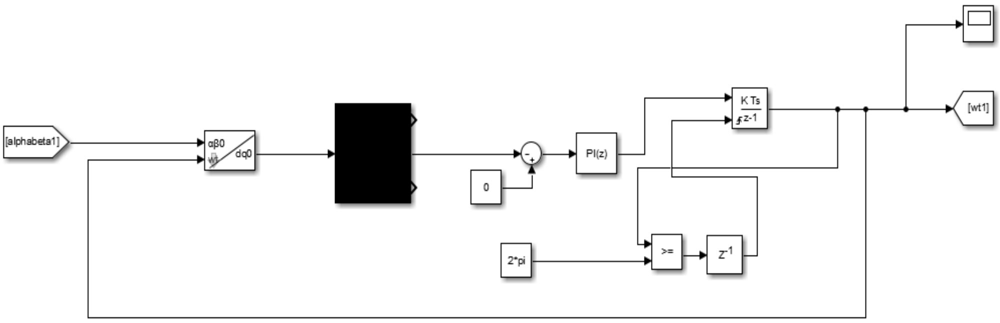

Figure 7.8. Geometrical demonstration of Park transformation (Tan, 2015)

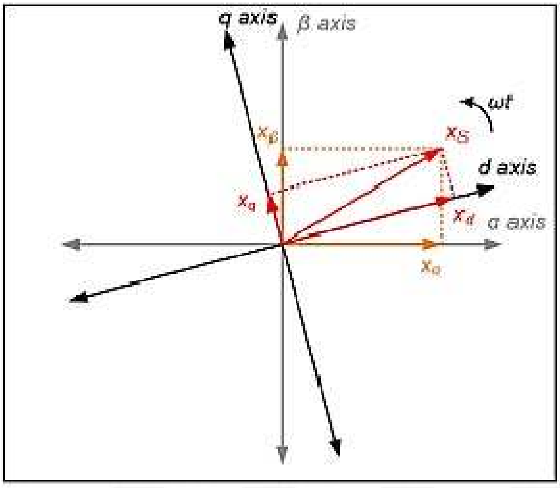

Figure 7.9. PLL block of rectifier

As mentioned before , to get dq rotating frame with the αβ stationary frame with the angular velocity of the AC signals, Matlab/simulink blocks are used. In Figure 7.9, the blocks used to obtain the angular velocity value of the AC signal are demostrated.

7.3. Simulation Study of DC/AC Conversion

7.3.1 Generating Gate Signals and Transformations

In this part of the study, DC/AC conversion is performed. DC/AC conversion is performed in a controlled converter which consists of IGBTs. Just as with the active converter in the first part of the simulation, the performance of the active inverter unit is closely related to the generation of gate signals and the appropriate triggering of the IGBTs. In this section, gate signals are generated with using the PWM method. Figure 7.10 shows the gate signal generation of the DC/AC conversion unit by means of Matlab/Simulink program. As can be seen from the Figure 7.10 ,comparision of the reference signal with the triangular carrier wave to get the desired output voltage is used.

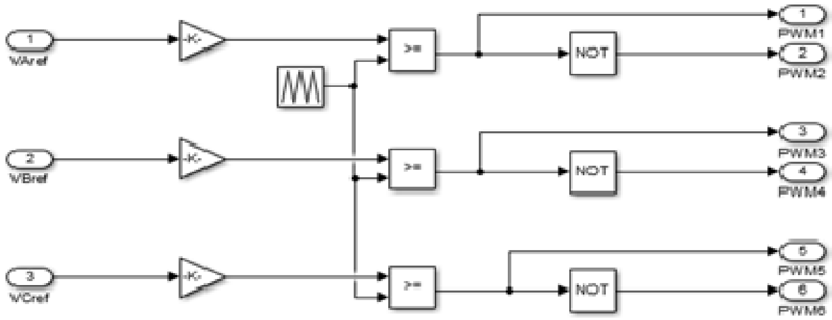

Figure 7.10. Gate signal geneation of active inverter unit

As explained in comherensively in the first part of the simulation study, AC values are used by converting them to the DC values by means of clarke and park transformations in order to simplify the system. In Figures 7.11 and 7.12, the transformations of voltage and current in the simulation are shown, respectively.

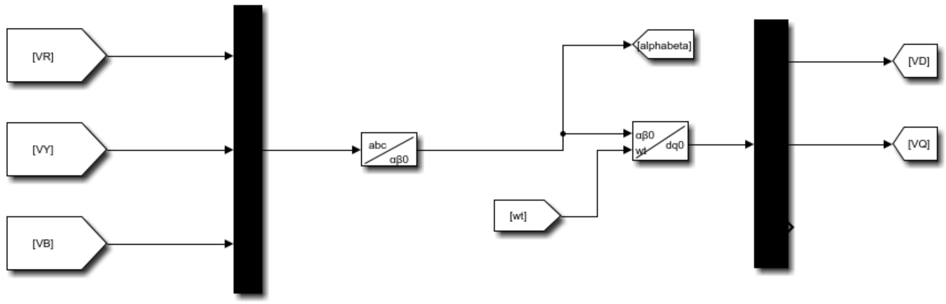

Figure 7.11. The d-q-0 transformation of the voltage

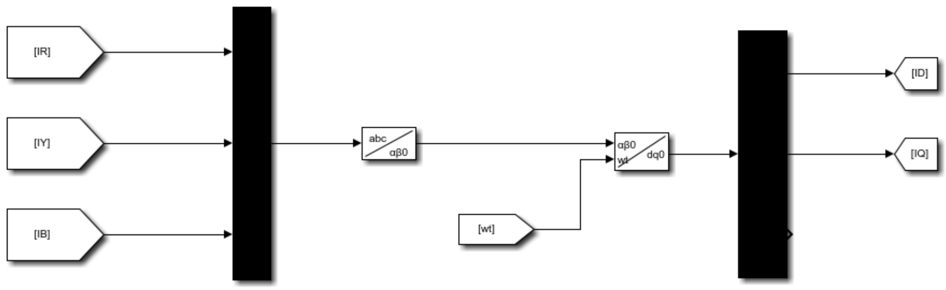

Figure 7.12. The d-q-0 transformation of the current

In order to get the correct angular velocities of the AC signals, the park transform is used in this section as in the first part of the simulation study. In Figure 7.13, the blocks used to get the angular velocity value of the AC signal are depicted.

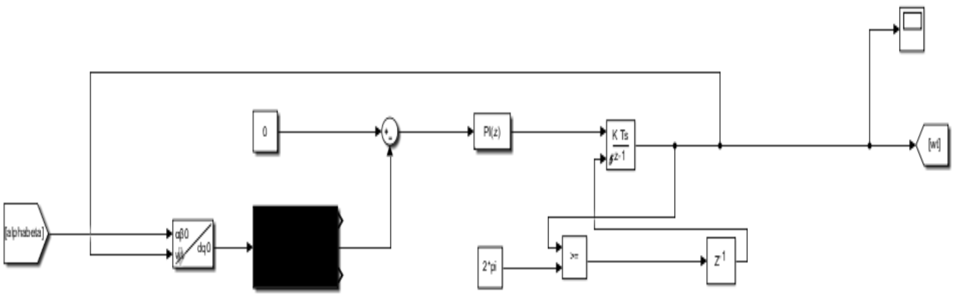

Figure 7.13. PLL block of Inverter

7.4. Simulation Study of DC/DC Conversion

When a voltage sag occurs in the system, as stated in the previous section, the DC bus voltage drops below the critical operation limit, and this situation makes the system to be disabled. In this study, the DC bus of the drivers is fed through the battery group, so that the DC bus voltage remains within the limits when a voltage sag occurs. The voltage required by the system during voltage sag is provided by battery based energy storage system through bidirectional DC-DC converter. To supply the DC bus properly, the design of the battery unit , design of the DC-DC bidirectional buck boost converter, design of the PI controller for the charge and discharge processes of the battery has very key role for the creation of the system.This part of the simulation is divided into two categories as , simulation of battery unit and bidirecitonal DC-DC converter.

7.4.1. Simulation of Battery Unit

In the simulation stage of the battery design the lead acid battery is chosen in battery block of MATLAB/Simulink with 563 nominal voltage and 63 Ah (ampere-hour) rated capacity. For the simulation study ,the lower and upper limits of SOC are determined as 50% and 90%, respectively. That means, a battery that discharge up to 50% and charge up to 90% has been designed. Details of the modeled battery group are given in the Table 7.1.

Table 7.1. Parameters of battery group

Parameter	
Type	Lead Acid
Nominal Voltage (V)	560
Rated Capacity (Ah)	63
Initial State of Charge (%)	70
Battery Response Time (s)	0.1
MaximumCapacity(Ah)	65
Cut-off Voltage (V)	445.5
Fully Charge Voltage (V)	594
Nominal Discharge Current (A)	180
Internal Resistance (Ohms)	1
Capacity (Ah) at Nominal Voltage	63

7.4.2. Simulation of Bidirectional DC-DC Converter

In order to keep the DC bus voltage within limits when a voltage sag occurs, the battery unit is connected to the DC link with a bidirectional buck-boost converter. Basic circuit diagram of Bidirectional DC-DC converter is shown in Figure 7.14. Also ,the simulink model of DC-DC bidirectional buck boost converter is conducted as shown in the Figure 7.15.

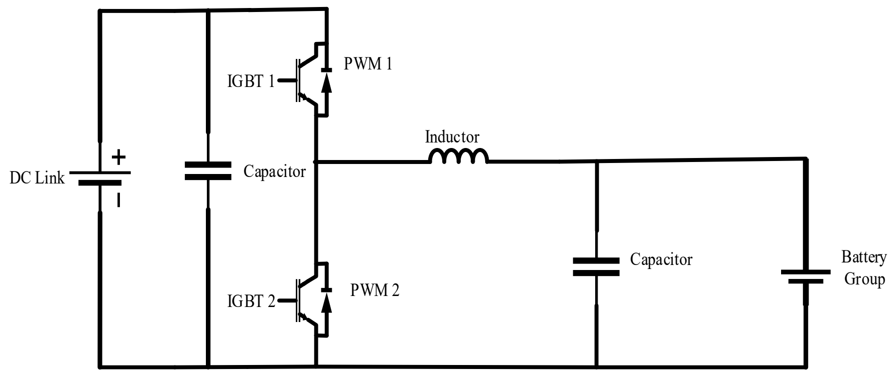

Figure 7.14. Basic circuit diagram of bidirectional DC-DC buck boost converter

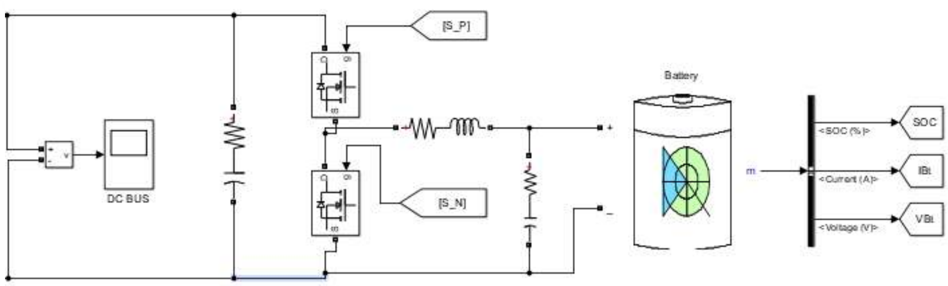

Figure 7.15. The DC-DC bidirectional buck-boost converter model in MATLAB / Simulink

As it is clear from the name, bidirectional DC-DC converter has two operation modes, buck, and boost modes, respectively. When there is no voltage sag in the system, it operates in buck mode which means that battery unit is charged. When a voltage sag takes place, battery unit is discharged in boost mode during this period. One of the most important parameter during the simulation of the system is the obtained correctly of the operating signals of the charge and discharge switches of the bidirectional DC DC buck boost converter. The charging and discharging states of the battery are studied separately.

To determine the charging status of battery unit , the difference between the voltage of the battery and the reference voltage is taken and this difference of this two value is controlled by the PI parameters and multiplied by (-1) to obtain the reference charging current (IB_ref) for battery at the output. With this situation, battery voltage is controlled and reference charging current is obtained according to the battery voltage. The charging is shown in Figure 7.16. After the determination of the reference charging current for the battery, the difference between this value and the measured battery current is subracted each other and controlled by the PI controller.The output of PI controller is then compared with a reference signal in the (0, 1) range to generate gate signals for charging situation.

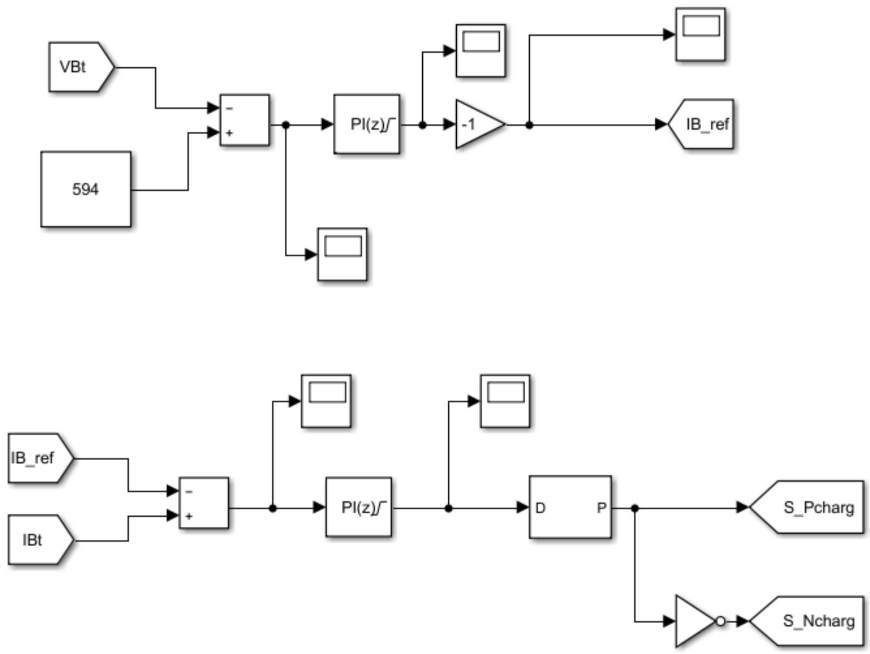

Figure 7.16. The charging status of battery unit.

To determine the discharging status of battery unit, the difference between DC link voltage and the reference voltage is taken and the difference of this two value is controlled by PI controller to get reference discharging current fort he battery unit. Thus, DC link voltage is controlled and maximum discharging current (IB_ref) of the battery is determined. The discharging process of battery unit is shown in Figure 7.17. After the determination of the reference discharging current for the battery, the difference between this value and the measured battery current is subracted each other and controlled by the PI controller. The output of PI controller is then compared with a reference signal in the (0, 1) range to generate gate signals for discharging situation.

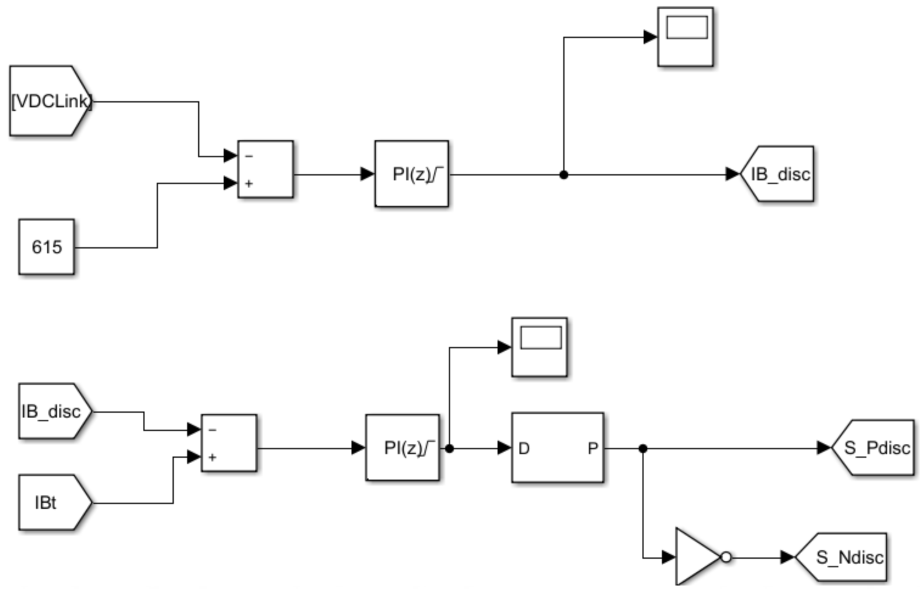

Figure 7.17. The discharging status of battery unit.

7.5. Simulation Study of Events

In the light of the data obtained by using the PowerLogic ION device given in Table 6.3, these two events are simulated and outcomes of DC bus voltage, mains voltage case during the voltage sag, battery charge-discharge status, battery current, are shown as schematically. In the first voltage sag event, the voltage sag lasted for 0.1 seconds, and the voltage dropped by 34.56% of the nominal voltage on the medium voltage bus. Simultaneously, on the low voltage side, where machine downtime occurs, the voltage has dropped by 18.75% of the nominal voltage. As a result, there is a disruption in production at the facility where the study is carried out and 38 machines are affected. Schematic representation of mains voltage is illustrated in Figure 7.18. As can be seen in Figure 7.18, a voltage sag happens between 1 and 1.1 seconds.

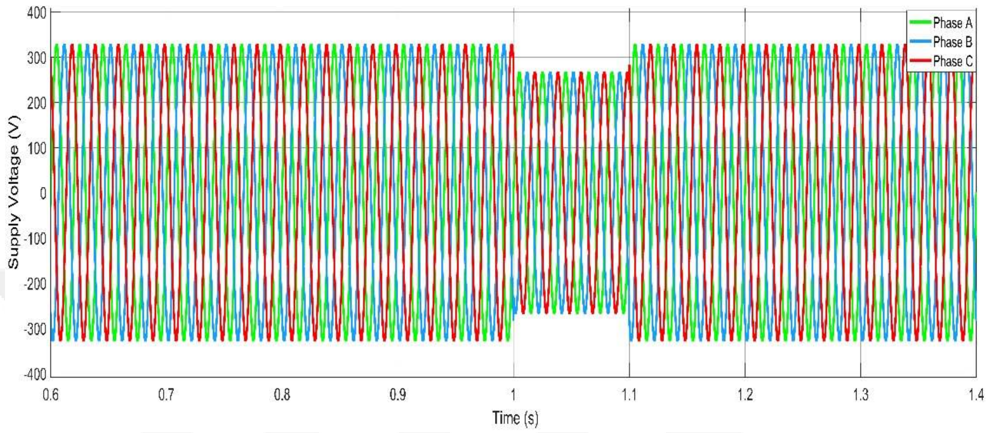

Figure 7.18. Mains voltage situation of case 1

In this system, operation voltage of DC bus is set between 590-615V. Minimum operation voltage of DC bus is equal to 0.9 of its nominal value. In this case, the trip value of the DC bus voltage is observed as $V_{dc,trip} = 553,5V$. In simulation, the minimum value at which the DC bus voltage drops is 598V. Since the DC bus voltage is within the operating limits, it is not affected by the voltage sag. DC bus voltage situation is shown in Figure 7.19.

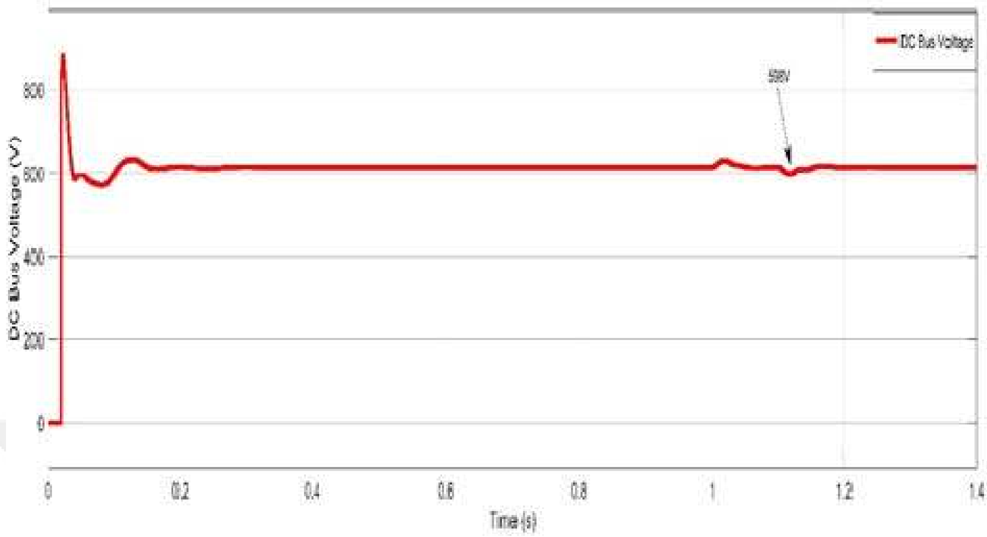

Figure 7.19. DC bus voltage

The working principle of battery charge and discharge switches is designed as follows.

- If the DC bus voltage is greater than or equal to 600 VDC and less than 620 VDC at the same time, the battery unit works in charge mode.
- If the DC bus voltage is greater than or equal to 621 VDC and less than 651 VDC at the same time, it does not work charge or discharge mode.
- If the DC bus voltage is greater than 549 VDC or equal to and less than 599 VDC, it works in discharge mode.

The positions of the charge and discharge switches of battery group that is connected to the DC bus are shown in Figure 7.21 and 7.22, respectively.

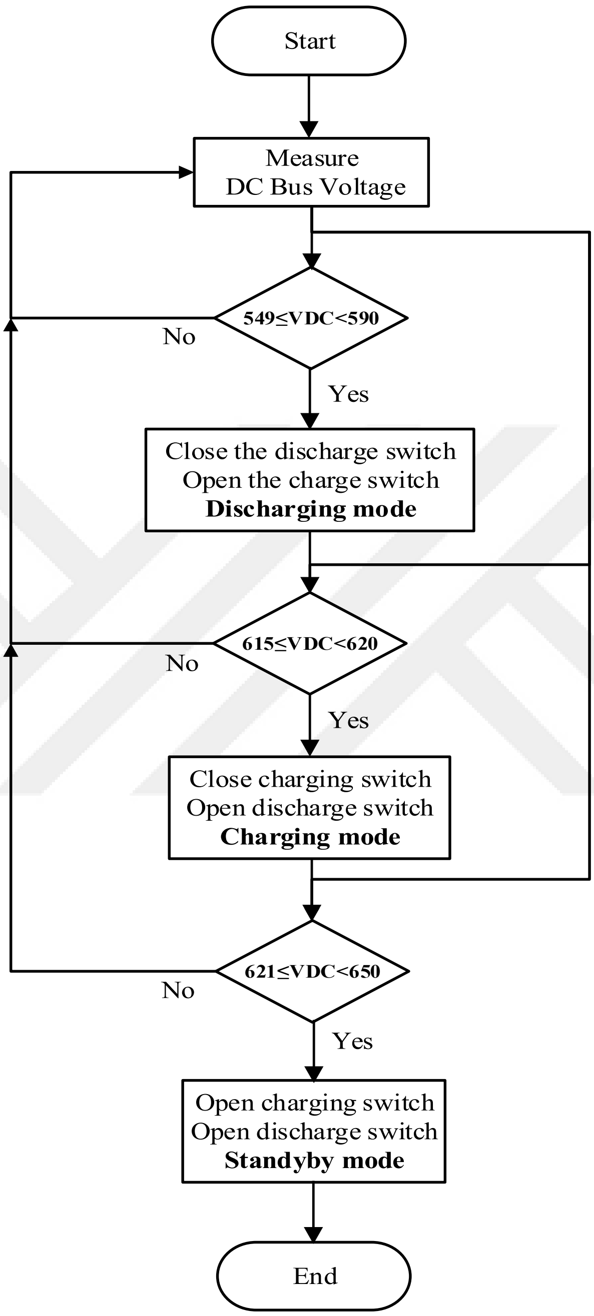

Figure 7.20. Battery switches algorithm

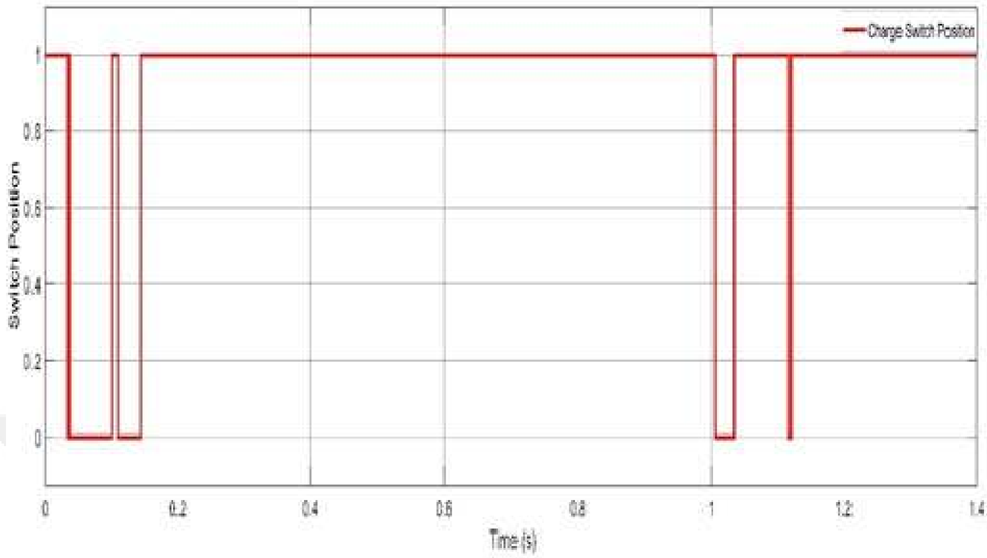

Figure 7.21. Charge switch position of battery group

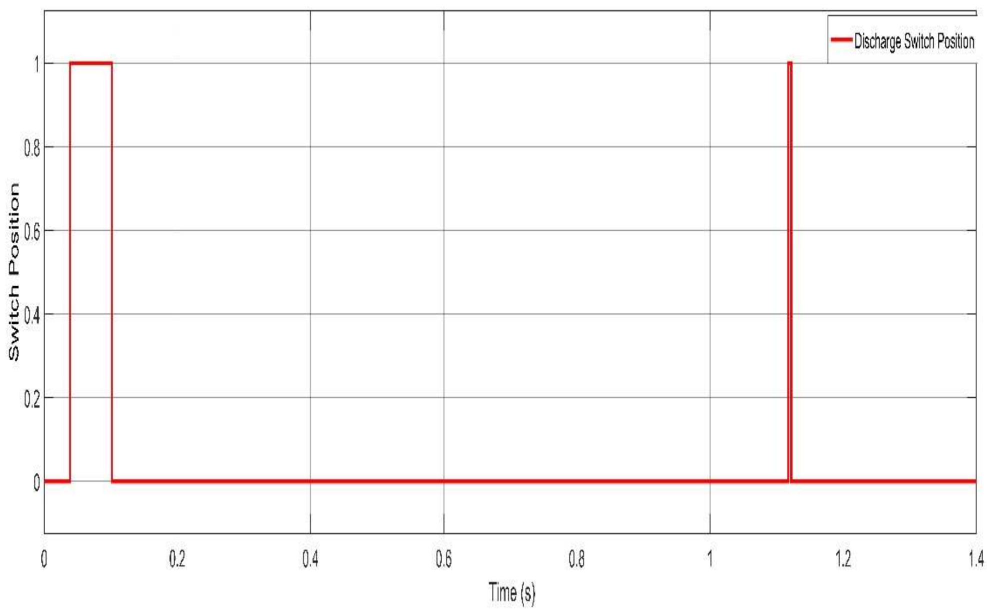

Figure 7. 22.Discharge switch position of battery group

Battery voltage and current of the first event are shown in Figures 7.23 and 7.24.

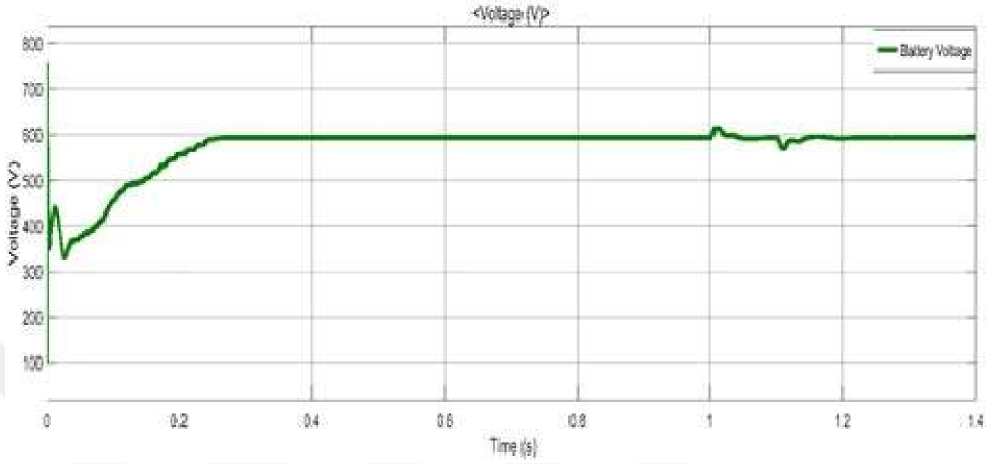

Figure 7.23. Battery voltage

Battery group has a voltage of 592 volts since the battery group consists of 44 series connected batteries which have 13.5 float voltage. It can be seen from Fgure 7.23 that the intervals which voltage of the battery group drops, feeds the DC bus and charge itself.

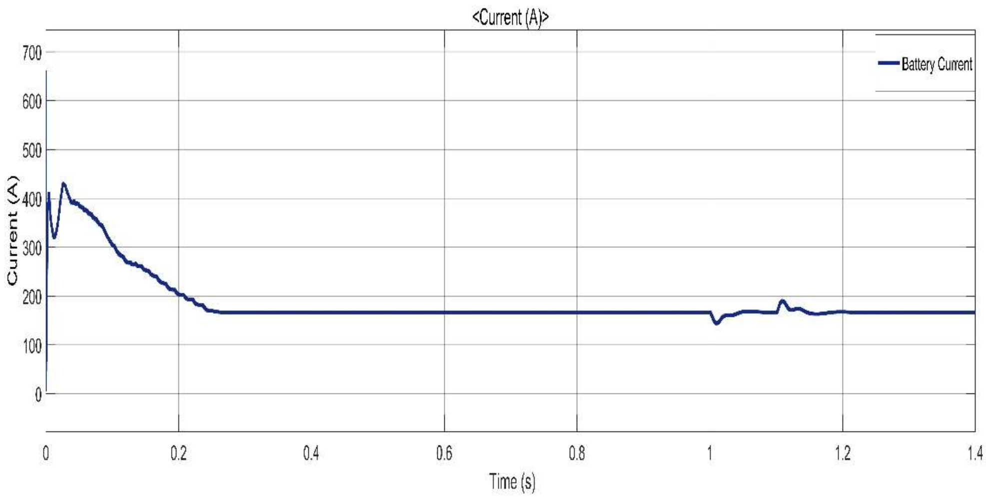

Figure 7.24. Battery current

In the second voltage sag event, the voltage sag lasted for 0.08 seconds, and the voltage dropped by 29.25% of the nominal voltage on the medium voltage bus. Simultaneously, on the low voltage side where machine downtime occurs, the voltage has dropped by 22.25% of the nominal voltage. As a result, there is a disruption in production at the facility where the study is carried out and 21 machines are affected. As can be seen in Figure 7.25. a voltage sag occurred between 1 and 1.08 seconds.

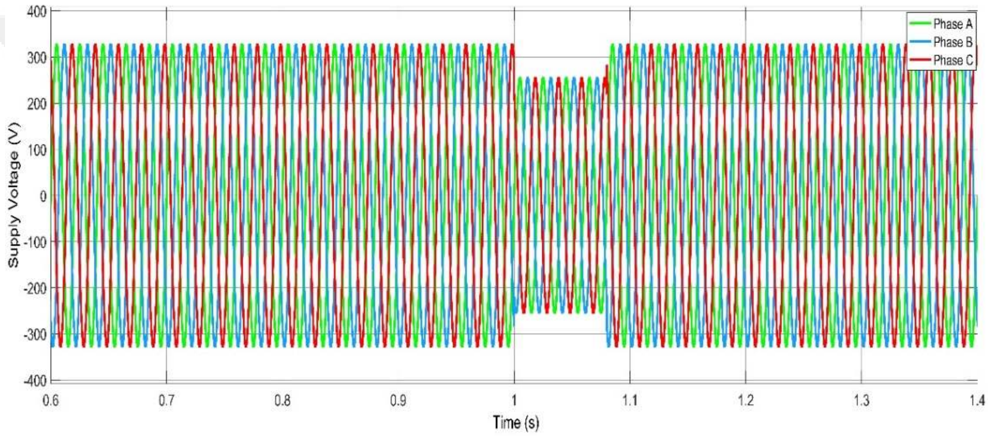

Figure 7.25. Mains voltage situation of case 2

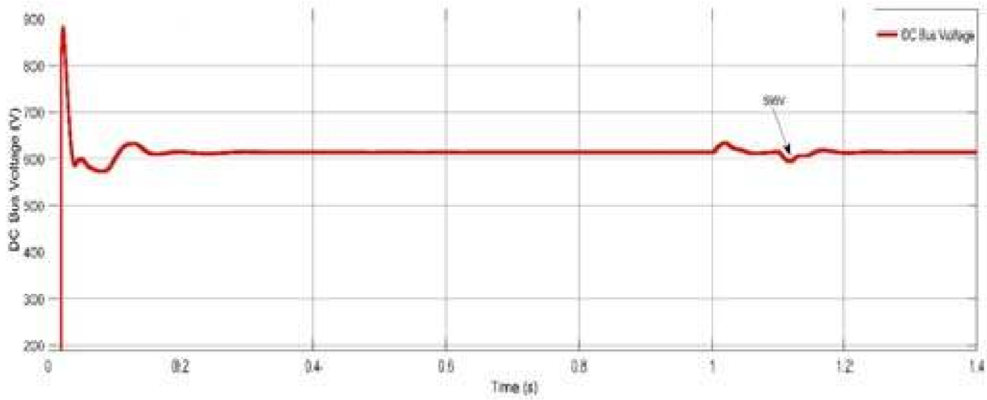

Figure 7.26. DC bus voltage

In the second simulation study, like in the first event, DC bus voltage is set between 590-615V.Minimum operation voltage of DC bus is equal to 0.9 of its nominal value. In this case, the trip value of the DC bus voltage is observed as $V_{dc,trip} = 553{,}5V$. In simulation, the minimum value at which the DC bus voltage drops in the simulation is 595V. Since the DC bus voltage is within the operation limits, it is not affected by the voltage sag. Figure 7.26. shows the DC bus voltage. The positions of the charge and discharge switches of battery group connected to the DC bus are shown in Figures 7.27 and 7.28, respectively.

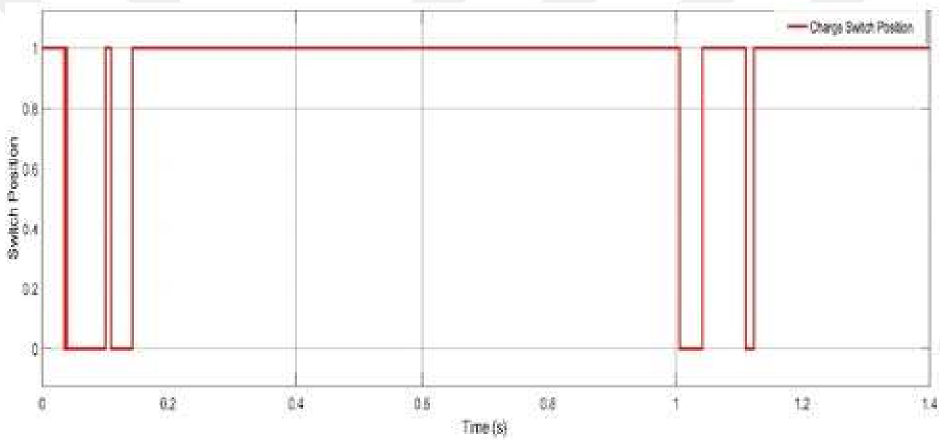

Figure 7.27. Charge switch position of battery group

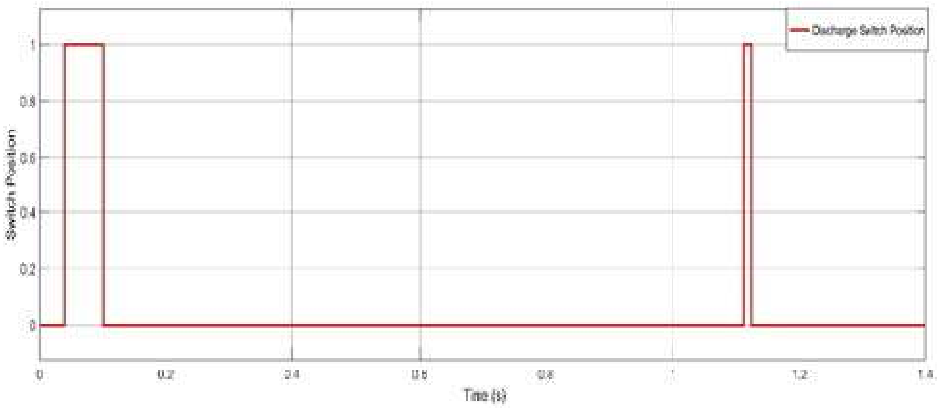

Figure 7.28. Discharge switch position of battery group

Battery voltage and current of the second event are shown in Figures 7.29 and 7.30, respectively.

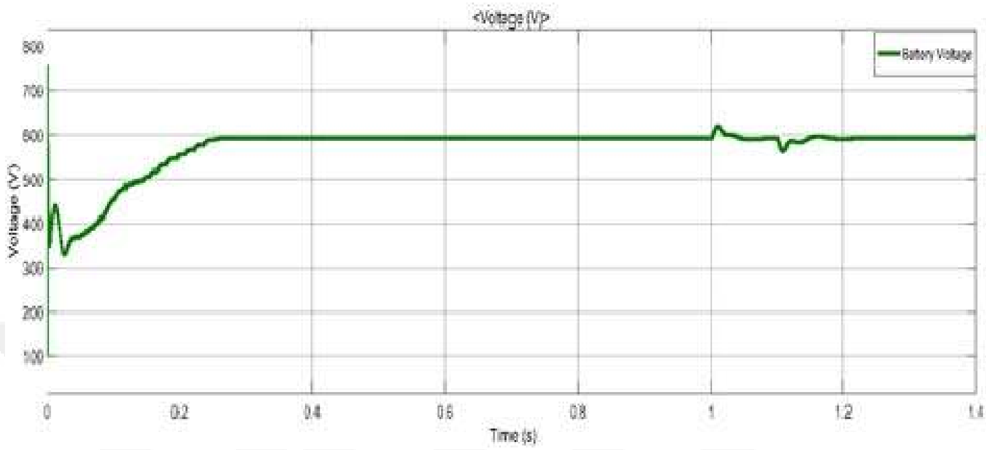

Figure 7.29. Battery voltage

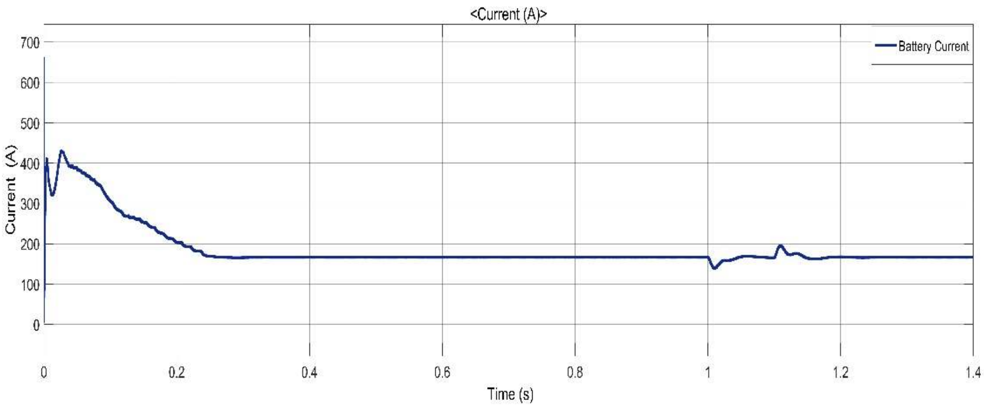

Figure 7.30. Battery current

The results of this simulation study and the studies carried out on the selected machine in the field are compatible with each other. It has been observed that the system to be installed will work correctly according to the simulation results. Thanks to this system, the selected machine is not affected by voltage sags. With this project, it is planned to reduce the negativities arising from power quality problems, especially voltage sag causing serious labor and financial losses in industrial facility. As a result of voltage sag events in the facility, 3.11% of all production in the last three years has been affected and not produced.When the system installation is completed for all machines, the effect of voltage sags on the plant and production will be eliminated, just like in the selected machine that was tested.

8. CONCLUSION AND FUTURE WORKS

Serious breakthroughs in the industrial field have been made possible by the recent quick advancements in technology and equipment. Device technologies utilized in industrial settings are likewise evolving in tandem with these changes, becoming increasingly complicated in design.These advancements in the industrial sector have had significant effects on energy efficiency, had a beneficial impact on production growth, and have led to significant increases in the quantity of energy utilized as production has increased. One of the devices developed for the efficient use of energy in industrial facilities is variable frequency drives. In order to lower the quantity of energy utilized in industrial facilities, variable frequency drives are used. Despite being widely utilized, variable frequency drives are quite susceptible to changes in power quality. As a result , the devices will receive uniterrupted and continuos power,which will improve both the quality of industrial process and energy efficiency. The concept of interrupted and continuos energy are explained in the literature together with the idea of power quality. The production process in industrial facilities will suffer as a result of the decline in power quality.

When the distribution of power quality events in the facility where the study was carried out was analyzed, it was determined that the most common problem was voltage sag. These voltage sags have affected the production stages where variable frequency drives are frequently used, causing some serious problems such as production stoppage, second quality production, personnel expenses etc. In this thesis ,existing methods developed for power quality problems have been evaluated and a hybrid method based on active front end technology and energy storage has been developed, proposed and simulated.The difference of the active rectifier from the classical rectifiers is that a controllable DC voltage can be obtained through IGBTs. Although adjustable DC voltage can be obtained, when voltage sag occurs in the system, DC bus voltage of variable frequency drives goes out of operating limits and downtimes occur in the relevant production process. In order to overcome this situation, a hybrid method based on active front end technology and energy storage system has been established and its connection to the DC bus has been provided. Since the DC bus voltage goes out of tolerance when a voltage sag occurs, the battery group is activated and the DC link voltage is kept within the previously determined operating range. Voltage sag events that have occurred before have been simulated with the Matlab/Simulink program, and it has been concluded that the proposed system is not affected by these events.Thanks to the proposed hybrid method, situations caused by voltage sag and causing serious costs are prevented. In addition, this method ensures continuity in production. 3.11% of the facility's total production has been impacted by voltage sag incidents and has not been produced. The influence of voltage sags on the plant and production will be eradicated after the system installation for all machines is complete, just like in the chosen machine that was tested.

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CURRICULUM VITAE

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APPENDIX

Matlab code for charge and discharge swtich

```
Discharging =0;
   Charging=1;
   if (VDCLink >= 600 & VDCLink < 620 )
   Discharging =0;
   Charging=1;
   end
   if (VDCLink >= 621 & VDCLink < 650)
   Discharging =0;
   Charging=0;
   end
   if ( VDCLink >= 549 & VDCLink < 599)
   Discharging =1;
   Charging=0;
   end
```