REPUBLIC OF TURKEY
ADANA ALPARSLAN TÜRKEŞ
SCIENCE AND TECHNOLOGY UNIVERSITY

INSTITUTE OF NATURAL AND APPLIED SCIENCE
DEPARMENT OF ELECTRICAL-ELECTRONICS ENGINEERING

POWER QUALITY PROBLEMS OF AN INDUSTRIAL ZONE FROM LOCAL HARMONICS TO NATIONAL BLACKOUT

Görkem OK

MASTER OF SCIENCE

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submitted by **Görkem OK** in partial fulfilment of the requirements for the degree of **Master of Science in Department of Electrical-Electronics Engineering, Adana Alparslan Türkeş Science and Technology University** by,

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Thesis Defense Date 12/10/2020

I hereby declare that all information in this thesis has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all information that is not original to this work.

Görkem OK

ABSTRACT

POWER QUALITY PROBLEMS OF AN INDUSTRIAL ZONE FROM LOCAL HARMONICS TO NATIONAL BLACKOUT

Görkem OK

Department of Electrical-Electronics Engineering

Supervisor: Assoc. Prof. Dr. Lütfü SARIBULUT

October 2020, 63 pages

With the increasing use of devices based on power electronics, negative effects such as harmonics have emerged in the electricity distribution networks. Due to these effects, the issue of power quality has become increasingly important due to the damage of sensitive electronic devices of industrial and end-users. Power quality problems are manifested by the faulty operation of the devices due to current and frequency changes on the consumer side. In addition, compensating energy needs from renewable energy sources (RES) increases the effects of these problems.

In this study, an Organized Industrial Zone (OIZ) was modelled at the simulation environment by using its electrical network data. By examining the system, the frequently encountered power quality problems were determined and solutions were tried to be presented. The establishment of PPSs has increased rapidly in OIZs within the framework of the RES and their effects on the network have been ignored. For this reason, a real PPS modelling has been made within the scope of the thesis, and the problems encountered and solutions found after commissioning have been examined and evaluated with case studies.

Keywords: Power quality, Industrial Zone, Solar Power Plant

ÖZET

BÖLGESEL HARMONİKLERDEN ULUSAL SİSTEM ÇÖKÜNTÜSÜNE BİR SANAYİ BÖLGESİNİN GÜÇ KALİTESİ SORUNLARI
Görkem OK

Elektrik-Elektronik Mühendisliği Anabilim Dalı
Danışman: Doç. Dr. Lütfü SARIBULUT
Ekim 2020, 63 sayfa

Güç elektroniğine dayalı cihazların kullanımı artmasıyla, elektrik dağıtım şebekelerinde harmonik gibi olumsuz etkiler ortaya çıkmıştır. Bu etkiler nedeni ile endüstriyel ve son-kullanıcıların hassas elektronik cihazların zarar görmelerinden dolayı güç kalitesi konusu giderek önem kazanmıştır. Güç kalitesi problemleri (GKP), tüketici tarafında akım ve frekans değişimleri nedeni ile cihazların hatalı çalışması sonucunda kendini göstermektedir. Buna ek olarak enerji ihtiyacını yenilenebilir enerji kaynaklarından (YEK) telafi edilmesi, bu problemlerin etkilerini arttırmaktadır.

Bu çalışmada bir Organize Sanayi Bölgesi'nin (OSB) elektrik şebekesi verileri kullanılarak benzetim ortamında modellemesi yapılmıştır. Sistem incelenerek sıklıkla karşılaşılan GKP'ler belirlenip, çözümler sunulmaya çalışılmıştır. YEK Kanunu çerçevesinde PPS'lerin kurulumu OSB'lerde hızla artmış ve şebekedeki etkileri göz ardı edilmiştir. Bu nedenle tez kapsamında gerçek bir PPS'nin modellenmesi yapılmış olup, devreye alındıktan sonra karşılaşılan sorunlar ve bulunan çözümleri örnek çalışmalarla incelenmiş ve değerlendirmeleri yapılmıştır.

Anahtar Kelimeler: Güç kalitesi, Sanayi Bölgesi, Güneş Santrali

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NOMENCLATURE

ACSR	: Aluminium-Conductor Steel-Reinforced
APF	: Active Power Filter
DVS	: Dynamic Voltage Support
EPDK	: Energy Market Regulatory Authority
FRT	: Fault Ride-Through
HVDC	: High-Voltage Direct Current
IEEE	: Institute of Electrical and Electronics Engineers
IEC	: International Electro Technical Commission
IHD	: Individual Harmonic Distortion
LV	: Low Voltage
NB	: National Blackout
OIZ	: Organized Industrial Zone
PCC	: Point of Common Coupling
PWM	: Pulse Width Modulation
PQ	: Power Quality
PQD	: Power Quality Disturbance
PPS	: Photovoltaic Power System
PV	: Photovoltaic
PST	: Phase Shifting Transformer
RLC	: Resistor (R), Inductor (L), Capacitor (C)
RES	: Renewable Energy Sources
SC	: Serial Capacitor
THD	: Total Harmonic Distortion
TL	: Transmission Lines
UPS	: Uninterrupted Power Supplies

1. INTRODUCTION

1.1. Scope of Thesis

European International Energy Transmission System which Turkey is also attendant as a member is able to keep the balance of supply - demand to be safe and sustainable. However, the sustainability of this community is going into a deadlock with turning the national energy transmission system into a commercial platform and releasing the energy policies without system analysis and the recovery scenarios. Market developments result in short-term commercial targets.

The integration of renewable energy generation centers such as wind and solar was not taken into account when the national energy transmission systems were designed. Therefore, they can connect to the network through the distribution systems and provide the services. With the increasing of their number, the network operation was become more difficult day by day and the transmission lines had to work more on their current capacities.

Within the scope of this study, one-year measurements of the electrical network dynamics (such as current, voltage, power factor) of an industrial area will be made and transferred into the simulation environment by using PSCAD / ETAP programs. In the case studies, the load characteristics of electrical network will be examined by using the measurements and the solutions of problems encountered due to the power quality problems will be focused. With the enforcement of the Regulation on Unlicensed Electricity Generation at the Electricity Market, the establishment of Distributed Power Plants became easier. The connections of these power plants at the high voltage level will be examined in terms of the technical infrastructure.

The solar power plants have the ability of scalable more easily than other renewable energy sources and to be installed everywhere. Especially in order to reach the end user in residential areas, it is intensely established at the nearest points. Therefore, in the case studies, the effects of solar power plants on the electricity grid will be examined, the problems that may be encountered will be identified and the solutions will be proposed for them. In the scope of thesis, the causes of system crashes will be examined with examples, and solutions will be presented in order to limit the effects in case of occurrence.

2. LITERATURE REVIEW

In the literature, the studies related with modelling of the power systems consisting of several busbars were carried out and then, the fault analysis such as single phase-to-earth, short-circuit between phases were made. Among of these studies, there are very few academic articles and studies that analysis of the power system in the simulation environment by using the measurement data and propose solutions. Some of these studies were given in the following.

Organized Industrial Zones are the production areas of goods and services established in order to accommodate the areas suitable for industry, to solve the environmental problems and to ensure the efficient use of resources (planned industrialization). Therefore, it has to produce the solutions in all areas that the industry needs. Hence, it is aimed to increase the competitiveness of industrial companies [Dursun, M., Goker, N., Tulek, BD., (2018)]. With the establishment of industrial zones, all infrastructure, especially the electricity network, needs to be built on solid foundations. The combination of high-power loads such as electric furnaces, rolling mills, cranes and the electrical devices based on the semiconductor technology were caused the electrical power quality problems that need to be compensated. In the solutions of these problems, the equipment such as current-voltage balancing elements and reactive power stabilizers were used [Bisanovic, S., Hajro, M., Samardzic, M., (2014)].

Today, the demand of electricity generation from the renewable energy sources is increasing rapidly. Among of these sources, PV plants are the mostly installed and connected directly to the electricity distribution network. The designs of these systems are made by assuming a balanced grid system. However, there is a critical voltage imbalance in the electrical networks of industrial zones. The integration of PV systems into the unbalanced distribution network and the effects of this integration have not been fully observed yet. This issue should be examined in detail without causing the serious problems of high PV penetration level in the future [Rodriger, S., Yan, R., Saha, TK., (2012)].

In the studies, the current and voltage controls of PV systems under the different conditions remain within their limits. In the laboratory and simulation studies carried out, it shows that as the number of inverters used in PV systems increases, current and voltage waveform distortions increase [Awadallah, M.A., Venkatesh, B., Singh, B.N., (2015)]. Power quality is becoming a popular research topic due to the rapid increase of the renewable energy generation systems.

3. ELECTRICAL POWER SYSTEM

3.1. General Description of Power System

The power system is a network which is planned and designed to supply the electrical energy to the consumers by considering the economy, quality, reliability and environmental impact. The first consideration is the basis of optimization that the power companies must be done regarding with their investments and daily operation. Therefore, the larger companies have special departments responsible for following the companies either obeying the laws and regulations within the environment area.

A power system consists of generation, distribution and transmission systems. These systems include the devices such as synchronous generator, motor, transformer, circuit breaker, conductor, etc. The main components of the power system are the switchyard, transformer, transmission line, substations, distribution line, and distribution transformer. The switchyard increases the electricity level by using the transformer (step-up type) for transmission. The transmission line transfers the power to the substations. Through the substation, the electricity level decreases to the appropriate value for the end users by using the distribution transformer (step-down type).

3.2. Organized Industrial Zones

There are many terms used to describe some aspects of the industrial organization of nations. Such as, 'industrial district' is a place of firms, specialized in a main industry and the auxiliary industries, 'industrial park' is an area planned for the industrial development and including heavy industry and 'organized industrial' is a kind of special economic zone related with industries or just a special industry. Every industry is not allowed to operate and there are considerable taxes and location (by making closer to the related industries) advantages. They are usually located on the edges of or outside the main residential area of a city, and close to the transport facilities (including highways, railroads, airports and ports).

With the growing of OIZs, some problems were emerged related with the utilization of the electricity. The electronic devices of consumers and end-users were daily broken down or crashed due to the electricity interruptions or other else. Increasing of these problems, a new term ‘quality in power service’ or ‘power quality’ is depicted in OIZs. PQ can be defined with two important factors. These are the variations on frequency and voltage.

In a power system, the frequency is a good indicator for the balancing of active power. If it is constant, the same amount of active power is produced as consumed by the loads (including system losses). If this is not, the frequency changes will occur. It is the important note that the active power is a global quantity. However, the reactive power is a local quantity due that it cannot be transmitted over longer distances. If a load increases according to the stable limits, the power deficit decelerates the generator rotors. Consequently, the frequency is reduced.

As a consequence of the fault occurred in the power system, the protection system separates the faulty equipment. The large reductions at the voltage frequency could lead to system collapse, since a lot of equipment does not tolerate too low frequencies. Also, a load reduction in the system leads to a frequency increase [Andersson, (2008)]. Such as, a blackout was occurred in Turkey due to the decreasing of the national voltage frequency. In Turkey, the interval of the permitted stationary frequency deviation for the interconnected power systems is ±%1 of its normal operation rating and the duration of frequency deviation is not normally permitted to be larger than 10second [resmigazete.gov.tr/eskiler/2008/02/20080220-2.htm].

For controlling of the voltage profile, the series capacitors are generally installed to increase the capacity of the transmission lines. During the excitation of synchronous machines, the reactive power limits of the system are exceeded. If the compensating of reactive power to the power system is larger than the reactive loads, it causes voltage drops. It should be avoided. It can be said that the voltage control of a system can be achieved by controlling the reactive power between the permission limits or vice versa [Andersson, (2008)].

3.3 Power Quality

PQ is defined as ‘the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment’. The other definition of PQ by IEC is a set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of continuity of supply and characteristics of voltage (magnitude, frequency, and waveform).

3.4 General Power Quality Disturbances in Power System

General power quality disturbances in high voltage systems are classified as given in the following.

- Harmonics, interharmonics [Chattopadhyay, Mitra, Sengupta (2011)],
- Voltage fluctuations (flicker) [Baggini (2008)],
- Voltage dips and interruptions [Dugan, McGranaghan, Santoso, Beaty (2004)],
- Voltage imbalance (unbalance) [Caramia, Carpilelli, Verde (2009)],
- Power frequency variations. [Fuchs, Masoum (2008)]

Among of PQDs, the harmonics are the most occurred in the power system by using the switch-mode electronic equipment and nonlinear loads. It can be defined as a sinusoidal waveform having frequencies that are integer multiples of the fundamental frequency. The harmonic currents can adversely interact with the utility supply system. The interaction often raises the voltage and current harmonic distortion level in many places of the system [Melville, (2004)]. Therefore, IEEE proposes a standard '519-1992' for the harmonic current injection to limit both voltage and current harmonic distortion. IEEE Standard 519-1992 provides a guideline for acceptable levels of the voltage distortion at the utility system. These are summarized in Table 1 and Table 2.

The harmonic currents injected into the system (or network) from the end users must be limited. These currents spread to the supply source through the system impedance causing a voltage distortion. If the amount of harmonic currents distortion is limited, the voltage distortion can also be limited. Even if the harmonic current distortion is within limits, the overall voltage distortion levels can be extremely high. This situation occurs especially when one of the harmonic current frequencies is close to the system resonance frequency. This is unacceptable in some system locations and can lead to destructive voltage distortion levels. The highest voltage distortion usually occurs in a capacitor bank that participates in resonance [Melville, (2004)].

Table 1. Limits of voltage harmonic distortion

Bus voltage at PCC, V_n (kV)	Individual harmonic voltage distortion (%)	Total voltage distortion, THD_{V_n} (%)
$V_n \leq 69$	3.0	5.0
$69 < V_n \leq 161$	1.5	2.5
$V_n > 161$	1.0	1.5

SOURCE: IEEE Standard 519-1992, table 11.1.

Table 2. Limits of current harmonic distortion

I_{SC}/I_L	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
$V_n \leq 69$ kV						
<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
69 kV $< V_n \leq$ 161 kV						
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20–50	3.5	1.75	1.25	0.5	0.25	4.0
50–100	5.0	2.25	2.0	0.75	0.35	6.0
100–1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0
$V_n >$ 161 kV						
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.50	1.15	0.45	0.22	3.75

*All power generation equipment applications are limited to these values of current distortion regard less of the actual short-circuit current ratio I_{SC}/I_L.
SOURCE: IEEE Standard 519-1992, tables 10.3, 10.4, 10.5.

3.4.1 Elimination Methods of Harmonics at Power Systems

Most renewable sources of energy (such as wind, solar, etc.) need to be interfaced to the existing power supply using a power converter. However, the power converters generate undesirable harmonics that will affect nearby loads at the point of common coupling to the grid [Channegowda, John, (2010)]. PWM drives that charge DC bus capacitor directly from the line without any intentional impedance are one of the main harmonic sources of the power systems. Adding a line reactor or transformer in series reduces significantly harmonics. It also provides the temporary protection. The transformers windings can also be used to reduce the harmonic currents in the three-phase system. If the phase of 6-pulse converters used in power system is shifted as 30°, the distortion level of 5^{th} and 7^{th} harmonics significantly decreases to the level of 12-pulse converter. The delta-connected transformers can block the flow of zero-component harmonics and third harmonics from the line. The zigzag and grounding transformers can eliminate the harmonic currents at the line [Melville, (2004)].

PST which is the combinations of RLC circuit is a cost-effective, economical, reliable apparatus and also efficient power flow control at the overloaded transmission lines. They are increasing the system efficiency and reliability while decreasing the operating costs. Its design, construction, and operation are unique and differ from the standard power transformer. They are used to control the magnitude and phase angle of the equivalent impedance of the filter [Chitsazan, Trzynadlowski, (2016)].

3.5 Importance of Stability for Power System Dynamics

A common characteristic of the instabilities can be said as an imbalance of the active or reactive power at the system in locally or globally. This imbalance can cause the unstable behaviour depending on the system characteristics.

3.5.1 Synchronous Stability

The total generated active power always equals to the active power consumed by the loads, including losses of the power system. However, there is not always a similar balance between the total power fed to the loads and generators by the main lines (depending on time and distance). If such an imbalance develops, the rotating parts of generators and other rotating machines act as an energy buffer, and the kinetic energy stored in these equipment will decrease or increase as a result of the imbalance. The rotor angle stability refers the ability of synchronous machines to remain in synchronism after the disturbance [Andersson, (2008)].

If the disturbance is local and substantial such as an earth fault close to the generator, the generator can fall down from its level since it has been accelerated during the fault. As quite big currents will flow in the generator windings in such a case, it must be disconnected to avoid that it is damaged. The typical time scale for development of such instability is from one-second to couple of seconds. This type of instability is called transient instability and it appears usually in form of aperiodic angular separation due to lack of synchronizing torque. It is also referred as the large-disturbance rotor angle instability [Andersson, (2008)].

3.5.2 Frequency Stability

If the total generated power is less than the amount of consumed by the loads, including losses, it causes the changes in frequency of the whole system. As explained above, the kinetic energy stored in rotating parts of the synchronous machines and other rotating electrical machines will compensate the imbalance resulting by frequency deviations. If the imbalance is not too large, the generators participating will regulate the active power and bring back the frequency deviation to acceptable values. If the imbalance is too large, the frequency deviation will be significant and result with possible serious consequences.

Particularly, the thermal power plants are sensitive to the large frequency drops in long durations, since detrimental oscillations could be excited in their turbines. As a last resort the generators are disconnected to prevent the situation even more serious (Blackout). This type of instability is called frequency instability and the time scale could be from a few seconds up to several minutes. Since the involved mechanisms could be quite different, one often distinguishes between the short-term and long-term frequency instability. In the latter case, the control and protections characteristics of the turbines, boilers, and reactors play important roles [Andersson, (2008)].

3.5.3 Voltage Stability

There is always a balance between 'produced' and 'consumed' reactive power in every node of the network. When one talks about the imbalance in this context we mean that the injected reactive power is such normally too small (or high), that voltage in the node cannot be kept to acceptable values. When we talk about the imbalance in this case we thus mean that the injected reactive power differs from the desired injected reactive power, it is needed to keep the desired voltage. If this imbalance gets too high, the voltages exceed the acceptable range.

The reactive power is a more local quantity than the active power since it cannot be easily transported in the power system where normally $X \gg R$. In the latter case, the instability develops into very low voltages in the system. The low voltages arise at the high load conditions, while the high voltages are associated with the low load conditions. Depending on the time scale, the voltage instabilities are classified as a short-term, couple of seconds, long-term and tens of seconds to minutes. The short-term voltage instability involves the dynamics of fast acting components such as induction motors, electronically controlled loads, converters (e.g. solar converters) and HVDC converters, while the long-term voltage instability involves the slower acting equipment such as tap-changing transformers, thermostatically controlled loads and generator current limiters [Andersson, (2008)].

The time scale of the long term voltage instability develops from a gradual lack of the reactive power at a node or in a part of the system. Even if the voltage stability phenomenon is closely coupled to the reactive power balance, the active power plays a very important role indirectly. The many loads have an inductive power factor that is not whole, and thus the active power will cause an increase in the reactive power consumption. Furthermore, the reactive losses in the transmission lines are proportional to the square of the active power transmitted, so heavily loaded lines will influence the reactive power balance significantly [Andersson, (2008)]. Therefore, the capacitor banks are used in the transmission lines

The contributing factors to a slow voltage collapse are given in the following.

- Load increase
- Load recovery after faults
- Reactive losses in line due to high power transfer
- Loss of reactive supply (capacitors, synchronous machines, etc.)

The loads depicted above such as induction motors consume a lot of reactive power just after the fault. The other loads that could be very detrimental in this context are some types of the power electronics based equipment. For example, the line commutated HVDC converter could be stabilising in a weak system, and if the system design is not properly accounted, it could be leaded to the system collapse for the critical contingencies. The induction motors are also troublesome in the slow voltage instability. This is particularly the case in some countries (e.g. Turkey) where the peak load contains a large amount of air conditioning driven by induction motors. If the voltage gets low, they can stall. This situation means the reactive power consumption in large amount [Andersson, (2008)]. The voltage drop below a certain level can lead to take the critical equipment, used in the renewable energy sources such as solar inverters, under the protection and reduced the reactive power generation.

4. PHOTOVOLTAIC POWER SYSTEMS

Electricity Market of Turkey, the Regulation on the Unlicensed Electricity Generation entered into force in 2011. Thus, the power plants can be connected to the distribution system from the low voltage level. Existing distribution systems have become open to the bi-directional energy flow with these power plants and a structure has started to be formed in which classical analysis, operation and planning methods are insufficient. There are some points to pay attention to the installation of PPS and the important ones are presented in the following [TEDAŞ, (2014)].

1. The generation facility should be compatible with the voltage level and the frequency level (50 Hz) of the distribution system at the point where the meter is located. In terms of the current and voltage harmonics and flicker effect, it should not have a negative impact on other distribution system users.
2. The production facility is designed, installed and operated in a way that it will be disconnected from the distribution system and will not energize the distribution system in case of a loss of mains or a short circuit failure in the distribution system and in the unusual network conditions.
3. The power of production facility to be established: If it is below 11 kW, it should be connected to the low voltage distribution system. If it is over 11 kW, it should be connected to the distribution system from the low voltage or high voltage level as a result of the technical evaluation.
4. The total of generation facilities to be connected from the low voltage level cannot exceed 30% of the power of the distribution transformer to which these generation facilities are connected.
5. The connectivity rate of the point to be connected: It is essential for the cogeneration plants with an installed power above 1.000 kW to be 30% and to 70% for other generation facilities. If the connectivity rate is below these values, the distribution company may offer another port for the connection. The connectivity ratio (such as system tightness ratio, stiffness ratio) is defined as the division of short circuit current of the distribution system at the connection point to the nominal power of the plant.

6. The impedance at the input of the inverter is desired to be below the mains impedance. If the mains impedance exceeds the critical value at the input of the inverter, the inverter may shut down. In this case, the cable cross-section and the inverter position arrangements can shift the impedance to the safe side.

In the upcoming period, in addition to the electrical protection in PPS to be connected from the transmission level during the licensed PPS process, the supply of ancillary services such as FRT, active / reactive power control and dynamic network support will be on the agenda. (FRT is defined as the ability to remain in the network without losing its stability after the network failures that may result with the voltage drop and to support the network until the fault is terminated and returned to the normal operating conditions.)

The voltage fluctuation, flicker, DC current injection, total current degradation and phase imbalance should not be allowed at the areas of high amounts different powers and the features of PPS. It is up to EPDK and the authorized distribution companies to prevent these nonconformities. It is necessary to use the panels, inverters, cables and protection elements that comply with the international standards, for both the maintaining the mains power quality and the sustainable system operation.

5. AN ORGANIZED INDUSTRIAL ZONE AT THE MEDITERRANEAN REGION OF TURKEY

Organized region, which will be examined within the scope of the thesis, operates in the Mediterranean Region of Turkey. Between the dates when the measurements were made, the power consumption was determined as 190MW. The electricity grid of the organized area has connections with three power plants at the 154kV rate, and the two power plants are always ready as a hot-backup. The industrial network (154 / 31.5kV, 100MVA (Δ / Δ)) is powered by two identical transformers. In the simulation program, the industrial zone was fed with a 31.5kV power source and presented in Figure 1.

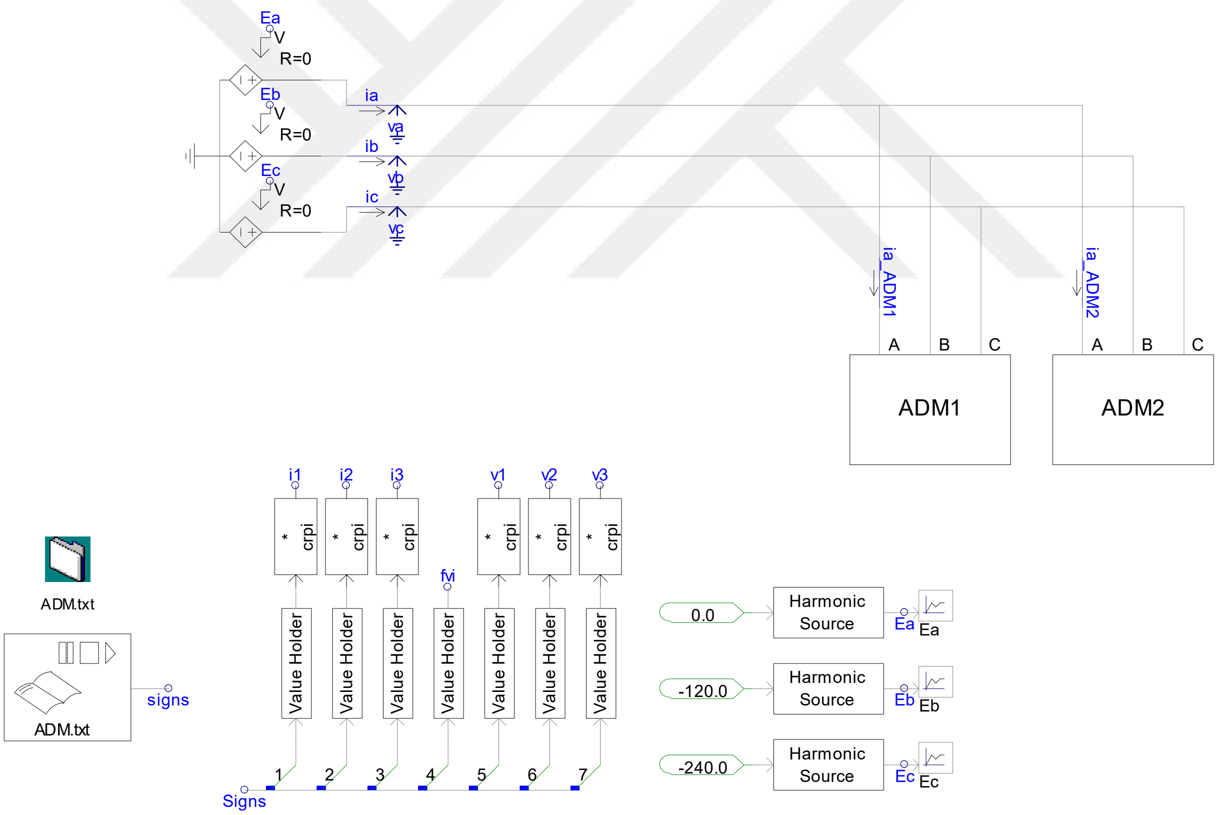

Figure 1. The distribution bus-bar and main two sub-branches of OIZ

The network dynamics (voltage / current and individual harmonics, active / reactive power and power factor (cosφ)) of OIZ were measured regularly with the remote monitoring system between the years 2013 and 2014. These data collected within the scope of the thesis were edited and integrated to the simulation program. Figure 1 is a simple model of the network. In this model, the set DC sources named 'Ea, Eb and Ec' were created as the voltage source of OIZ system by taking the voltage values from the 'ADM.txt' file.

The two main sub-groups of OIZ are separated in parallel with the electricity network 'ADM1 and ADM2'. In these groups, each of them is divided into the secondary subgroups in parallel and shown in Figure 2 (a) and Figure 2 (b).

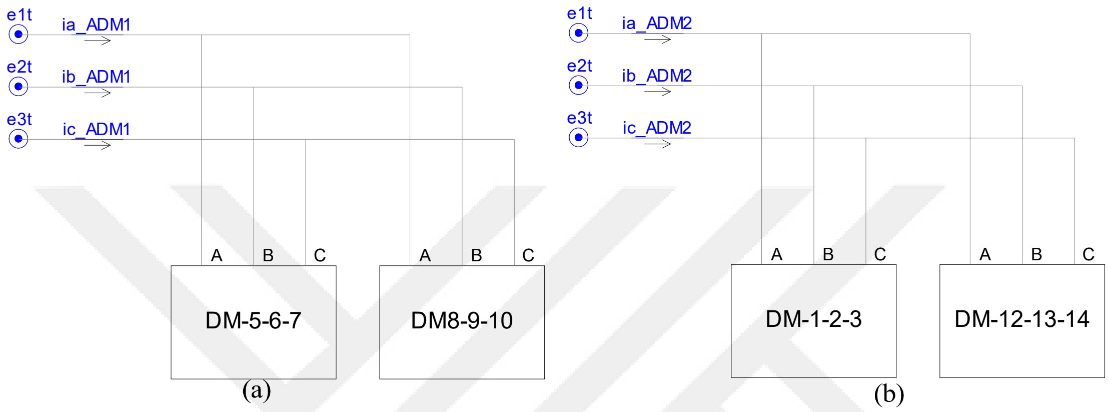

Figure 2. The sub-branches of ADM1 (a) and ADM2(b)

DM-5-6-7, DM-8-9-10, DM1-2-3 and DM-12-13-14 are subdivided among themselves. As an example, DM-5-6-7 is connected to each other as DM5, DM6 and DM7 rings shown in Figure 3.

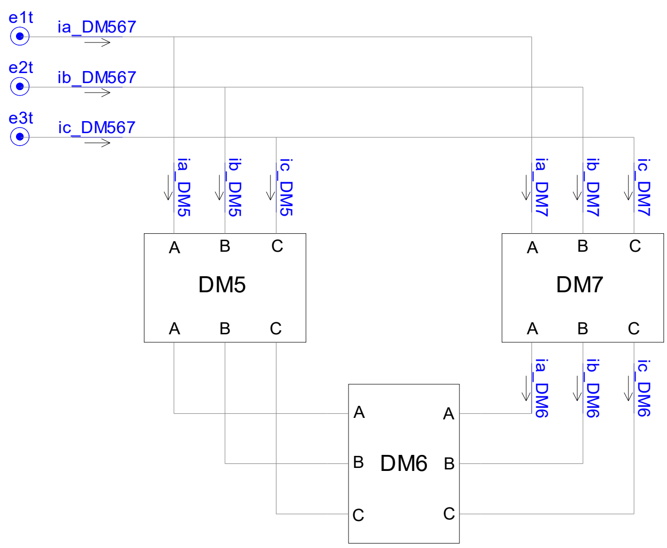

Figure 3. The sub-groups of DM-5-6-7

DM5 of DM-5-6-7 is also divided into the subgroups and these groups are connected in parallel with each other. Each group represents the measuring points of the total strength of the firms having of various numbers and sizes. As an example, DM5 in Figure 4 consists of five blocks (feeders) with the different powers.

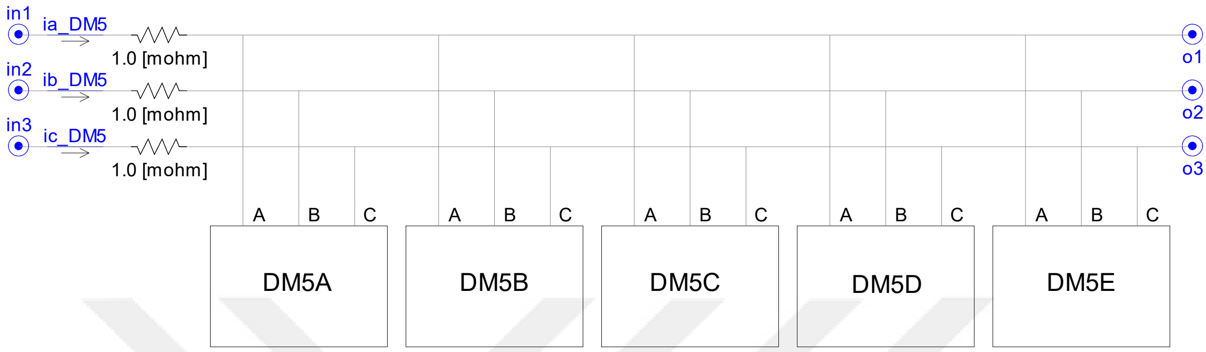

Figure 4. The sub-groups of DM5

The current sources are used to model the lowest blocks of OIZ, and the phase current values among the measurements of the system are draw to the simulation by using 'File Reader' modules of the PSCAD program. This process is given in Figure 5 for the DM5A and the modules used in the simulation of OIZ are explained in detail in section 6.

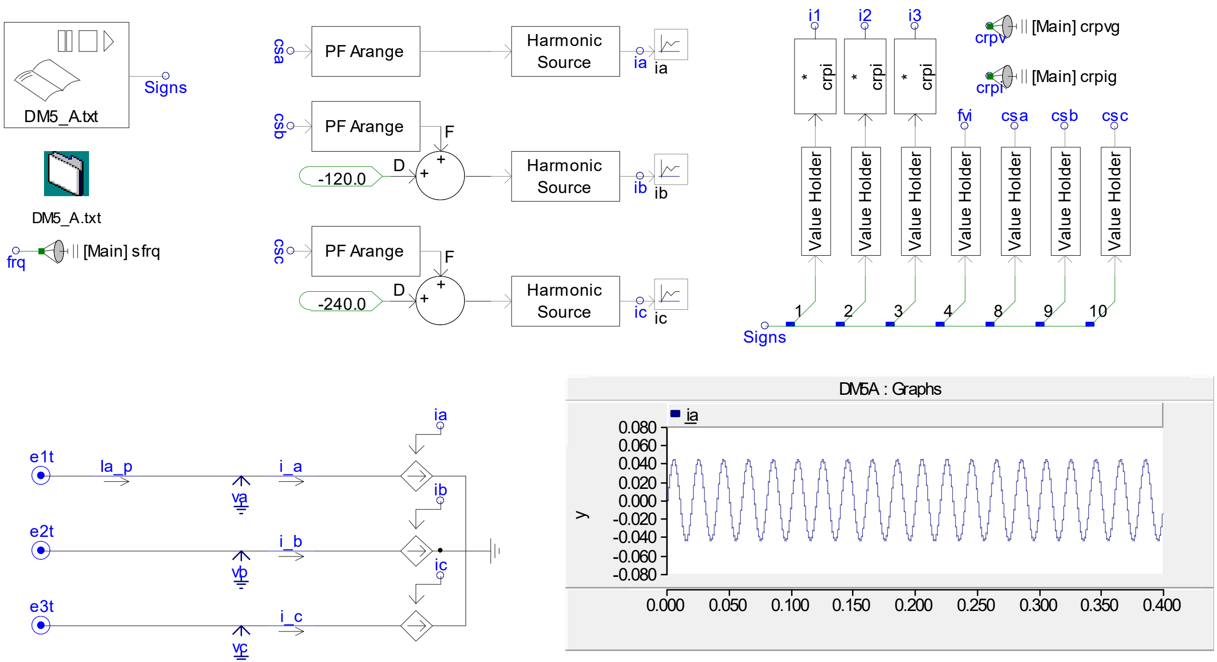

Figure 5. The load modelling of DM5 by using three-phase phase current values

6. DETAILS OF OIZ SIMULATION

OIZ's measurement data includes the hourly values of the system variables, and the three phase current / voltage, frequency and power factor values for each phase were taken from these data for the simulation. These values are examined by using the file reader modules mentioned in the previous section and given in Figure 6. The module given in Figure 6 (a) shows the path of the file containing the data to be read, and in (b) it helps us to examine the data by opening the file throughout the simulation.

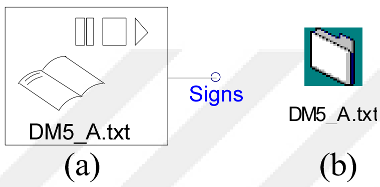

Figure 6. The file Reader (a) and file pointer (b) modules of PSCAD

The angle between current and voltage is required before creating the signals of the power system. This value is included in the measurement data as ‘csa’ and made it suitable for the simulation by using 'PF Arrange' module. In the simulation, the angle of this value is transferred to the 'Harmonic source' module in degree format with the module given in Figure 7.

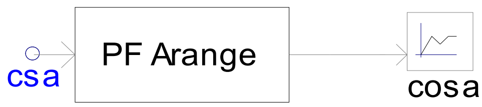

Figure 7. The power factor arranger and phase extracting in degree format

The power factor angle obtained for the three phases is used in the 'Harmonic Source' module given in Figure 8. The desired harmonic components can be added to the main harmonic and, then the harmonic signal is produced by using this module.

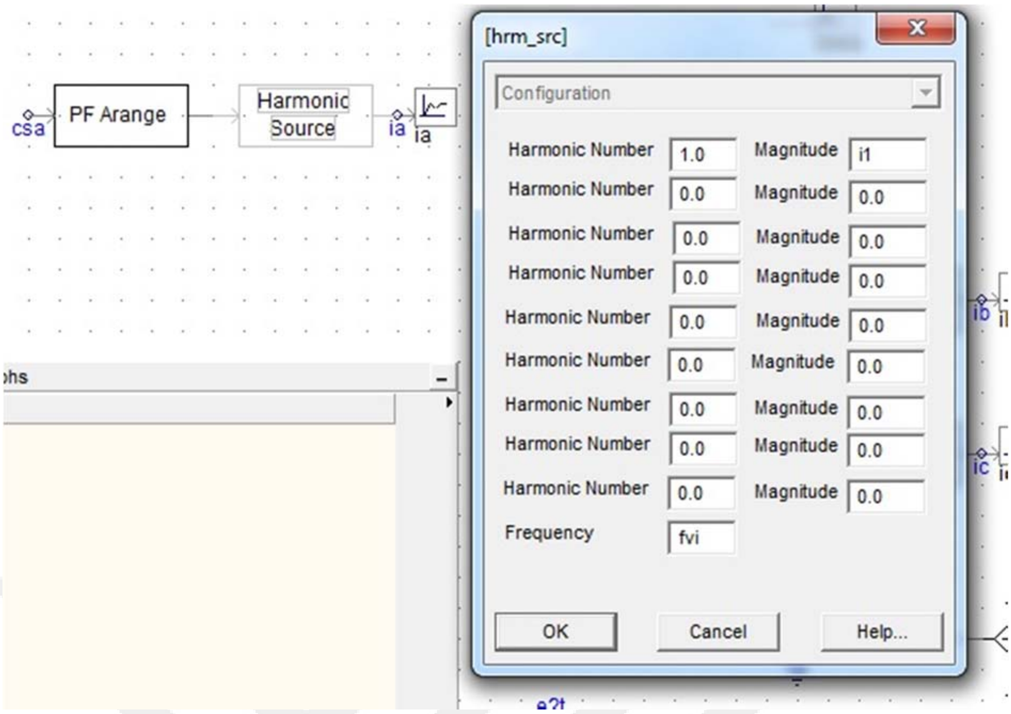

Figure 8. The harmonic signal generator and its data input interface

The measurement data for each subgroup consists of 8500 rows and 10 columns. Each row represents the one-hour in a one-year period. The 'Value Holder' module given in Figure 9 was developed in order to operate the simulation between the desired dates.

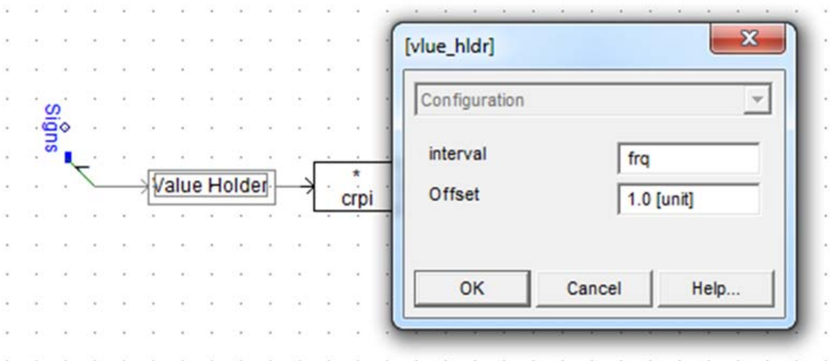

Figure 9. The value holder and skipping time

7. PROPOSED ACTIVE POWER FILTER

The information of the harmonic currents and associated harmonic powers must be taken from the utility system. The most important issues regarding the harmonic supply to the non-linear loads are severe overheating. The increased operating temperatures of the generators and transformers disrupt the insulation material of their windings, as well as the cooling systems and insulation materials of the electronic devices that are sensitive to this increasing temperature. If this heating were continued to the point at which the insulation fails, a flashover would occur. This would partially or permanently damage the device and result in loss of the generation or transmission that could cause blackouts. One solution of this problem is to install a harmonic filter for each nonlinear load connected to the power system. There are different types of harmonic filters including passive, active, and hybrid configurations. In the scope of the thesis, the passive and active filtering methods will be applied.

APFs are the indispensable for solving the power quality problems of the distribution networks such as compensation of the harmonic current and voltage and reactive power of the system. In other words, it increases the system reliability and supplies better power quality. Therefore, a new control algorithm for APF is proposed for OIZ and integrated to ADM1 given in Figure 10 [Ozenbaugh, (2001)].

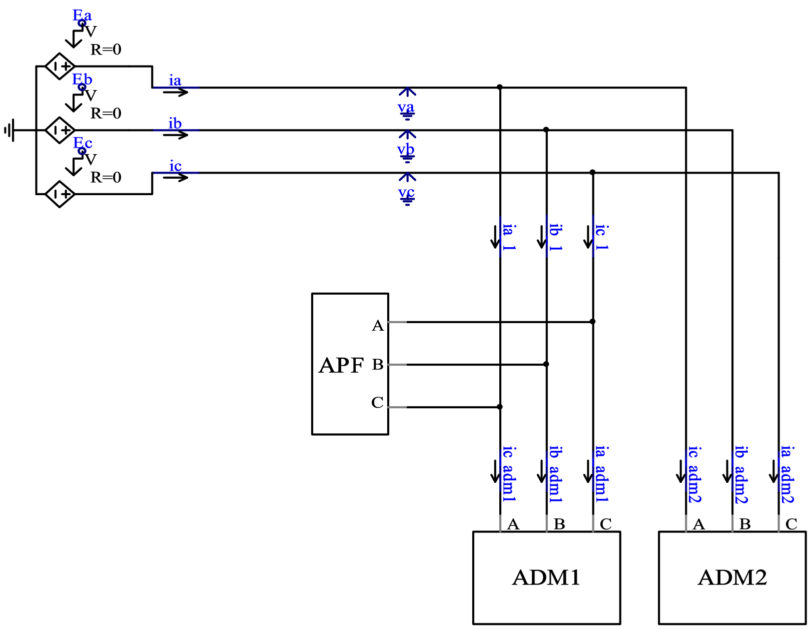

Figure 10. The integration of APF to ADM1

A new control algorithm is proposed for APF system within the scope of the thesis, and is given in Figure 11. The zero-transition point of phase-a current (ia_adm1) is determined by the ‘zero crossing’ module and the ‘enblea’ signal is obtained. The measurement values taken from the zero-crossing algorithm are transferred into an array. It generates a logic signal as ‘1’ if the values are greater than zero, and also ‘0’ if it is small. When the signal output is '1', it provides the starting time to produce a reference sine signal (ref_sina) having of unit magnitude.

The magnitude of reference signal (maga) is obtained by passing of ‘ref_sina’ signal through the ‘Averaging Filter’ and then integration of the output signal [Saribuut, (2016)]. The reference signal (ia_ref) is obtained by multiplying of 'maga' and 'ia_ref' signals. The total harmonic content (ia_err) is calculated by subtracting 'ia_ref' from 'ia_adm1'. Hence, ‘ia_err’ is injected into the power system by APF.

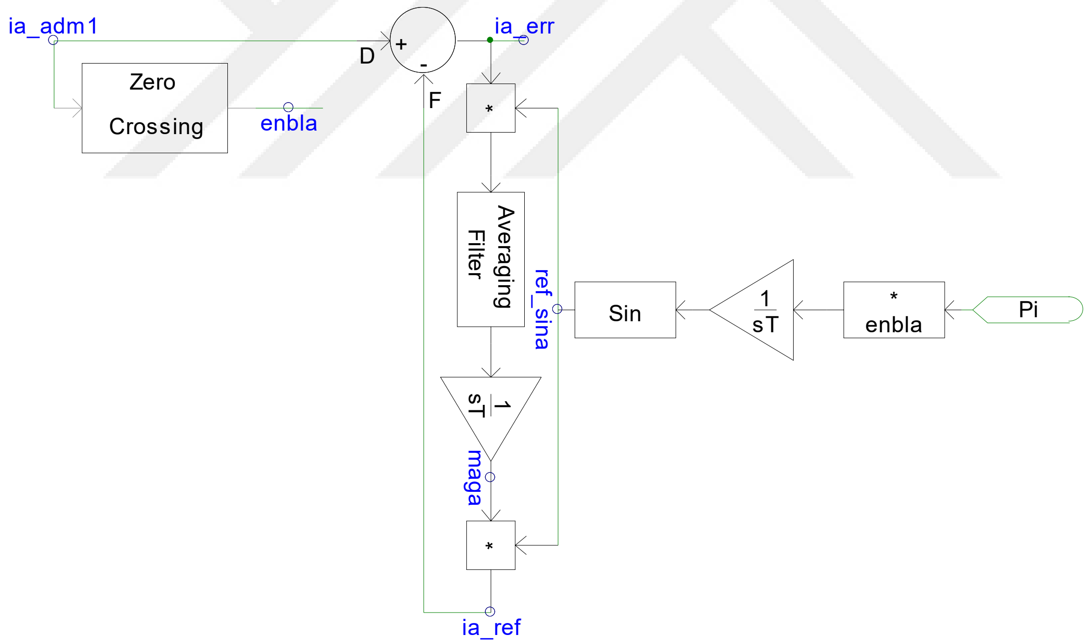

Figure 11. The control algorithm of proposed APF

8. CASE STUDIES

OIZ was modelled by using PSCAD (vrs.4.2.1) and ETAP (vrs.16.0) simulation programs in the case studies. The measurement data can be easily integrated to the PSCAD models. In addition, the modelling of devices with semiconductor technology can be easily done. For this reason, the detailed studies of the system's errors and their eliminations with active methods were carried out in the PSCAD. At the other case studies, the ETAP program was used, which provides the opportunity to perform the load and short-circuit analysis of the electrical system. In ETAP, ADM1 of the system was modelled and then PV system was added. In the case studies, the short circuit value of the bus bars, the effects of PV systems to the power quality of the bus bars and network (by adding current harmonics in real ratios) and the elimination of these effects by passive filters were examined.

Case Study 1: Verifying the Validation of Proposed System

In this case study, the simulation system was operated to show a 6480 hour time frame. Then, the current graphics of ADM1 taken from the simulation and real system are compared in Figure 12. In the comparison, the three points ((1), (2), and (3)) are circled to show the similarity between of them. (Note: The resolution of the real system is much lower than the simulation.)

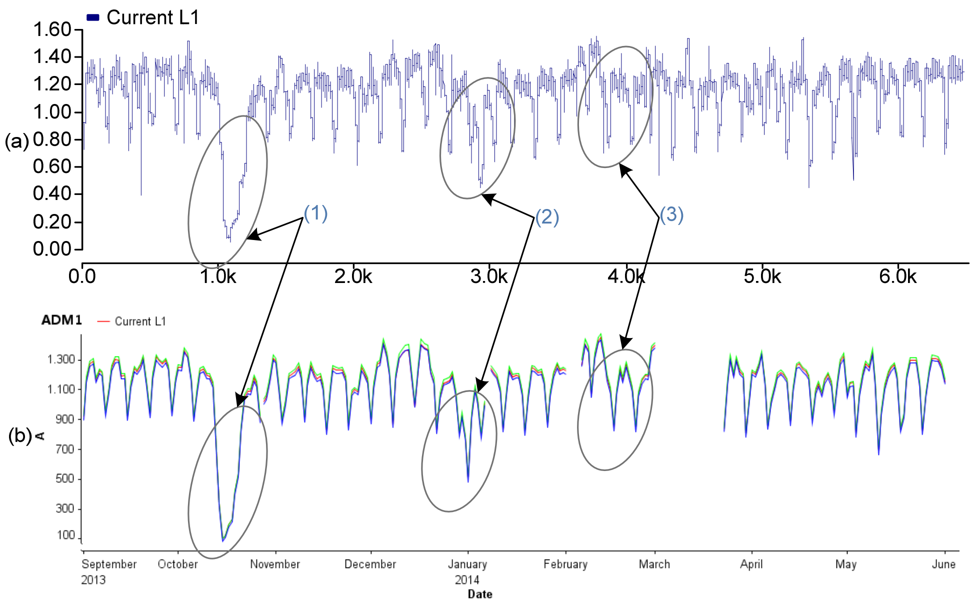

Figure 12. Simulation system (a) and real system (b) currents of ADM1

Case Study 2: Frequency Variations in OIZ

When the power quality data of the OIZ was examined, it was observed that the frequency of C feeder at DM5 (subgroup of ADM1) decreased to 32.1Hz on 19.09.2013 at 5:00am. The data at this date corresponds to 440th row of the voltage and current data blocks used in the simulation. In order to see this situation in PSCAD and to offer a solution, the resolution of simulation was decreased during the study. They are presented in Figure 13.

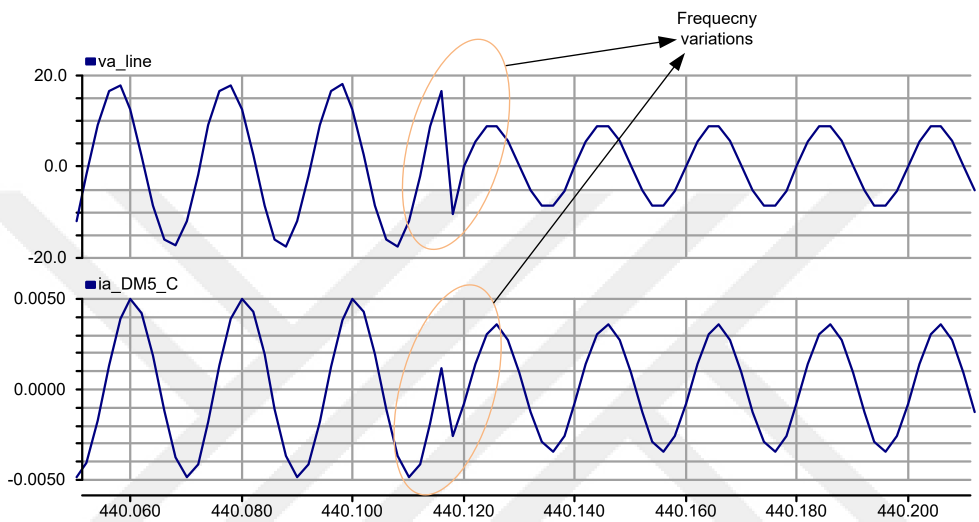

Figure 13. The voltage and current wave forms of ADM1/DM5/C

As can be seen, the line voltage (va_line) decreased due to the frequency drop. Also, a similar problem occurred on the feeder current (ia_DM5_C) of the system. The 440th row of data given in Table 3, it is seen that the frequency has decreased to 32.1 Hz and also the voltage and current values have decreased.

Table 3. C feeder data of DM5

ADM1/DM5/C-Cur.			Freq.	ADM1/DM5/C-Voltage			ADM1/DM5/C-PowFac.			Number
Ia	Ib	Ic		Va	Vb	Vc	Pfa	Pfb	Pfc	
7.51	7.28	7.27	50.00	17956.70	18052.60	18005.80	0.98	0.98	0.98	435
6.74	6.54	6.56	50.00	17869.30	17982.40	17930.40	0.98	0.98	0.98	436
8.56	8.32	8.35	50.00	17908.80	18017.90	17969.80	0.98	0.98	0.98	437
8.19	7.91	7.93	50.00	18050.60	18140.20	18093.60	0.98	0.98	0.98	438
8.42	8.19	8.25	50.00	18065.00	18155.70	18114.70	0.98	0.98	0.98	439
5.34	5.36	5.33	32.10	11616.30	11676.90	11641.60	0.64	0.63	0.63	440
2.65	2.70	2.65	22.50	8087.80	8137.20	8099.40	0.41	0.41	0.41	441
6.19	6.30	6.24	49.90	18034.80	18139.60	18073.30	0.98	0.97	0.97	442
5.22	5.33	5.28	49.90	17969.80	18073.80	18045.10	0.98	0.97	0.97	443
3.01	3.19	3.15	50.00	17974.70	18071.40	18045.40	0.97	0.96	0.96	444
7.20	7.32	7.30	50.00	18006.30	18098.60	18087.80	0.98	0.98	0.98	445

The problem given above started with the connection of a load having of large power to the circuit. It wanted to draw the proportional current from the network by demanding power that it needed. The network tried to balance this demanded power, but it could not compensate. According to the inverse ratio in the power equation, the voltage starts to decrease while the current increases. This situation is derived by mathematically in the following equations.

$$V(t) = V_m \,.Sin(\omega t) \tag{1}$$

where V(t) is the line voltage, Vm is the maximum value of V(*t*), *ω* is the angular velocity and *t* is the time (t = 0.005).

$$\omega t = \arcsin(\frac{V(t)}{V_m}) \tag{2}$$

$$2\pi f t = \arcsin(\frac{V(t)}{V_m}) \tag{3}$$

where f is the frequency of the line voltage.

$$f = \frac{1}{2\pi t} \,.\arcsin(\frac{V(t)}{V_m}) \tag{4}$$

Considering (4) as a time-dependent function, *t* and V(*t*) can be accepted as independent variables. However, since V(*t*) will be the constant value at the fault time, the independent variable will be '*t*'. In this case, '*f*' is not constant and will vary for each '*t*'. For this reason, (4) must be re-evaluated independently from '*t*'. Therefore, it will be accepted as 1 at the assumptions. Then, (4) can be expressed in the following.

$$f = 0.159.\arcsin(\frac{V(t)}{V_m}) \tag{5}$$

where 0.159 is a constant and comes from $\frac{1}{2\pi t}$.

$\frac{V(t)}{V_m}$ of (5) is a proportional expression. Its value will vary between 0 and 1. Similarly, the arcsin function will vary from 0 to 90 degrees with proportion to this value. This reveals a direct proportion between the frequency and V(*t*). The relation of frequencies in the rows 440 and 441 with the voltage values can be easily figured out.

For example, the 'Va' ratio between the rows 440 and 439 (11616.3 / 18065) is 0.643. If this value is multiplied with main frequency (50 * 0.643), 32.15Hz is obtained. This value is similar to the frequency of row 440.

As another example, the 'Va' ratio between the rows 441 and 439 (8087.6 / 18065) is 0.447. If this value is multiplied with main frequency (50 * 0. 447), 22.35Hz is obtained. This value is similar to the frequency of row 441.

As you can see, the frequency drop is directly proportional to the voltage drop. This causes the decreasing of the harmonic values, deteriorating of the network balance and stability, causing the larger problems and even partial or complete collapse of the network (blackout).

Case Study 3: Blackout of 31 March 2015 in Turkey

Electric energy has a feature that must be produced when needed and consumed when it is produced. This situation requires the production, transmission and distribution activities to be carried out in a central planning manner and simultaneously. The network is in a fragile structure with the infrastructure problems and others. If the problems encountered in the network cannot be canalized efficiently, it results with the network collapses completely. Large-scale blackouts experienced in history are listed in Table 4.

Table 4. Large-scale blackouts in history

Country/Region	Date	Blackout Reason / Type
France	1987	Voltage Sag
America / Canada	1989	Geomagnetic Storm
America	1996	Swing
Netherlands	1999	Voltage Sag
France	1999	Extreme weather conditions
Italy	2003	Frequency Shift
Sweden / Denmark	2003	Breakdown
Germany	2004	Voltage Sag
Europe	2006	Frequency Shift
America (Arizona, Southern California and Western California Peninsula (MEX))	2011	Breakdown
Turkey	2015	Frequency Shift
Netherlands	2015	Breakdown
Austria	2016	Extreme weather conditions

Turkey provides 19.8% of the electric energy from the water power. In addition, there is an approximately 8-9GW installed capacity of hydraulic potential at the Central and Eastern Black Sea Regions. Turkey experienced the similar case given above in the March 31, 2015 and its entire electricity grid collapsed (in other words blackout). This crisis could not be managed efficiently due to the poor analysis of the power system. As a result, there was a loss of about $1.5 billion. To concretize this loss, it corresponds to 1000 units of 1MW solar power plant (1GW).

The highest consumption in the distribution lines (peak) occurs in the summer period and the lowest consumption occurs in the spring period. The maintenance and repair works in transmission lines must be done before the peak period. Therefore, maintenance is planned and performed during the low load period. The occurrence of NB coincided with this period and the all of system collapsed in 11 seconds. Before the analysing of this event, some considerations that were needed to know are presented in the below.

There are eleven important TLs (higher than 265km long) used for supplying the electricity service from the eastern to western of Turkey. In addition, the serial capacitor (SC) banks (16 units) used to compensate the voltage drops were taken out of service. Hence, the electricity service provided by the main transmission corridor from the East to West parts of Turkey weakened due to these reasons.

The hydroelectric power plants located at the west region of Turkey's are the higher number and the more power than the east region. Due to the spring rains, the floods occurred at the dams located in Eastern Black Sea, South and Eastern Anatolia. In order to prevent these overflows, the dam and river hydroelectric power plants served at full load. Hydroelectric power plants located at the west were taken in off-line from operation since the energy demand was met from the east. Due to the disabling of four TLs, 400kV lines that provide the power flow from the east to west were overloaded.

The Northwest Çankırı TL (Osmanca-Kurşunlu) has a 206km length and ACSR conductor type having of 3-bundles was used throughout the entire line. According to the datasheet of the conductor, it has the ability to withstand up to 400kV/2350A values. At the incident day, the Çankırı TL was disabled at 09:36:09.418 and the tripping values of the breaker were recorded as 393kV/1820A at the incident time [ENTSOE, (2015)].

ACSR type conductor can be operated in emergency operation with the large overloads, at least until 20 to 30 minutes until it reaches the limit temperature. This feature provides competent staff on duty with the time required to overload, reconstruct or drop some loads.

According to ENTSO-E report, when the frequency of electricity network reaches 48.4Hz, it is required that 35.5% part of the current load should be released. During NB, 35.5% load of the electricity network corresponded to 4.8GW. However, the load shedding-rate could not be reached to the required percentage during the imbalance and the tripping events occurred at the system. The main reasons for not reaching this level are given in the following.

- The relays used at the system could not perform the fast electromechanical opening/closing manoeuvres and the new ones made in accordance with current technology were needed to replace with them.
- The stability of several power plants was broken due to the lower amount of load-shedding than the required. During temporary frequency distortion, many large thermoelectric power plants were out of service at frequencies above 47.5Hz.

- During NB, the frequency-decreasing occurred while increasing of the load, and also the frequency-increasing occurred while decreasing of the load. In this situation, many other power plants left the system and switched to the island mode.

Hence, Turkey power grid had lost its synchronization with ENTSO-E system, and then Turkey - Bulgaria and Turkey - Greece interconnections was lost after a second. The frequency-shifting had started at about 09:36:10 and the electricity-lost at the system occurred at 09:36:21. NB took place in about 11 seconds. Figure 14 (taken from the report published by ENTSO-E) shows the start of the frequency-shifting and NB (dropping of the frequency to lower than 47.5Hz) [ENTSOE, (2015)].

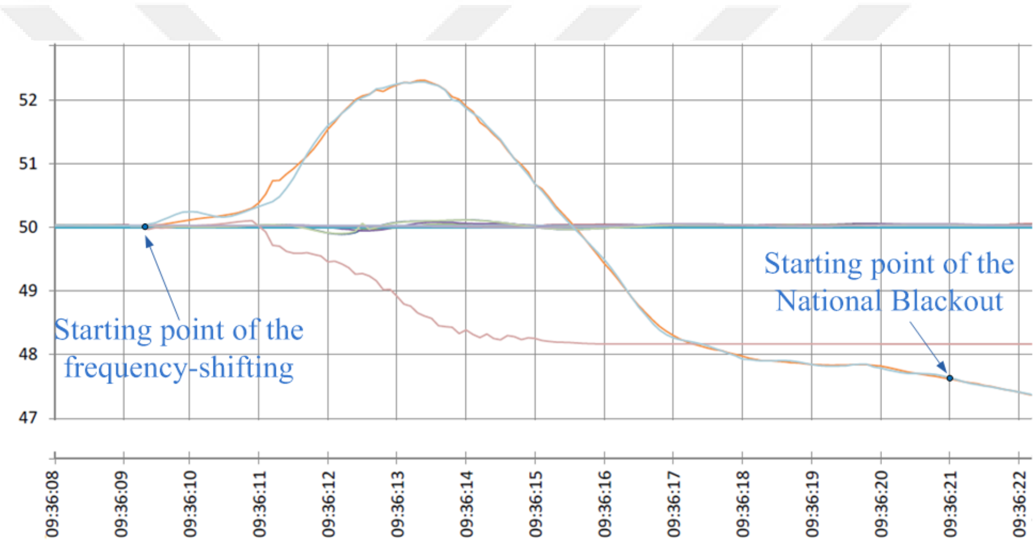

Figure 14. Frequency variations of the national electrical network before NB

The above-mentioned issues had led to the power outages in Turkey on March 31 in 2015, and caused to the material and moral damages that are difficult to compensate. If this situation had been foreseen before, it could be compensated by the recommendations given in the below.

<u>**Solution 1:**</u> The all power plants should not be disabled very fast during the frequency shifting and comply with the obligations specified in the Electricity Network Regulation given in Table 5. According to this regulation, they should remain at the system for 10 minutes at 47.5Hz. However, any power plant did not obey this rule on 31 March. If attention was paid to this issue, the electricity service would not be interrupted.

Table 5. The power plant connection requirements for the Turkish power system

Frequency Range	Minimum Time
51.5Hz ≤ f ≤ 52.5	10 Minute
50.5Hz ≤ f < 51.5	1 Hour
49.0Hz ≤ f < 50.5	Permanent
48.5Hz ≤ f < 49.0	1 Hour
48.0Hz ≤ f < 48.5	20 Minute
47.5Hz ≤ f < 48.0	10 Minute

Solution 2: It shows that if SCs were active, the Kayabaşı-Kurşunlu and Kurşunlu-Osmanca Tls current would be approximately 1570A. This value indicates that SCs would not exceed rated currents and all 400kV Tls currents would remain below thermal limits. Thus, it is concluded that there would be no power cut between Kurşunlu and Osmanca. This issue can be seen in detail in Figure 15 [ENTSOE, (2015)].

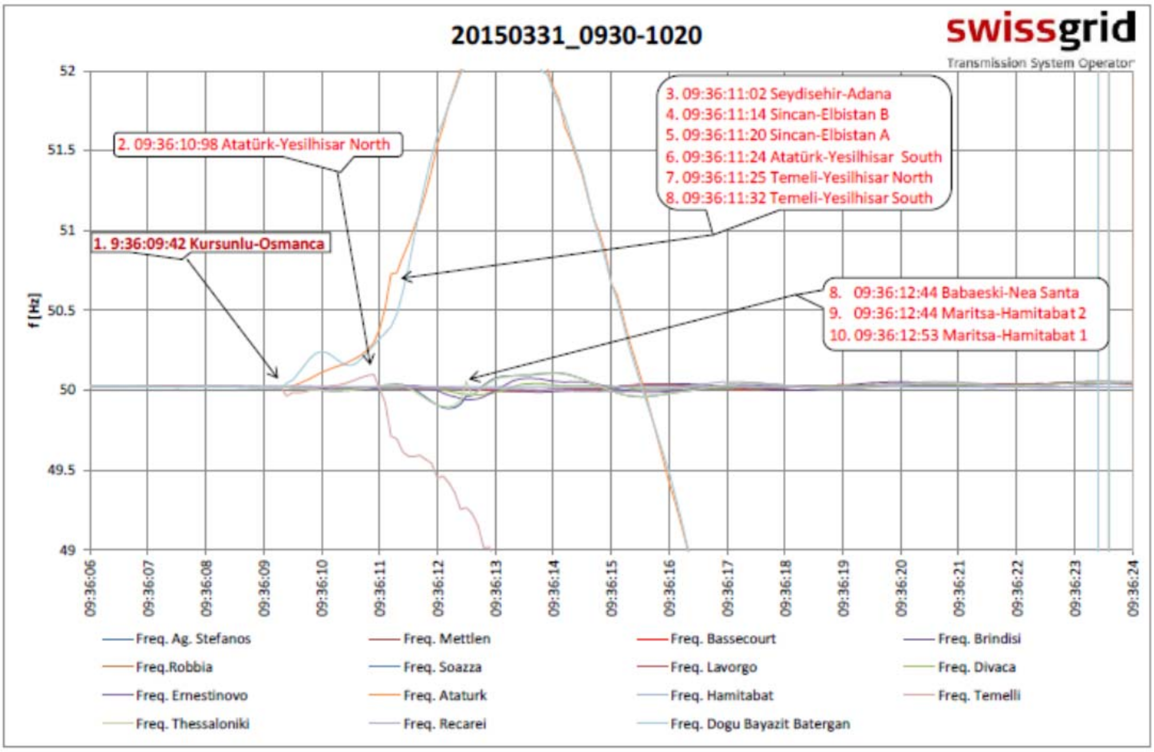

Figure 15. Frequency variations of the national electrical network before the NB

Solution 3: Relays that are responsible for opening and closing the system should be monitored with the smart systems, intervened remotely when necessary and show how long it takes to reach the limit temperature in case of the overload. Thus, early opening will be prevented.

Solution 4: The frequency drop in the electricity network for any reason decreases the turbine speed of the gas power plants. The power obtained from the power plants decreases in direct proportion with the decrease in speed. The necessary precautions should be taken to prevent the turbine speed falling down from the linear characteristic given in Figure 16.

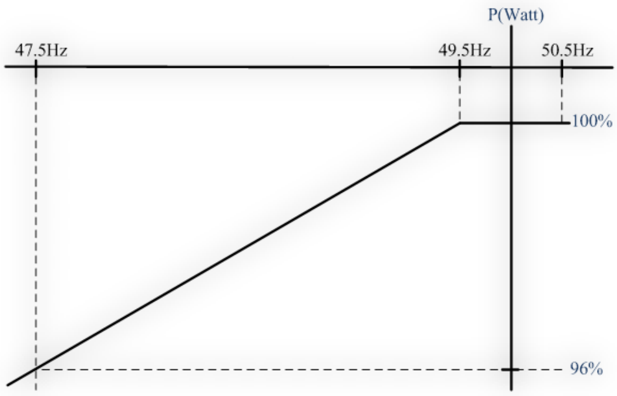

Figure 16. Active power derivation of gas turbines to the frequency range

After NB, many manoeuvres had been made to stabilize the power system. First attempt was done at 12:00 and 20% of the system was recovered. Later, 50% of the system at 14:30, 80% of the system at 16:12, 95% of the system at 18:31 and 100% of the system at 18:35:50 were recovered respectively. During the commissioning of the system, the status of the frequency changes that occur during the commissioning of the power plants can be easily seen in Figure 17 [ENTSOE, (2015)].

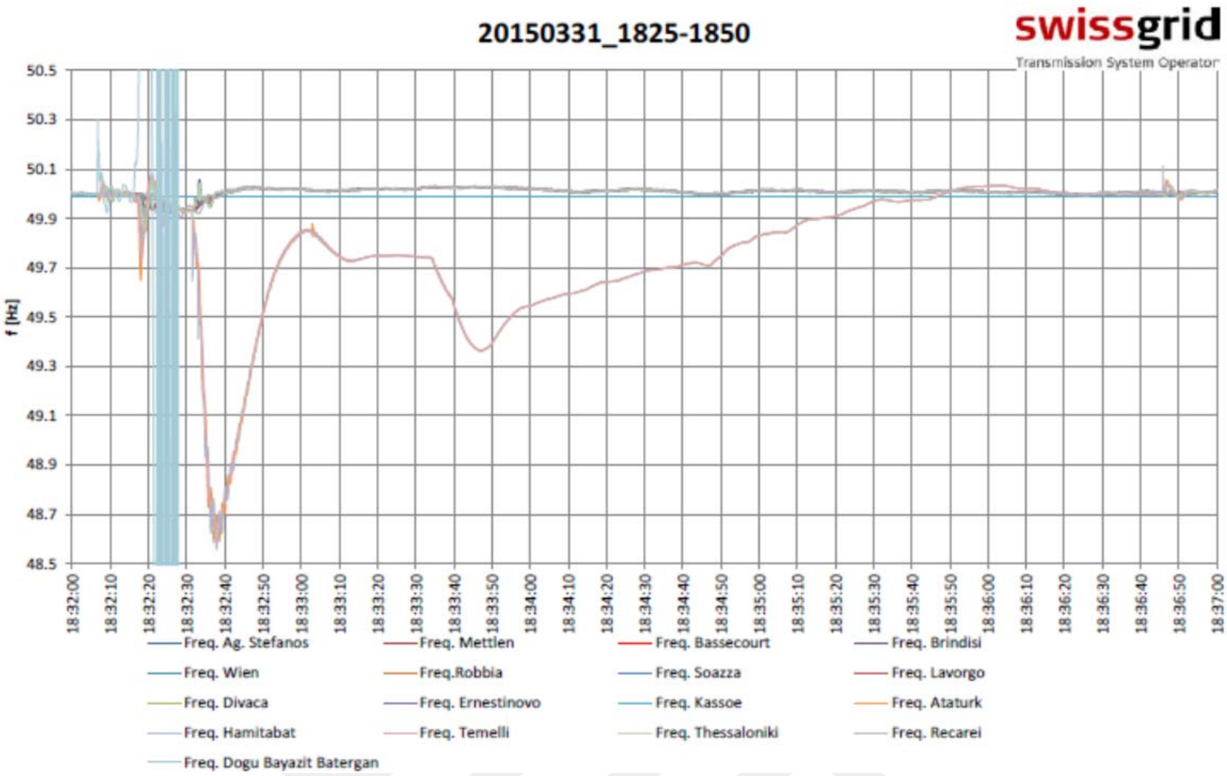

Figure 17. Duration of the start-up electricity service after the Blackout

Case Study 4: Harmonic Compensation of ADM1 by Using APF

When the event records of the power analyser connected to ADM1 were examined, it was determined that THD of the current increased on the date of 23.08.2014 at 04:28:53. Then, the data of this event was transferred to the PSCAD program and simulated. The effects of harmonics on the system current have been reduced by using the proposed APF and the case study result is presented in Figure 18.

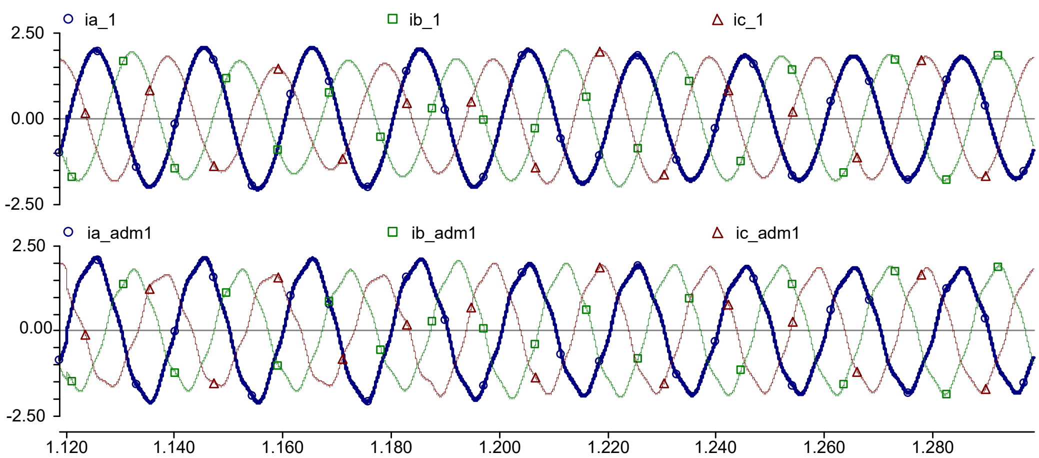

Figure 18. Simulation result of Case Study 2

THD of ADM1 current (ia_adm1) was measured as 7.76%. When APF connected to the system was activated, this harmonic distortion was reduced to 0.829%. Considering the current waveform, it has been seen that the system has an unbalanced load in phase-A. After 1.20s, the balanced current was drawn. The proposed APF kept THD value of the current under 1% during the whole case duration.

Case Study 5: Short-Circuit Analysis of Buses without PV

The lumped load network structure of ADM1 was modelled by using ETAP and given in Figure 19. It was made by considering the industry load distribution (80% motor and 20% static) and the average values of system dynamics. Then, the three-phase-to-ground short-circuit was applied to Bus3 of the distribution centre by considering IEC60909 standards. The cable properties used in ADM1 distribution line and their lengths were added to the system model. They are also given in Table 6

Table 6. Type and length of cables used in the distribution line

Location	Type	Description	Lenght	Unit
Bus1-Bus2	Cu	4(3(1x240mm2/16) 36kV XLPE	1900	m.
Bus2-Bus3	Cu	3(1x240mm2/16) 36kV XLPE	625	m.
Bus3-Bus5	Cu	3(1x240mm2/16) 36kV XLPE	880	m.
Bus5-Bus6	Cu	3(1x240mm2/16) 36kV XLPE	1300	m.
Bus6-Bus2	Cu	3(1x240mm2/16) 36kV XLPE	800	m.

Note: R:0.098Ω/km. - L:0.397mH/km. - X:0.125μF/km.

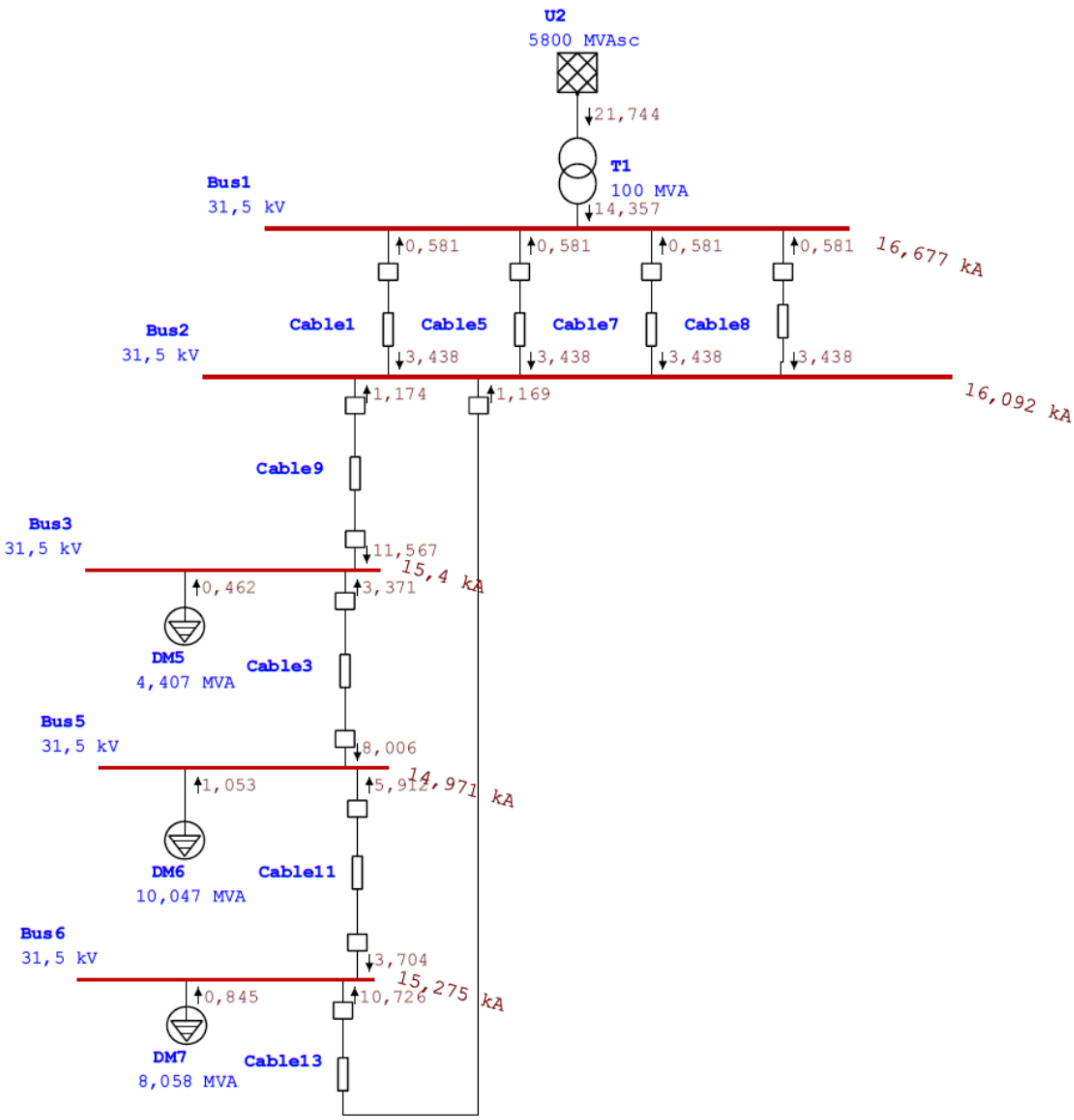

Figure 19. Simulation results of Case Study 5

The system dynamics of bus bars during the fault are presented in Table 7. The power circuit and short-circuit current values are given in Figure 19.

Table 7. Power ratings of busses during the short-circuit

Bus Des.	Current (A)	Voltage (V)	Power (MVA)	Frequency (Hz)	Power Factor (PF)
DM5	81.6	31213	4.407	49.98	0.941
DM6	192	31313	10.407	49.94	0.954
DM7	148.8	31284	8.058	49.97	0.903

Case Study 6: Connection of Real PV System to ADM1

1MW PV system (PWA2) was added to Bus3 of the system with a transformer (T2 - 1.25MVA, 0.4/31.5kV) and given in Figure 20. Then, the three phase to ground short-circuit was applied to Bus3 of distribution centre. The panel and inverter features of PV plant used in the system are given in Table 8.

Table 8. Power ratings of panels and invertors of PVs

	Unit Power (W)	Vmp-Voc (V)	Imp-Isc (A)	Irrad (m2/W)	Pieces	Total Power (kW.dc)
PV Panel	320	37.7-46.8	8.49-9.34	1500	7334	2347.4

		Power	Voltage (V)	FLA	%
PV Inverter	DC	2400kW	1000	2400	90(EFF)
	AC	2160kVA	400	3118	100(PF)

The short-circuit values of this case were compared with the previous case results and their changes were examined. It was observed that the short-circuit currents of all buses were increased. However, the amount of increasing was very small when they were compared to the short-circuit current. It is concluded that the effect of PV system on short-circuit currents can be neglected. The power circuit and short-circuit current values are given in Figure 20.

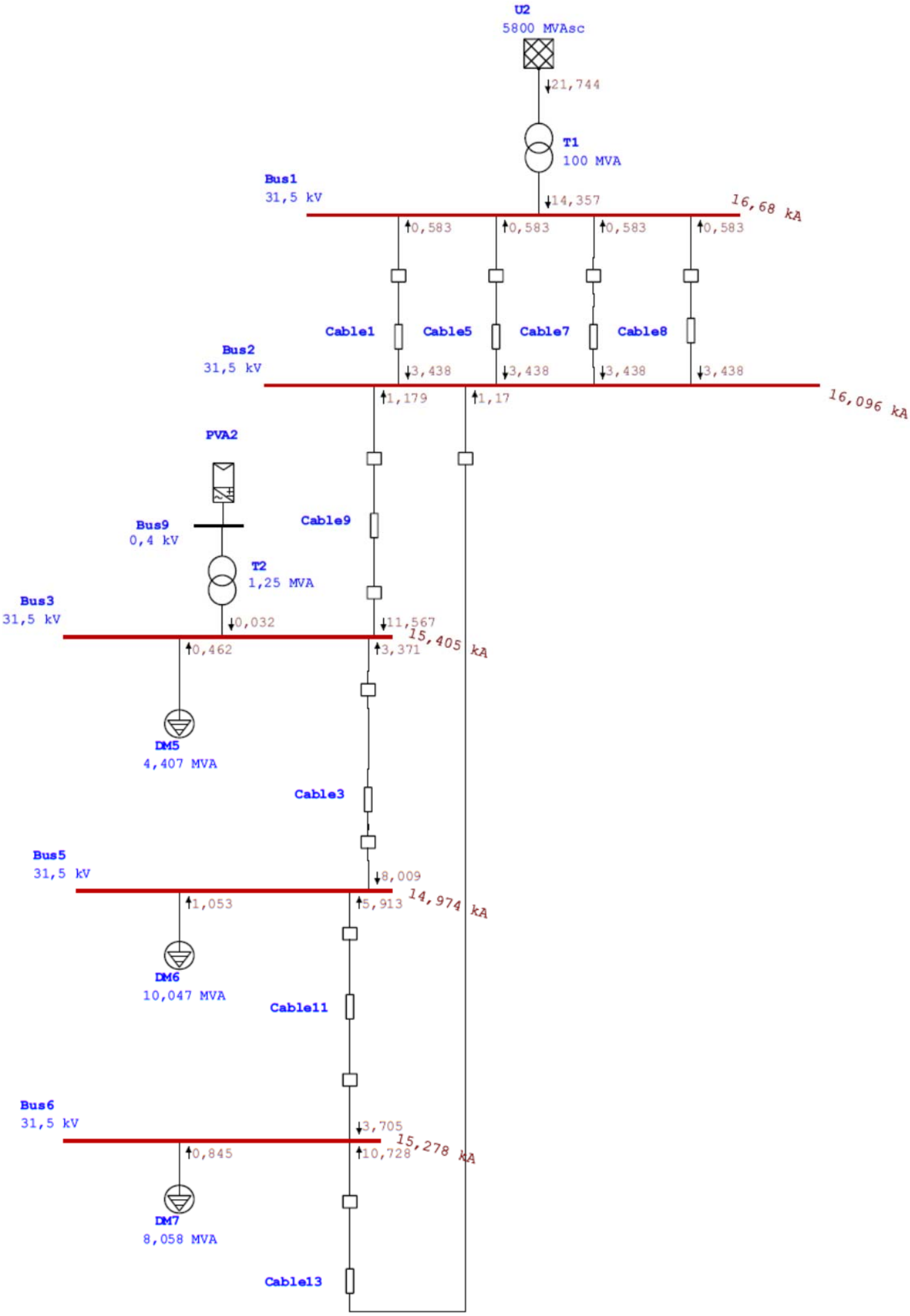

Figure 20. Simulation results of Case Study 6

Case Study 7: Connection of Two Real PV System to ADM1

Recently, the increasing of PV number has revealed the necessity to examine its effects on electricity distribution systems. For this reason, the two 1MW PVs (PVA2 and PVA4) were connected to Bus3 (DM5) and Bus6 (DM7) with the transformers (2.5MVA - 0.4/31.5kV) to the power system of Case Study 5. According to the simulation results, it was observed that the short-circuit currents of Bus3, Bus6 and other buses were increased. It was concluded that the amount of increasing at the short-circuit currents are proportion with the power of PV system when compared with the results of previous example. The increasing amounts ratio of short-circuit currents is less than 1% of their nominal values. The power circuit and short-circuit current values are given in Figure 21.

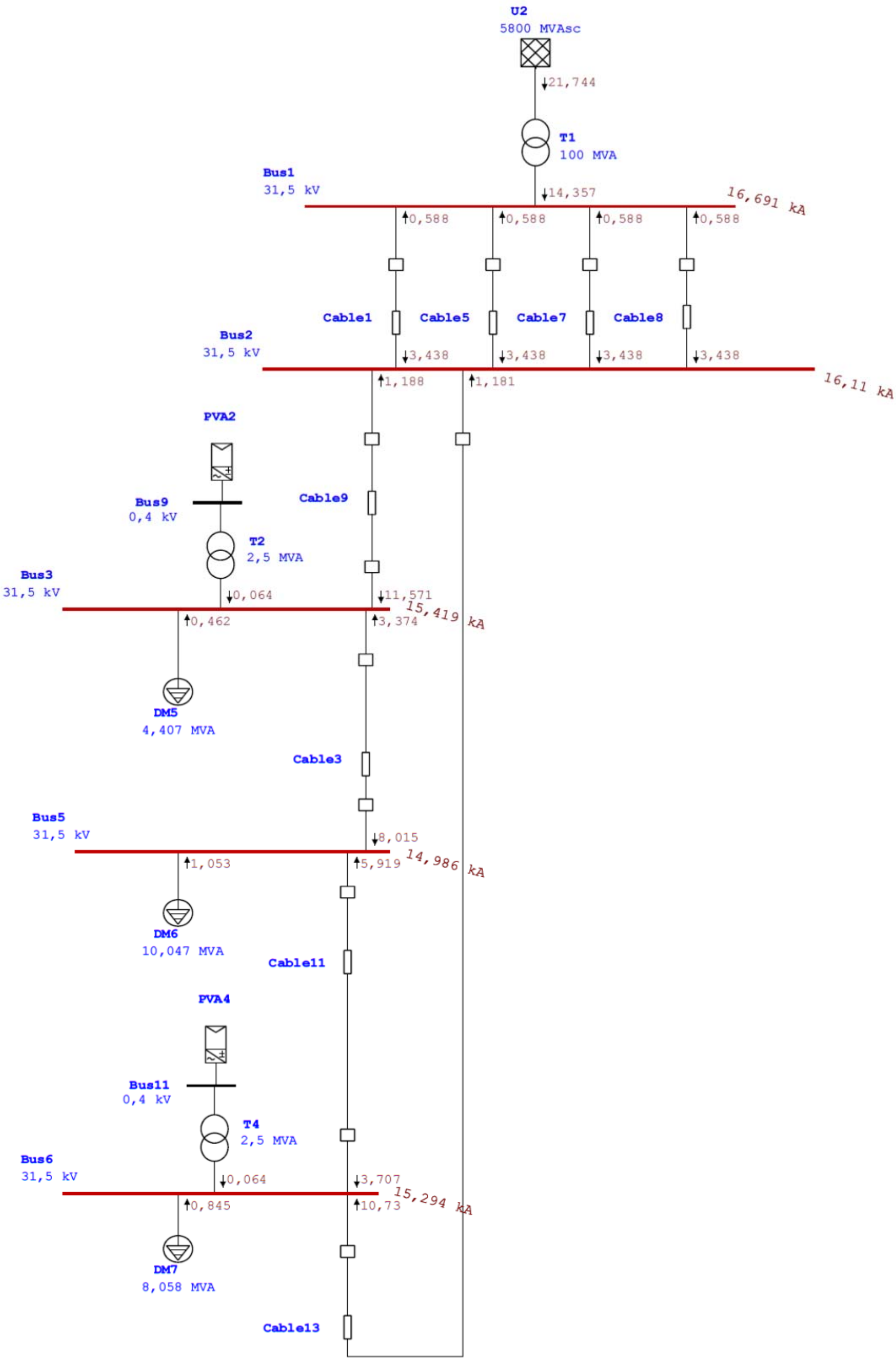

Figure 21. Simulation results of Case Study 7

Case Study 8: a) Harmonic Analysis of PV System

In order to examine the negative effects of the simulated PV system to the grid, the harmonic models of commercial inverters used at the library of the ETAP were added. Then, the simulation case was examined. According to the results, the harmonics exceed the critical values are given in Table 9.

Table 9. The harmonics exceed their critical values

Critical						
Device ID	**Type**	**Condition**	**Rating/Limit**	**Operating**	**%Operating**	**Harmonic**
Bus11	BusIHD	Exceeds Limit	1.5	2.78	185.02	11.00
Bus11	BusIHD	Exceeds Limit	1.5	2.24	149.34	13.00
Bus11	BusTHD	Exceeds Limit	2.5	4.34	173.41	Total
Bus9	BusIHD	Exceeds Limit	1.5	2.77	184.89	11.00
Bus9	BusIHD	Exceeds Limit	1.5	2.24	149.24	13.00
Bus9	BusTHD	Exceeds Limit	2.5	4.33	173.3	Total

The values given in Table 9 are prepared by considering the limits of IEEE519 standards.

Case Study 8: b) Integration of Harmonic Modelling to OIZ System

The results given in Table 10 were obtained by averaging the harmonic values of OIZ between dates of 09.2013 and 09.2014.

Table 10. Average current THDs of OIZ

		Current Harmonic		Voltage Harmonic	
Order	Hz	Mag(%)	Mag(A)	Mag(%)	Mag(V)
1	50	100	1126	100	31500
3	150	4.4	49.5	0.5	157.5
5	250	25.2	283.8	4.8	1512
7	350	21.9	246.6	1.7	535.5
9	450	1.9	21.4	0.1	31.5
11	550	8	90.1	0.9	283.5
13	650	4.2	47.3	0.6	189
15	750	0.1	1.1	0.1	31.5
17	850	0	0	0	0
21	1050	0	0	0	0

In this case, the static load (load2) was modelled with these harmonic values. Hence, the harmonic population of both OIZ and PV system was provided. The simulated power system is given in Figure 22.

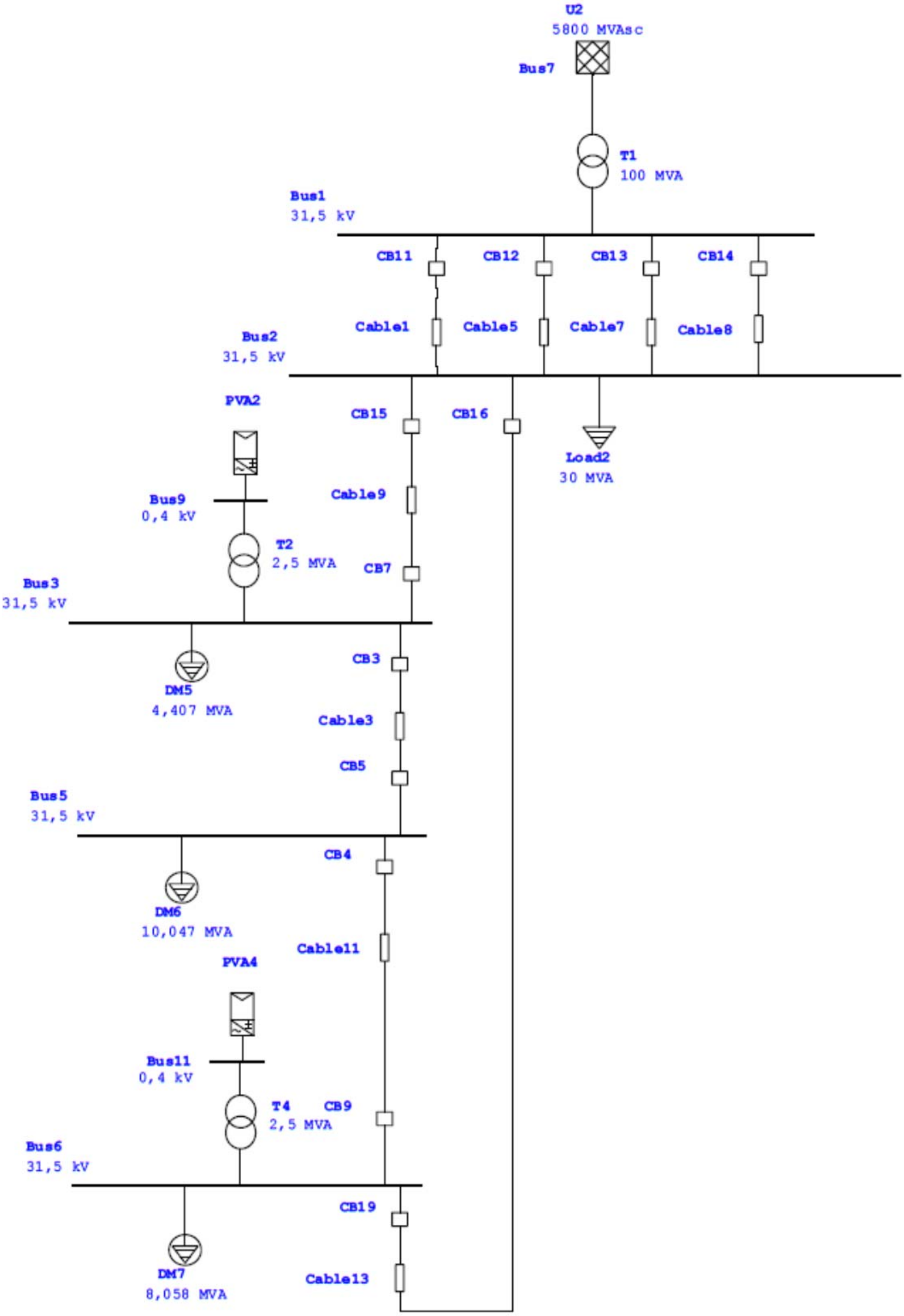

Figure 22. Harmonic modelling of OIZ with PV system

The simulation results of the system given in Figure 22 are presented in Table 11. When the values of Table 9 and Table 11 are compared, it was observed that there is an increase at the harmonic values. Especially, 5th and 7th harmonics have the higher increasing among of others. According to the results, it is concluded that PVs have negative effects on the network harmonics and also it may be possible to happen the losses and faults caused by harmonics in the electricity network.

Table 11. The higher current THDs of OIZ with PVs

Critical						
Device ID	**Type**	**Condition**	**Rating/Limit**	**Operating**	**%Operating**	**Harmonic**
Bus11	BusIHD	Exceeds Limit	1.5	5.32	354.64	5.00
Bus11	BusIHD	Exceeds Limit	1.5	5.95	396.96	7.00
Bus11	BusIHD	Exceeds Limit	1.5	2.49	166.08	11.00
Bus11	BusIHD	Exceeds Limit	1.5	2.01	134.3	13.00
Bus11	BusTHD	Exceeds Limit	2.5	8.92	356.64	Total
Bus9	BusIHD	Exceeds Limit	1.5	5.32	354.62	5.00
Bus9	BusIHD	Exceeds Limit	1.5	5.95	396.94	7.00
Bus9	BusIHD	Exceeds Limit	1.5	2.49	165.96	11.00
Bus9	BusIHD	Exceeds Limit	1.5	2.01	134.18	13.00
Bus9	BusTHD	Exceeds Limit	2.5	8.91	356.58	Total

Case Study 8: c) Harmonic Compensation of OIZ with Passive Filter

There are two types of methods to reduce the negative effects of harmonics at the industrial applications. The active is the one of these methods and also presented in Case Study 4. Another is the passive method and the passive filters are used to eliminate the system harmonics [Husnayain F., Purnomo, N. D., Anwar, R., Garniwa I., (2014)]. As can be seen in Table 11, the highest harmonic distortion was measured at 5th harmonic. For this reason, a passive filter that will both reduce this harmonic and compensate will be added to the system. In this case study, load2 connected to Bus2 has 30MVA and 0.9 power factor (cosφ). The power factor must be increased to 0.99.

Firstly, the active power is found by using (6).

$$P = S.cos\varphi \tag{6}$$

where 'S' is the apparent power in MVA.

$$P = 30.(0.9) = 27\text{MW}$$

The reactive power required for the compensation is then calculated by using (7).

$$Q_c = P.(tan\varphi 1 - \ tan\varphi 2) \tag{7}$$

where 'φ1' is the power factor, φ2 is the desired power factor.

$$Q_c = 27.(0.3410) = 9.229 \text{ MVAr}$$

By calculating Qc, the required capacitance value at base frequency is obtained by using (8).

$$C = \frac{Q_c}{2\pi f V^2} \tag{8}$$

where f is the system frequency, V is the line-line system voltage.

$$C = \frac{9.229.(1000)^2}{2.(3.14).50.(31.5.)^2(1000)^2} = 29.61\mu F$$

After determining the capacitance of filter, the inductance value is found by using (9) according to the harmonic degree.

$$L = \frac{1}{(2\pi f h)^2 C} \tag{9}$$

where h is the harmonic degree.

$$L = \frac{1}{(2.(3.14).(50).5)^2.(0.00002961)} = 13.7mH$$

Due to the nature of the inductance, it has an internal resistance. It is calculated by using (10).

$$X_L = (2\pi f h L)/Q \tag{10}$$

where Q is the quality factor.

$$X_L = 2.(3.14).(50).5.(0.137).(\frac{1}{30}) = 4.3004\Omega$$

The values of filter components were added to the harmonic filter module in ETAP program given in Figure 23.

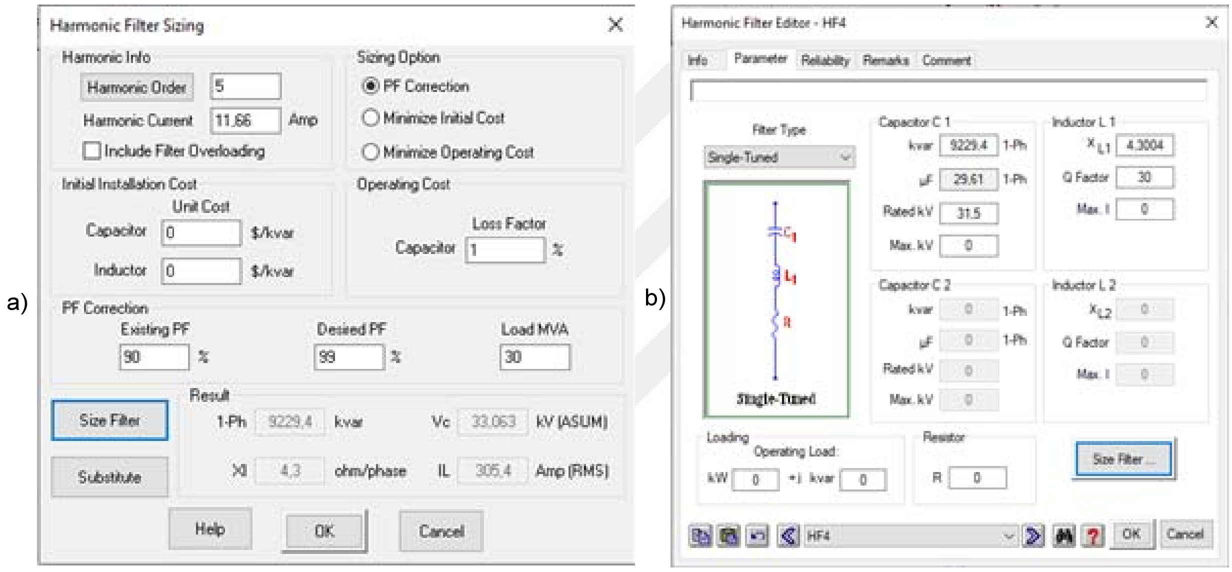

Figure 23. Harmonic filter module of ETAP

a) Harmonic filter sizing b) Harmonic filter editor

The case results are presented in Table 12. According to these results, THD of the system current is decreased from 8.92% to 4.78%. Especially, the better result is obtained at 5th harmonic. Its THD is decreased to 0.48% when compared to its previous value.

Table 12. Current harmonic THDs of OIZ after filtering

Critical						
Device ID	**Type**	**Condition**	**Rating/Limit**	**Operating**	**%Operating**	**Harmonic**
Bus11	BusIHD	Exceeds Limit	0.1	0.48	483.41	5.00
Bus11	BusIHD	Exceeds Limit	0.1	3.92	3915.56	7.00
Bus11	BusIHD	Exceeds Limit	0.1	1.76	1762.44	11.00
Bus11	BusIHD	Exceeds Limit	0.1	1.61	1610.64	13.00
Bus11	BusIHD	Exceeds Limit	0.1	0.13	133.80	17.00
Bus11	BusIHD	Exceeds Limit	0.1	0.11	114.91	19.00
Bus11	BusIHD	Exceeds Limit	0.1	1.14	1136.14	23.00
Bus11	BusIHD	Exceeds Limit	0.1	1.16	1160.57	25.00
Bus11	BusIHD	Exceeds Limit	0.1	0.1	100.69	29.00
Bus11	BusIHD	Exceeds Limit	0.1	0.82	819.65	35.00
Bus11	BusIHD	Exceeds Limit	0.1	0.82	820.51	37.00
Bus11	BusIHD	Exceeds Limit	0.1	0.78	781.17	47.00
Bus11	BusIHD	Exceeds Limit	0.1	0.76	761.65	49.00
Bus11	BusTHD	Exceeds Limit	2.5	5.15	205.63	Total
Bus9	BusIHD	Exceeds Limit	0.1	0.48	483.06	5.00
Bus9	BusIHD	Exceeds Limit	0.1	3.92	3915.34	7.00
Bus9	BusIHD	Exceeds Limit	0.1	1.76	1760.6	11.00
Bus9	BusIHD	Exceeds Limit	0.1	1.61	1608.94	13.00
Bus9	BusIHD	Exceeds Limit	0.1	0.13	133.72	17.00
Bus9	BusIHD	Exceeds Limit	0.1	0.11	114.84	19.00
Bus9	BusIHD	Exceeds Limit	0.1	1.14	1135.44	23.00
Bus9	BusIHD	Exceeds Limit	0.1	1.16	1159.87	25.00
Bus9	BusIHD	Exceeds Limit	0.1	0.1	100.63	29.00

9. ADVICES AND CONCLUSIONS

Advices

- The new generation inverters used in the solar power plants have passive filter equipment to reduce the harmonics caused by the power electronics. Harmonics that may occur from these equipment will adversely affect the electricity quality. In order to reduce this possibility, the power plant outputs must be constantly monitored with the power analysers and intervened when necessary.

- Harmonic components consume the reactive power such as motors or uninterruptible power supplies. High harmonic distortion will increase the reactive power consumption of the system and the consumers will be penalized or cause high costs. It is possible to reduce the total harmonic distortion with both cheap and passive equipment. One of them is the "phase shifting" method by utilizing the transformers. The phase shifting method is realized by using the windings with different inductive values at the low voltage side of the three-phase transformer and utilizing star-delta conversion. Thus, a suitable angle is obtained to eliminate harmonics and the phase of the transformer outputs is shifted.

As an example principle is that, the star-to-delta transformation is made in the transformer windings at the network exit of any factory. Thus, the harmonics that are three or a multiple of three naturally cancel to each other out. The purpose of using the phase shifting transformers can be considered to be the same as this principle.

a. In this method, 60° is required between the two three-phase outputs to eliminate 3rd harmonic,
b. 30° is required between the two three-phase outputs to eliminate 5th and 7th harmonics,
c. 15 ° is required between the two three-phase outputs to eliminate 11th and 13th harmonics.

- The low impedance phase shifting transformers are used to reduce the values of harmonics in the voltage waveform. In particular, these transformers are designed to withstand the additional overheating caused by the harmonic currents. Thus, the quality and reliability of the electrical system can be significantly increased.

- Fault-Ride-Through (FRT) is the ability of PV systems to remain in the grid until it returns to normal operating conditions without losing the stability of the systems in case of the problems in the grid voltage (voltage drop / cut, frequency loss). In order to prevent the gradual frequency loss experienced today, the interconnection of PV systems with the grid has become an issue due to FRT feature. New FRT requirements have been proposed in the results of a study by the government of Japan. According to these results;

a. It does not require PV inverters to be shut down due to fluctuations on the grid voltage,
b. In order to prevent fluctuations in the frequency of the grid voltage, the PV system should be able to recover to normal operating conditions as soon as possible even if it is disabled
c. PV systems can provide the reactive power control (injection of reactive power) of the system through its inverters.
   This feature is called Dynamic Voltage Support (DVS). The aim of this is to keep the voltage of PV system around the normal operating conditions by controlling the reactive power to supply the short-term voltage stability. Thus, the number of PV systems shut down due to voltage drop can be reduced.
d. Similarly, it is predicted that PV systems will support the frequency losses of the network. Therefore, it has been revealed that an attention should be paid to FRT capability and capacity at PV system designs.

- The panel side of PV systems is negatively affected by the voltage fluctuations in the network and the voltage ripple may occur at DC bus side. The panel and panel equipment will be damaged due to these fluctuations. For this reason, the points where PV systems are connected should be selected by considering the bus bars where the grid voltage is stable.

- The harmonic filters of PV inverters may malfunction. In this case, they can pollute the network to which they are connected in terms of harmonics. For this reason, in case of filter failure, the inverter should be disabled. At the case studies, it has been observed that the adding of PV systems into the electrical networks causes the increasing of the short circuit currents and total harmonic distortion.

- PV systems adversely affect from the high index harmonics of the grid. In order to avoid problems in the power flow, the short-circuit analysis of the network should be made, if PV plants are added, the short-circuit analysis should be updated and the network harmonics should be suppressed with a suitable method.

- At the transformers used in the networks with the high harmonic density, THD level may decrease when converting the power from the high to low winding. These properties of transformers are called K factor (or Factor K). Transformer selection should be made by taking into account the characteristics of the load. Thus, both the total harmonic distortion and transformer losses can be reduced.

- It is very important that the maintenance of transformers is done on the time. Especially in oil-type transformers, the testing of oil and preferring the new generation organic transformer oils allow the transformer life to be extended. Thus, having more efficient and healthy transformers in the network will facilitate the operation of the network and increase its reliability.

- When the drivers and inverters are operated below their nominal power or at low frequencies, the filters at their outputs will not filter harmonics completely. Therefore, these equipment should be operated at their nominal power.

- The Inverter selections should be made according to the power needed. Depending on the needs, inverter selection with high power may cause losses (power and equipment) and increase in harmonics. For this reason, inverter selection is important in terms of network stability and health.

- Today, with the proliferation of data centers, uninterruptible power supplies (UPS centers) are used frequently at high power level (up to 6MVA). Since UPSs come into play in case of interruptions in the network and provide the energy to the data centers, they wait as idle capacity at other times. Since UPSs come into play in case of interruptions in the network to provide the energy to the data centers, they wait as idle capacity at other times. In addition, these reserves can be used to support the planned infrastructure works and to regulate the deviations in the supply-demand balance.

- As a result of both organized industry measurements and simulation studies (as the worst case scenario), it shows that the problems that may occur in the network can be faced with the complete collapse of the network (Blackout) at any time.

Conclusion

In this study, the system dynamics of an Organized Industrial Zone operating in the Mediterranean Region were recorded regularly by remote monitoring method between the dates 2013-2014 and then transferred to the simulation environment by using PSCAD and ETAP programs. In addition, a new control algorithm has been developed for APFs used for the harmonic compensation and its validity was presented in the case study.

To demonstrate the transferring of OIZ into the simulation environment successfully, the two case studies were presented by comparing the results with their real values. Then, the most harmonic bus bar of the system was determined and the proposed APF system was connected there. In the case study, APF has successfully performed the harmonic compensation. In the other case study, the formation process of the blackout occurred in Turkey and its results were examined in detail. The some recommendations have been made on this issue.

In another case study, the short circuit currents of OSB's main bus bars were examined and its effects on the short circuit and THD of the system were examined by adding a reality based PV plant. In case studies, it has been observed that the negative effects of PV systems with low THD on the network can be neglected. Finally, a simple passive filter was designed for harmonics and applied for OSB. In the simulation results, it was seen that the passive filter successfully eliminated the harmonic to which it was tuned.

The next step of this thesis is planned to be applied APF design. It is considered to be designed at low power and then tested the prototype where it is n

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CURRICULUM VITAE

Görkem Ok was born in Sarıkamış/Kars in 05.01.1982. He was graduated from Trabzon High School in 1999 and registered in electrical engineering department of Kocaeli University in 2000. Then he received his BSc degree on electrical engineering in 2004. In 2015, he enrolled into joint MSc program of Adana Science and Technology University and Çukurova University. He's been working as an electrical contracting sector since June, 2004.