JANUARY 2019 M.Sc. in Electrical and Electronics Engineering HAKAM H. ABDULHAKEEM

REPUBLIC OF TURKEY

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DESIGN OF MODULAR MULTI-LEVEL CONVERTER AND PERMANENT MAGNET SYNCHRONOUS GENERATOR-BASED WIND ENERGY CONVERSION SYSTEM

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HAKAM H. ABDULHAKEEM

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Supervisor

Assoc. Prof. Dr. Ahmet Mete VURAL

by

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Hakam H. ABDULHAKEEM

ABSTRACT

DESIGN OF MODULAR MULTI-LEVEL CONVERTER AND PERMANENT MAGNET SYNCHRONOUS GENERATOR-BASED WIND ENERGY CONVERSION SYSTEM

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M.Sc. in Electrical and Electronics Engineering

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Wind is the important type of clean energy originated from sun. Wind energy conversion systems are important actors in developing smartgrids and microgrids. On the other hand, wind energy is a premier resource which has been one of the world's fastest growing renewables for producing clean electrical energy. Due to higher efficiency, reliability, and controllability, nowadays, variable speed wind turbines employing permanent magnet synchronous generators (PMSG) have been extensively adopted as the major source for power generation in wind energy conversion systems. As the power and voltage levels increase, utilizing multi-level converters are inevitable due to the salient features such as redundancy, high flexibility, low switching losses, low harmonic content, and less electromagnetic interference. Among multi-level converter topologies, modular multi-level converter (MMC) topology is a promising candidate which has been originally proposed for high voltage direct current transmission systems. The purpose of the thesis is to design, simulate, and validate a three-phase wind energy conversion system connected to the electric power grid. The overall system consists of a full-scale MMC and PMSG with no gearbox. In MMC topology, the capacitor voltage balancing problem is solved by a closed-loop control. Various case studies have been conducted in a simulation platform to verify the overall model of the proposed system.

Keywords: Wind energy conversion system; Permanent magnet synchronous generator; Modular multi-level converter; Simulation.

ÖZET

MODÜLER ÇOK-SEVIYELI ÇEVIRGEÇ TABANLI VE SABIT MIKNATISLI SENKRON JENERATÖR TABANLI RÜZGAR ENERJISI DÖNÜŞÜM SISTEMI TASARIMI

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Rüzgar enerjisi, güneş temelli önemli bir temiz enerji türüdür. Rüzgar enerjisi dönüşüm sistemleri akıllı şebekelerin ve mikro şebekelerin gelişimlerinde önemli aktörlerdir. Diğer taraftan rüzgar enerjisi, dünyanın hızlı büyüyen yenilenebilir enerji türlerinden biri olan lider bir kaynaktır. Yüksek verim, güvenilirlik ve denetlenebilirliklerinden dolayı bugünlerde sabit mıknatıslı senkron jeneratör (SMSG) kullanan değişken hızlı rüzgar türbinleri geniş ölçüde rüzgar enerjisi dönüşüm sistemleri için güç üretimi amacıyla başlıca kaynak olarak uyarlanmışlardır. Güç ve gerilim seviyeleri yükseldikçe, çok seviyeli çeviricilerin kullanımı bolluk, yüksek esneklik, düşük anahtarlama kayıpları, düşük harmonic içerik ve daha az elektromanyetik girişim gibi belirgin özelliklerinden dolayı kaçınılmazlardır. Çok seviyeli dönüştürücü topolojileri arasında ilk başta yüksek gerilim doğru akım iletim sistemleri için düşünülen modüler çok seviyeli (MÇS) topoloji umut vaat eden bir adaydır. Tezin amacı, elektrik güç şebekesine bağlı bir üç faz rüzgar enerjisi dönüşüm sisteminin tasarımı, benzetimi ve doğrulanmasını kapsamaktadır. Tüm system tam-ölçekli bir MÇS'den ve vites kutusuna sahip olmayan bir SMSG'den oluşmaktadır. MÇS topolojisinde, kondansatör gerilim dengeleme problemi bir kapalı-döngü denetimi ile çözülmüştür. Çeşitli vaka çalışmaları önerilen sistemin tüm modelini doğrulamak için bir benzetim platformunda yürütülmüştür.

Anahtar Kelimeler: Rüzgar enerjisi dönüşüm sistemi; Sabıt mıknatıslı senkron jeneratör; Modüler çok seviyeli çevirici; Benzetim.

This thesis is dedicated to my family (father, mother, brothers, sisters, and friends) for their endless love, encouragement and support.

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LIST OF SYMBOLS

AC	Alternative Current
APOD	Alternative Phase Opposition Disposition
BTB	Back To Back
CD-PWM	Carrier Disposition Pulse Width Modulation
CMLC	Cascade Multilevel Converter
DC	Direct current
DCMC	Diode Clamped Multilevel Converter
DFIG	Doubly Fed Induction Generator
FCMC	Flying Capacitor Mutilelevel converter
I	Current
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Commated Thyristor
MMC	Modular Multilevel Converter
P	Active Power
PD	Phase Disposition
PMSG	Permanent Magnet Synchronous Generator
POD	Phase Opposition Disposition
PSC-PWM	Phase-Shifted Carrier-Based PWM
PWM	Pulse Width Modulation
Q	Reactive Power
SCIG	Squeril Cage Induction Generator
STATCOM	Static Synchronous Compensator
V	Voltage
WECS	Wind Energy Conversion System
WRIG	Wound Rotor Induction Generator
WRSG	Wound Rotor Synchronous Generator

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Many renewable energy sources have deemed as a replacement for classical sources. Newly, the wind energy has considered as one of the fastest renewable energy type. Wind energy is significant because it holds vast potential in supplying electricity across the world [1], [2]. While other sources of electricity need fuel in processing plants electricity through wind energy generators. The energy produced by wind turbines has become a focus of interest from countries around the world [3]. When it comes to achieving renewable energy ambitions, wind turbines are the key to achieving this goal. In the last ten years, the focus has increased significantly on the wind. The wind energy has considered as one of the most popular subject, and this is due to its benefit, including lower operating costs. The renewable energy can be used in many applications. It is not using water or fossil fuels. It can be integrated with minimal cost [3], [4]. The wind energy has some disadvantages; the noise is issued in all cases and the noise and is heard by the human. So they are usually located for away from homes and residential areas.

Wind turbine converts the power from the wind to electric energy. The types of wind turbines are divided mainly into types: The first type is vertical and the second is horizontal [5]. In the vertical turbines, the axis of rotation is vertical on the ground, and it is more profitable in small enterprises, because the power produced by the vertical mills is very few and this is a major disadvantage for vertical turbine.

In horizontal turbine, the rotation of the turbine is horizontal [5], [6]. In these years, this type is the most widely used. Horizontal turbine is more preferred because it is successful in small and large projects, in addition to the ability to generate a quantity of energy greater than the amount of wind, major advantages are high efficiency, expensive and they can produce electricity in any wind direction.

Horizontal turbine often consists of two or three blades [6]. The rotor is divided into two types according to the direction of rotor (in same direction is called downwind and in opposite direction is called upwind). The design of horizontal turbine includes generator, with/without gearbox or without, shaft, mechanical brake, coupling, and wind meter.

As mentioned above, turbines are used to convert wind energy into electric energy, but not in the strict sense that the wind is converted to energy. There must be a generator in the windmill system to complete the conversion process, but not in the strict sense that converts wind into energy. There must be a generator in the wind system to complete the conversion process [7], [8]. The converter is used in turbine system to regulate the internal voltage according to the required voltage and connect the generator to the grid. These are the two most important elements in the wind system, both of them have many types and each type has the benefits and disadvantages, and assesses their suitability for wind turbine through their qualities, benefits, and disadvantages.

One motivation of the thesis is to balance the DC-capacitor voltages in each cell of MMC in wind energy conversion system (WECS)

1.2 Brief History

The wind turbine was not a source of power generation in ancient years until 1887. In 1887, in Scotland, Prof James Blyth designed the first electric power wind turbine. This wind turbine was used to charge the accumulators and then used to power the lights in the cottage after being developed by Camille Alphonse [9]. In 1891, Danish developed the concept of generating electric energy from wind turbines. This expert discovered how to supply a constant stream of mills using the regulator. In addition, he discovered that four-blade wind turbines are more efficient and faster than three-blade wind turbines [10].

In Denmark, electric mills are spread widely. In 1900, about 2500 wind turbines were installed in Denmark for mechanical uses. In 1908, 72 wind turbines generating electricity more installed in Denmark and the amount of electricity that was produced was between 5-25MW [10].

In 1927, the brothers Joe Jacobs and Marcellus Jacobs designed a wind turbine for the farm that they own; the purpose of the wind turbine was for lighting, and charging batteries or other purposes that were necessary in the farm.

In 1930, there were many wind turbines in America, because at that time there were no distribution systems. On that date, the use of small wind turbines was very large in America that consisted of two blades, and it produced approximately 200MW. These wind turbines were used during 1930-1988.

In 1941, the expert Palmer Cosslett Putnam designed a wind turbine to be considered as the first mill produced in the amount of megawatt level (1.25MW) which was connected to a local distribution system in America.

In 1980, nearly 20 wind farms were installed in the world, and Denmark began installing marine turbines. In a short period, interest in wind turbines increased. In 1990, 20 wind farms were installed in the United States.

In 2000, the United States had 97 wind farms producing electricity, about 2554 MW of electricity. Two years later, the number of wind farms producing electricity in the United States was 149. From one year to the next, the interest was increasing and the world's direction of wind turbines was increasing very fast. Within two years, there were about 52 wind farms which were installed in the United States. In 2008, the United States had 416 wind farms used to produce the electric power for residences [11].

As for the United Kingdom in 2003, the first offshore wind farm consisting of twenty wind turbines was established. Five years later, United Kingdom had 2000 wind farms producing electricity for residential areas [11].

Until 2009, United States had become at top in world in terms of windmill, but in 2010, China passed the United States and became the country that has the largest number of windmills producing electricity.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Many studies and research have been studied on modular multilevel converter (MMC) and permanent magnet synchronous generator (PMSG) based wind energy conversion system (WECS). This chapter includes relevant studies and research related to MMC and PMSG based WECS.

2.2 Related Works

Marc Cheah-Mane, Jun Liang and Nick Jenkins in 2014, they showed that in their research a description of the control and modeling of PMSG for wind turbines based voltage source converter (VCS) [12].

Marcelo A. Perez in 2014, this research has presented the last implementations related to MMC including circuit topologies, modeling, control schemes, modulation strategies, and applications [13].

Main Wang, Yaowei Hu, Wenjian Zhao, Yue Wang and Guozhu Chen in 2016, proposed a research for the control method of back-to-back MMC and PMSG based WECS. In this research, the control method that has been introduced was a second current circulating injection [14].

Rui. M, V.M.F. Mendes, J.P.S. Catalao in 2010, proposed the integrated model for variable speed WECS. The model in this study was pulse width modulation space vector modulation (PWM-SVM) linked with sliding mode used for the control of converter [14].

Prerna Badoni and P.S.Jagdeesh Kumar in 2013, presented a research that includes many topologies of converter with PMSG for WECS [16].

They presented a deep, extensive, and basic study on the structure and topologies of converter connected between generator and grid in wind conversion system.

Debabrata Thatoi in 2015, designed a control method for PMSG based Stand-Line WECS. The researcher used MATLAB/SIMULINK program for modeling and performing simulation [17].

Makoto Hagiwara, and Hirofumi Akagi, in 2008, proposed a new control strategy with modulation technique for MMC. This control is based on PWM [18]. They designed this control for controlling on every capacitor voltage balancing in legs of MMC. They also published a research in 2009 [19]. This research includes also the control of MMCs. Both these searches include a way to control the converter with a power supply to convert from AC to DC.

Zaijun Wu, Xiaobo Dou, Jiawei Chu, and Minqiang published in 2013 a research [20] about the difference and similarity between the active power filter and the converter connected to the network for the direct driven PMSG. In addition, in this research, the control method and strategy for generator were included. The control method in the search was Low Voltage Ride-Through (LVRT) for generator side converter at the output.

U.N. Gnanarathna, S.K. Chaudharyt,A.M. Gole, and R. Teodorescut, described MMC based high voltage direct current (HVDC) system for grid connected wind turbine. The kind of wind turbine was offshore and they had the proof that the MMC had low harmonics [21].

Sumitha Mohan and Rajendra Naik described a back-to-back AC-DC-AC converter system without simulation. In this research, the current losses in the MMC were measured completely. The kind of power semiconductor switch that they used in research was Integrated Gate Commutated Thyristor (IGCT) [22].

Maira Z, David Xu, and Bo Yuwen published a research in 2011 and this research focused on the transformer, which was connected to the squirrel cage induction generator (SGIG) based wind turbine. This research presented a method of independent controller design to guarantee the distribution of energy equally between the parts of the transformer connected. They used MATLAB/SIMULINK to test the controller for its effectiveness and efficiency [23].

2.3 Place of Work in The Literature

Many researchers have studied many types of converters in wind energy systems. In this thesis, the comparison between MMC and the other types was also discussed in the research. One side of MMC is connected to the PMSG based WECS and the other side is connected to the AC voltage source. The first MMC is connected to the PMSG and works to convert AC power to DC. The second MMC is also three-phase and connected through the DC-link capacitor to AC-DC MMC in back-to-back (BTB) arrangement, the other side is connected to grid. The control of two MMCs has been modeled and designed to achieve the capacitor voltage balancing in each sub-module of MMCs. Modulation technique in the control is designed and discussed. In this research, the benefits, kinds, and characteristics of the PMSG have been discussed. PMSG have been compared with other species, which is more convenient and more suitable. The types of sub-module in MMC have been discussed, the types and characteristics of power electronic switches in sub-modules have been discussed in this study. Finally, the controllers of the overall system have been tested under steady-state and dynamic cases to see and verify the performance and efficiency of the controllers.

CHAPTER 3

MMC AND PMSG BASED WECS

3.1 Introduction

We have already noticed the evolution and over-interest of wind energy throughout history. With the respect, Figure 3.1 shows the wind power global capacity increase between 1996 and 2012 [5]. We see clearly the development and growth of wind energy generation from 1996 to 2012. This development and attention are mainly due to the most important reasons that the wind energy does not use fossil fuels. In this chapter, the concepts of WECS with related components are reviewed and described.

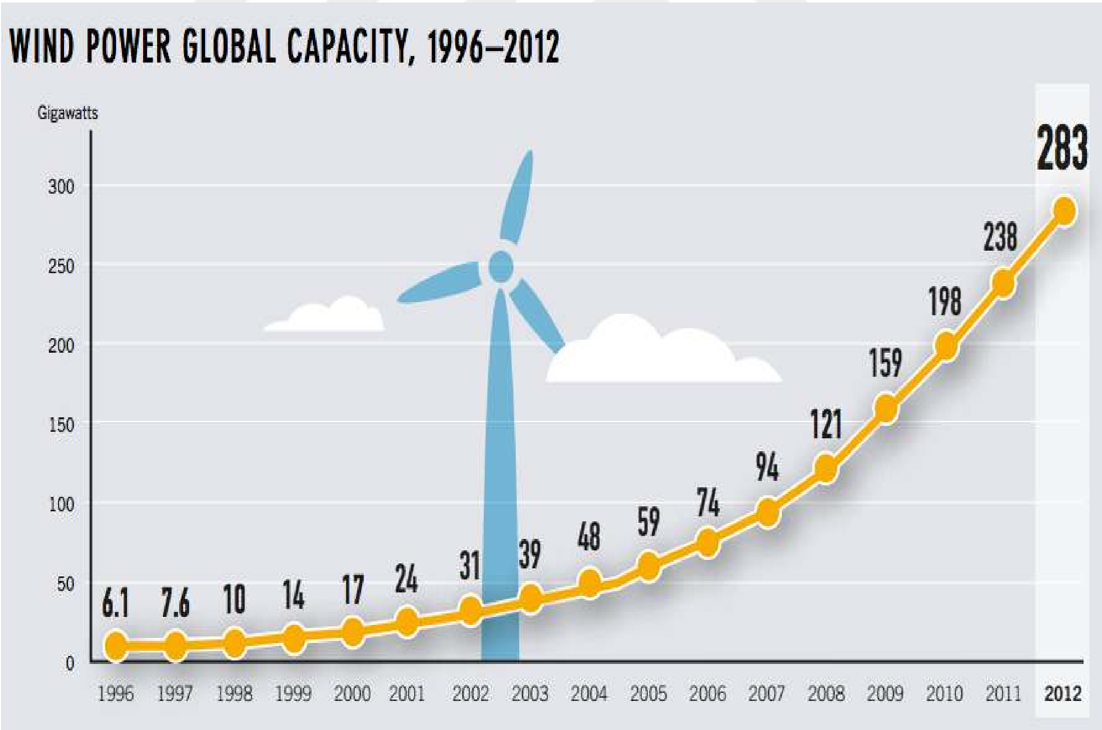


Figure 3.1 Wind power global capacity [5].

3.2 Wind Farm Types

Wind turbines are installed either on the land, called (onshore wind farms) or installed in the sea called (offshore wind farms) [6], [24]. Table 3.1 shows the comparison between the onshore and offshore wind turbines.

Table 3.1 Comparison between onshore wind offshore wind turbines

Offshore wind turbine	Onshore wind turbine
The cost of maintenance is higher	The cost of maintenance is less
The transmission lines are far for wind turbine system	The transmission lines are closer for wind turbine system
Need for strong foundations and marine cables must be used to connect the wind turbines farms with the grid through sea	No need for marine cables
The maintenance is higher	The maintenance is less

3.3 Wind Turbine Types

Wind turbines are classified as three types according to the speed concept. These types are summarized as follows:

3.3.1 Fixed Speed Concept

The fixed speed concept "Danish concept" is the most widely used concept for the wind turbines. This concept has some bad qualities such as the voltage level produced in this principle is not possible to be controlled according to the voltage required [25], [26]. Moreover, the presence of gear box makes it heavy and the major disadvantage of fixed speed concept is the increase of the mechanical stress on the wind turbine. The speed is constant in this principle, therefore, it deals with generators that operate at limited speed. In this concept, the generator is connected to the grid by means of a transformer, gearbox, and capacitors. The generator speed in this concept depends upon the number of pole pairs and the grid frequency [3], [26].

Advantages of fixed-speed wind turbines are:

- The electrical part is cheap,
- It is simple and robust.

Disadvantages of fixed-speed wind turbines are:

- Serious power quality problems,
- The speed cannot be controlled precisely because it is fixed to the mains frequency,
- High starting currents,
- Mechanical stress on the drive and gear system,
- Reactive power cannot be controlled [7].

The soft starter is used to reduce the instantaneous current that many causes the power failure. The soft start reduces the current and voltage drop, as well as the torque in the gearbox and the generator [7]. The capacitor bank improves power factor and reduces the losses caused by the reactive power of the grid. It also improves voltage stability. The major advantage of capacitor bank is to compensate the low power factor.

3.3.2 Semivariable Speed Concept

Semivariable speed concept in WECS is characterized by using the external resistance (variable external rotor resistance). Semivariable speed concept is called as "optislip concept" [7]. The working principle of this is different from the others as the fundamental thought is to use the variable external rotor resistance to control the rotor of generator via power converter. The reactive power compensation and soft starter are necessary in this concept. The wound rotor induction generator (WRIG) is used in this wind conversion system concept [7].

3.3.3 Variable Speed Concept

In the variable speed concept, the generator is not linked directly to the grid. However, the generator is connected to the grid through full-scale power or partial-scale power converter [3]. This concept provides high efficiency despite the wide range of wind speed [26]. This principle allows the control of the rotor speed. This is one of its advantages that distinguishes it from the fixed speed concept. The advantages and attributes of this principle are as follows:

- Improved the quality of power [15],
- Low mechanical stress,
- Reduced noises,
- Higher aerodynamic efficiency,
- Power waves can be absorbed by changing the rotor speed,
- Reactive power control with power electronic elements.

The disadvantages of variable speed wind turbine are:

- This concept is more complicated because of the existence of power converters [12].
- The losses are increased in power electronics and the cost is higher because there are more power electronics components used in variable speed concept.
- The major disadvantage of variable speed concept is the existence of a gearbox where its presence causes a high percentage of noise and increases the loss and cost of maintenance [25], [26]. The gearbox is used in this concept to increase the speed of generator shaft. Double fed induction generator (DFIG) can be used in variable speed concept with a partial-scale/full-scale power converter.

3.4 Wind Turbine Structure

The WECS consists of three main parts in order to convert the kinetic energy into electric energy [13]. The parts are electrical, mechanical, and the control system of the power converter.

3.4.1 Mechanical Part

The main mechanical parts used in the production of electric energy are nacelle, rotor, brake, gearbox, blades, pitch driver, tower, and generator. Below are brief descriptions of these main elements [1], [2], [3]. The mechanical system mainly consists of:

a) Rotor: A central rotor that combines blades. There are 2 or 3 blades on the rotor.
b) Brake: Brake stops the rotor when there is overload or emergency situation.
c) Gearbox: The angular velocity of the blades is proportional to the required value of the electric frequency. Gearbox systems have a low-speed shaft speed connected to the high-speed shaft of the generator [26].

d) Pitch driver: When the wind speed is too low or too high to produce electricity, the lift force generated by the wind is changed by changing the angles of the rotor blades against the wind to control generated power.

3.4.2 Electric Part

The electric part in WECS is the generator. The kinetic energy from the wind is converted to mechanical energy by the rotor, and then the generator converts this mechanical energy into electrical energy. The generator size is determined by the rating of the WECS. In wind turbines, either direct current (DC) or alternating current (AC) generators are used. If the electric current obtained here is an insufficient AC or DC, it can still be supplied to the network by the power electronic circuits. The generators are already classified according to the wind turbine concepts in the earlier sections [4].

There are many generators, each with its advantage, characteristics, and benefits, according to the characteristics and benefits of the generators demonstrating their suitability to the wind energy [14]. The types of generators are as follows.

3.4.2.1 Asynchronous Generators:

The types of asynchronous generators (induction generators) are described as follows.

- **DFIG**

The stator of the DFIG obtains the reactive power from the grid via power converter, and the rotor receives the voltage from the power converter [7]. For these two reasons it is called "doubly fed". The gearbox is required because the speed of DFIG is usually 12-19 revolutions per minute, which is so far from the turbine speed [27]. The rotor circuit of DFIG has capable of magnetizing the DIFG. As a result, there is no need for power grid magnetization. The DFIG is used in wind turbine systems according to its advantages which are listed below [29]:

- Suitable for large power wind turbines (megawatt level),
- The reactive power is transferred to the stator by the converter on the network side,
- Relatively cheap,
- Easy and simple maintenance.

The disadvantages of DFIG are:

- Gearbox is necessary,
- The control strategies are complex [26, 27],
- Large size and low efficiency.

Figure 3.2 shows the scheme of DFIG with partial-scale power converter in WECS. The side of converter that is linked with the DFIG is called "generator side", and the side of converter that is linked with grid is called "grid side". The reactive and active power can be controlled via the generator side. The stator is linked to the grid in direct way and works for feeding power to the grid [28].

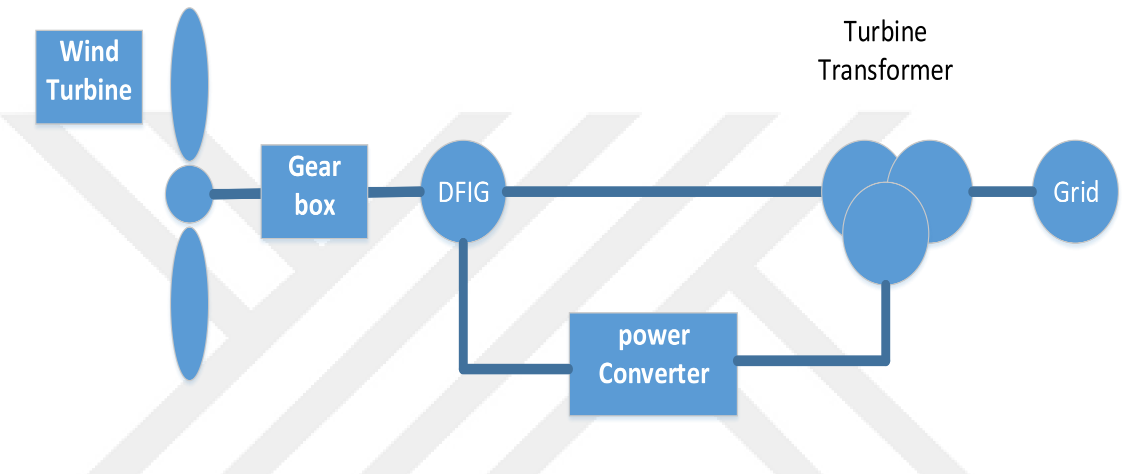


Figure 3.2 Scheme of DFIG with partial-scale power converter in WECS [26].

- **SCIG**

The SCIG operates at a limited speed and operates under a narrow range of speed according to the synchronization speed [29]. When using SCIG with the concept of fixed speed, the system needs compensator to offset the relative voltage, because SCIG drags the reactive power from the grid and this is one of the major disadvantages of SCIG. However, the advantages of SCIG are strong, simple, achieve stable frequency, and not being expensive [7]. SCIG is formed by shortening the copper rods buried in the grooves on the rotor along the ring at both ends to reduce magnetic noise and achieve good developed momentum. This name is given to the generator because the size of the rotor shorting bars is similar to a squirrel cage. For SCIG, the structure is brushless, reliable, economical, and powerful thereby it is used a lot in practice.

The SCIG has some disadvantages for example, the generator parameters change with temperature and frequency that complicates the control of the system. Thus, fluctuations in wind power are transmitted directly to the grid. This is one of the most important situations to look out for. This means that there is no winding in the rotor for SCIG, which means that the required interactive energy is provided from the outside because there is no excitation circuit. The generator should take the active power from the outside [19]. This can be achieved through the capacitors that are connected in parallel near the grid. If this is not done, when the generator gives active power at the moment of operation, there is a backlash flow in the opposite direction from the grid. Figure 3.3 shows the scheme of SCIG.

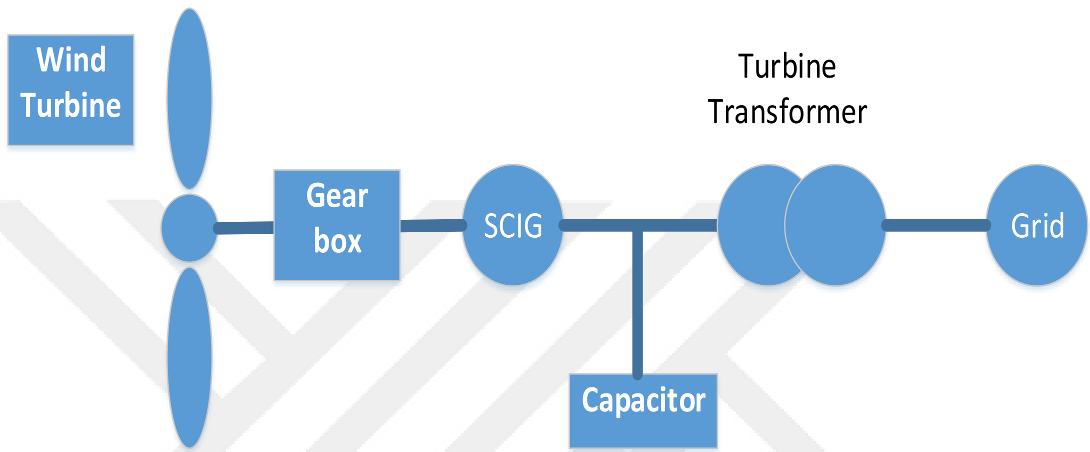


Figure 3.3 Fixed speed wind turbine system with SCIG [26].

- **WRIG**

The wound rotor induction generator (WRIG) is generally used in the concept of semi-variable wind turbines. In 1990s, Vestas applied this generator to the wind turbine using the converter [30]. The WRIG is applied to wind turbines in two forms. In the first design, WRIG consists of slip rings, series resistance, soft starters, and compensator. The compensator is used to compensate for the reactive power. Resistance is used to provide speed control. Where Vestas has replaced the slip rings with the converter and this is the second design. In the WRIG, the electrical properties of the rotor can be controlled from the outside [26]. As a result, it is possible to change the rotor voltage. This generator is connected from the first side to the wind turbine through the gearbox. The other side is connected to the grid through power converter as shown in Figure 3.4.

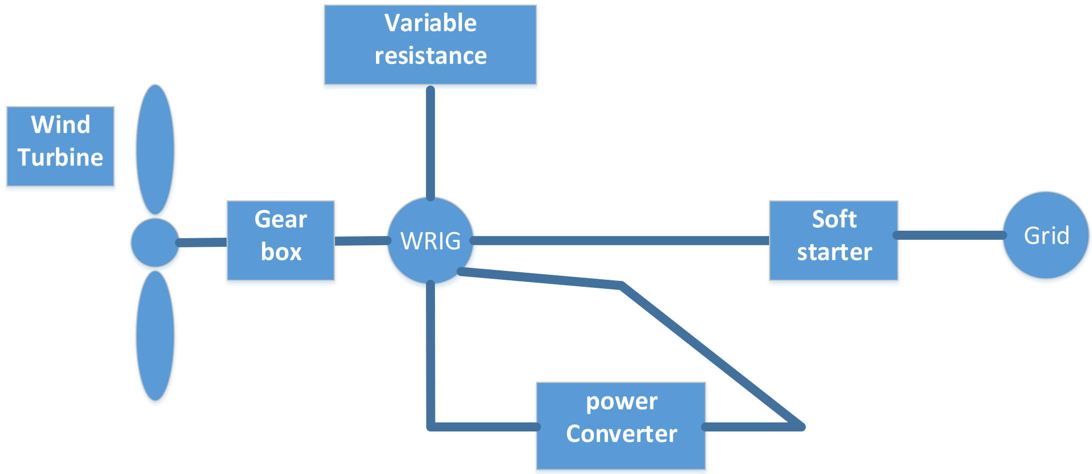


Figure 3.4 WECS with WRIG in semivariable-speed concept [26].

3.4.2.2 Synchronous Generators

The types of synchronous generators are described as follows:

- **WRSG**

Figure 3.5 shows the scheme of wound rotor synchronous generator (WRSG) in WECS. The converter is connected to the stator from generator side and the converter is connected to the grid side to regulate the active and reactive power generated by this system. The windings on the rotor are fed with a DC power supply to create a constant magnetic field in the air gap [30]. This magnetic field rotates the rotor and passes through the stator, and induces the voltage in the stator**.** The advantages of WRSG are as follows:

i. Since the entire constant current is used to produce electromagnetic torque, the output of this device is usually high.

ii. The greatest advantage of using a WRSG with a separate field winding is to allow the machine's power factor to be controlled directly. As a result, the constant stream can be reduced in many operating situations.

The presence of the rotor winding circuit is a disadvantage when compared to a permanent magnet synchronous generator (PMSG). In addition, to regulate the active and reactive power that are produced by the system, converters should be used [26].

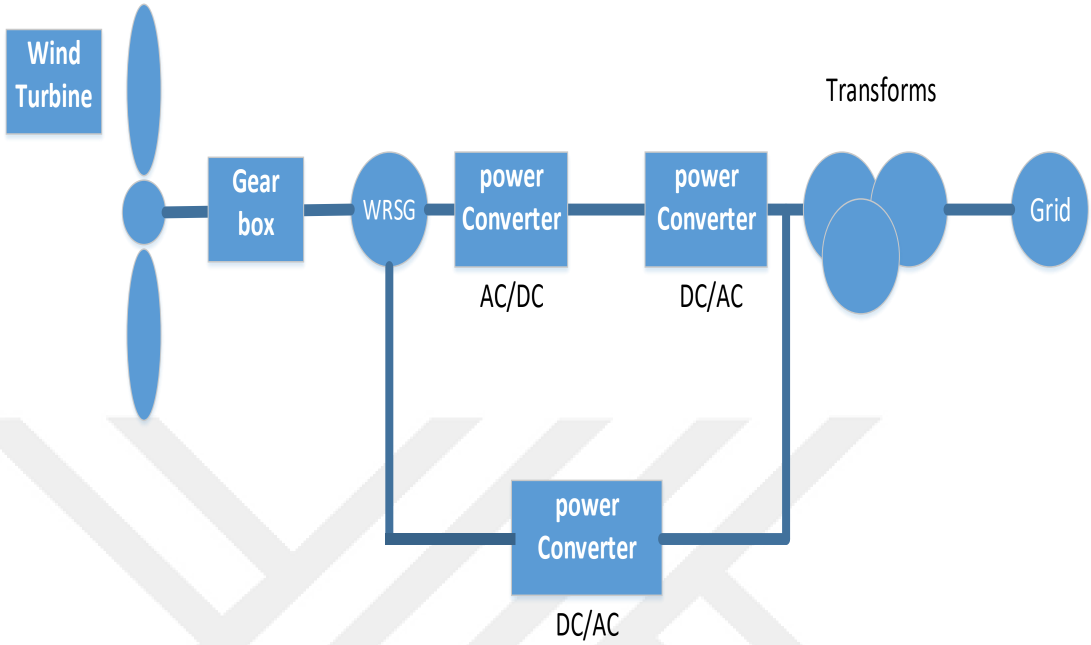


Figure 3.5 WECS with WRSG [31].

- **PMSG**

In recent years, the permanent magnet synchronous generator (PMSG) has become popular due to its features, such as, brushless structure, no need for the gearbox, and high efficiency/reliability [31]. Due to the presence of a permanent magnet in PMSG, the need for an electrical excitation in rotor is removed. As a result, the losses in the windings are reduced and the overall efficiency is increased. In addition, the weight of the generator becomes lower due to the absence of the excitation windings on the rotor [26], [30]. However, the PMSG has some disadvantages. It needs a full-scale back-to-back (BTB) converter for grid-connection, which increases the overall cost of the WECS, and the cost of the PMSG is higher than its alternatives, because of the permanent magnet used in the rotor [32]. As shown in Figure 3.6, the PMSG consists of the main parts: 1) Stator, 2) Rotor, 3) Permanent magnet, and 4) Air space.

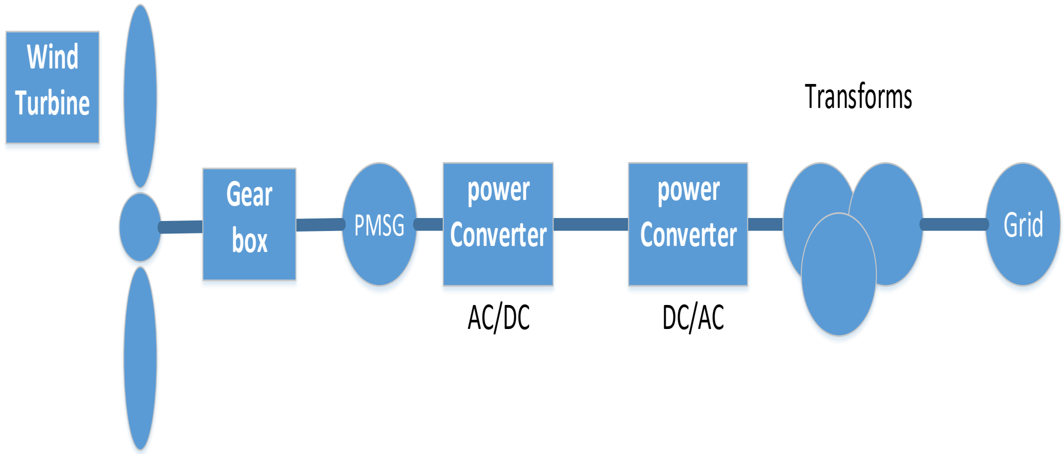


Figure 3.6 WECS with PMSG [31].

Table 3.2 compares the PMSG, SCIG, and DFIG generators in terms of their suitability for the WECS.

Table 3.2 Comparison between PMSG, SCIG, and DFIG

Type of Generator	**PMSG**	**DFIG**	**SCIG**
Cost	Expensive	Cheap	Cheap
Efficiency	High	Low	Low
Durability	Robust	Robust	Robust
Losses	Low	high	high
Gearbox	Not needed	needed	needed
Ride through performance (RTP)	perfect	Bad	perfect
Weight	Heavy	Light	Middle
Noise reduction	Yes	No	Yes
presence of brush	Brushless	Existed	Existed
Capacitor bank	Not required	Not required	required

These generators have been in market with different power levels, speed, and manufactures. Table 3.3 shows these wind turbine with a rated power greater than 2MW from various manufactures such as Vestas, Repower, Ge wind, according to the wind turbine concept, generator types.

Table 3.3 Wind turbine concepts on the market over 2 MW [31]

Wind Turbine Concept	Generator Type	Power/speed	Manufacturer
Variable speed multiple-stage concept with partial scale convertor	DFIG	4.5 MW / 14.9 rpm	Vestas
Same concept	DFIG	2 MW / 19 rpm	Gamesa
Same concept	DFIG	3.6 MW /15.3 rpm	GE wind
Same concept	DFIG	5 MW / 12.1 rpm	Repower
Same concept	DFIG	2.5 MW / 14.85 rpm	Nordex
Same concept	FDIG	3 MW / 14.25 rpm	Ecotencia
Limited variable speed with multiple-stage gearbox	WRIG	2 MW / 17 rpm	Suzion
Limited variable speed multiple-stage gearbox with full-scale power convertor	SCIG	3.6 MW / 13 rpm	Siemens
	PMSG	2 MW / 16.5 rpm	General Electric
Variable speed direct drive with full-scale power convertor	PMSG	2 MW / 23 rpm	Zephyros

3.4.3 Working Principle of PMSG

Despite the difference in the rotor between PMSG and asynchronous generator, the stator of PMSG does not differ from the stator of an asynchronous generator. The stator of asynchronous generators is squirrel cage or wound. In contrast, the rotor of the PMSG consists mainly of permanent magnets. The working principle of the PMSG is based on the interaction between the magnetic field generated by the rotor and the rotating magnetic field generated by the stator [31]. The magnetic field generated by the stator will rotate with the voltage provided by the windings. The rotation speed of the magnetic field obtained is called the synchronous speed, which is proportional to the frequency (f) of the stator voltage. Synchronous speed is formulated as follows:

$$N = 120f/P \tag{3.1}$$

where (P) is the number of poles. There is no difference between electromotive force (EMF) that are generated by the permanent magnet and field winding. The three-phase stator windings have angularly placed at 120 degrees in PMSG according to each other [12], [32].

In Chapter 4, the kinds of PMSG and working principle with complete modeling are summarized.

3.4.4 Control System

In order to maintain the performance of the WECS and perform its work as required, the control system must be necessary. It is required to use a power converter in WECS, but when using the power converter, it is required to use a control combination to control the reactive power and active power at the same time. In Chapter 4, the controls of power converters are explained clearly. The power converters are used to convert the frequency and voltage of the wind generator from variable value to fixed frequency/voltage.

3.5 Power Converter

In last years, the industry has started to need tools with higher power more than previous years. New group of multi-level converter has been developed as the arrangement for working with higher voltage level [13], [15]. As of late, many researchers and designers of power electronics have participated with multi-level converters aimed at accomplishing medium-voltage power conversion (MVPC) without transformers [18]. The types of the converters are 1) The diode-clamped multi-level converter (DCMC), 2) The flying-capacitor multi-level converter (FCMC), 3) Cascaded multilevel converter (CMLC), 4) Modular multi-level converter (MMC).

3.5.1 DCMC

The concept of DCMC is to utilize diodes and gives the various voltage levels through the diverse stages to the capacitor banks, which are connected in series [33]. In 1991, the DCMC showed in the technical literature and since this date, many studies have been submitted. The DCMC has been considered to be the highest elasticity and the most popular. But it has a problem in the voltage imbalance of capacitors. When the number of levels is increased, this problem becomes more complex [19], [33]. Academic investigators have examined the DCMC fundamentally and they found it inappropriate to be alluring for the industry. This can be ascribed for two primary reasons. The first reason is that the structure is complicated and the second reason is the DC-link capacitor voltage is not easy to be balanced. Figure 3.7 shows the three-phase three-level DCMC structure.

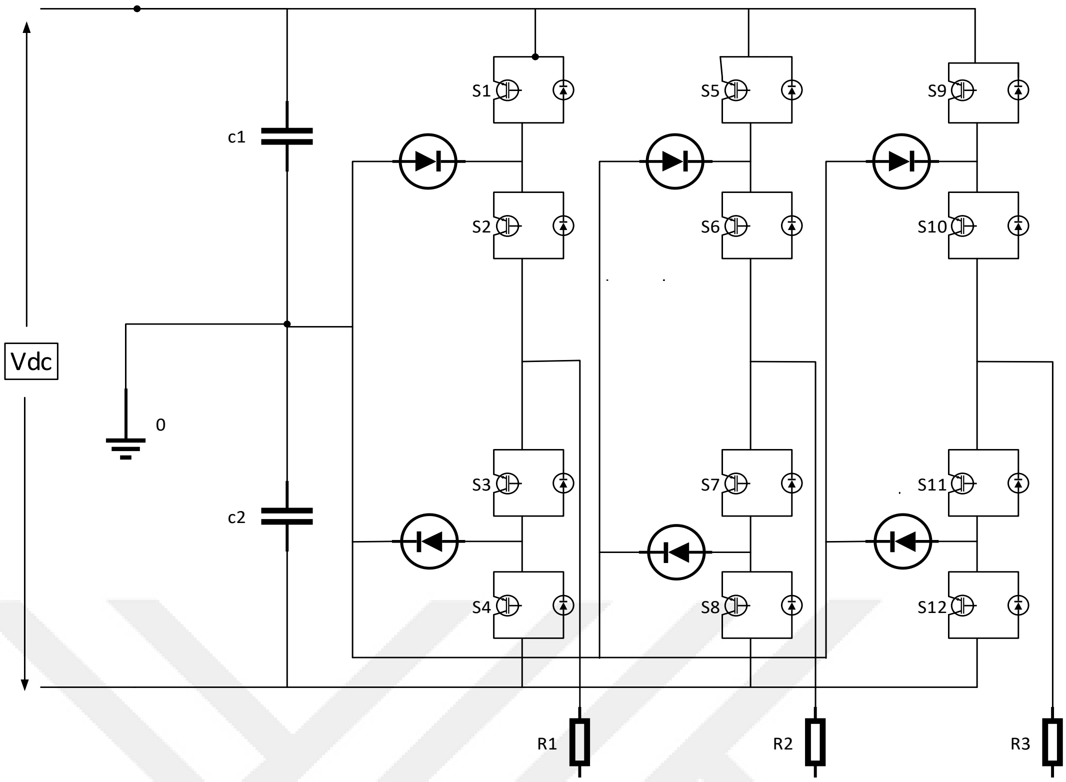


Figure 3.7 Three-phase three-level DCMC structure.

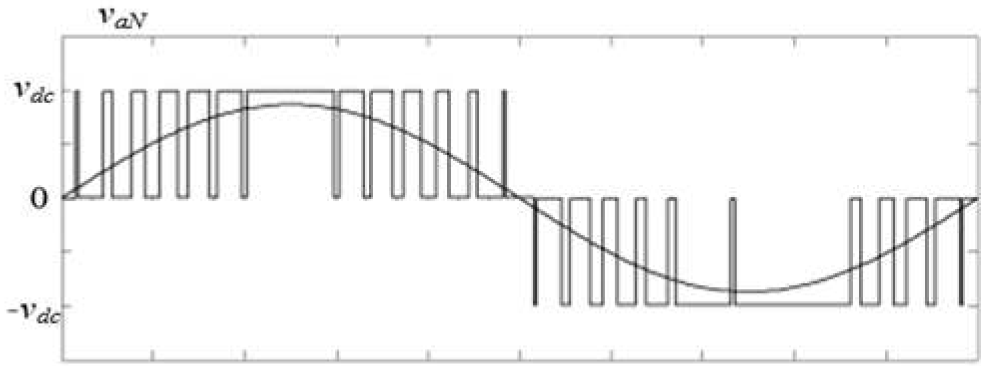


Figure 3.8 Per-phase output voltage waveform of DCMC [33].

3.5.2 FCMC

The concept of this converter is to use capacitors instead of diodes. Figure 3.9 shows the circuit configuration three-phase three-level FCMC. In this converter, the output voltage has decreased to half of the input voltage, thus, it is considered as a disadvantage for this converter. Additionally, the FCMC needs many capacitors, and when the number of the levels increases, the control of the system becomes more complex [16], [33].

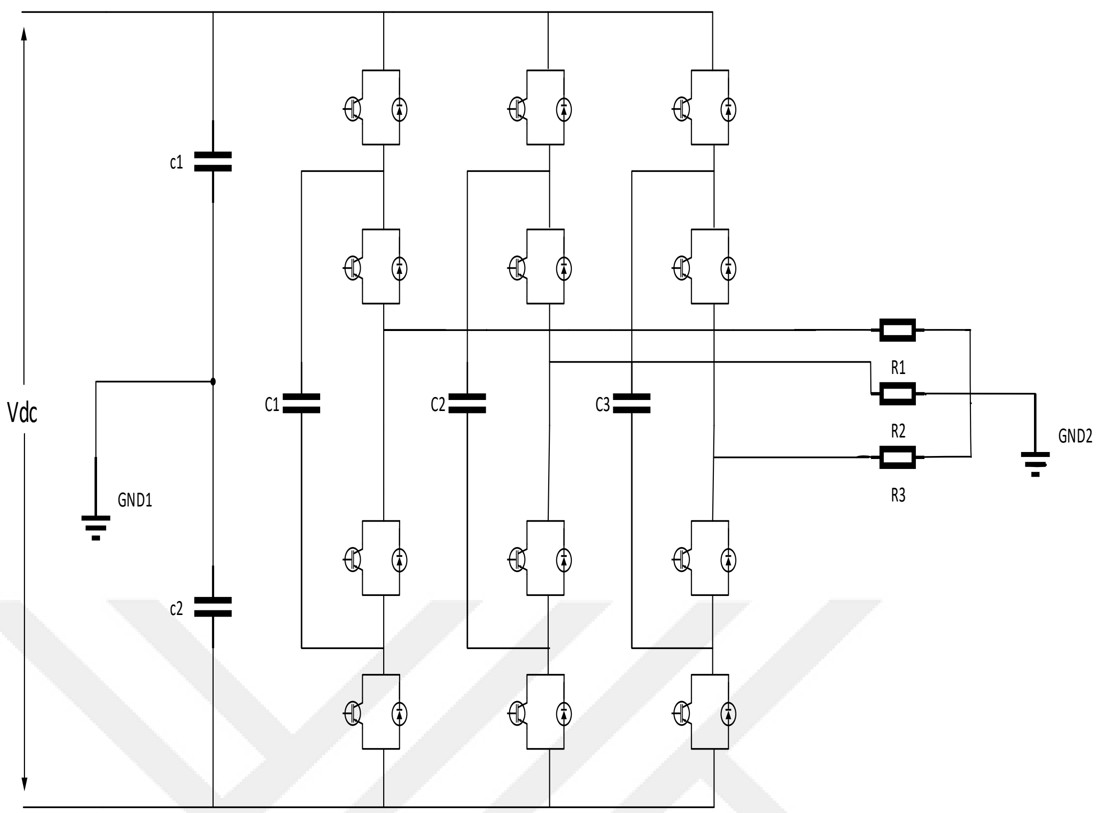


Figure 3.9 Circuit configuration of three-phase three-level FCMC.

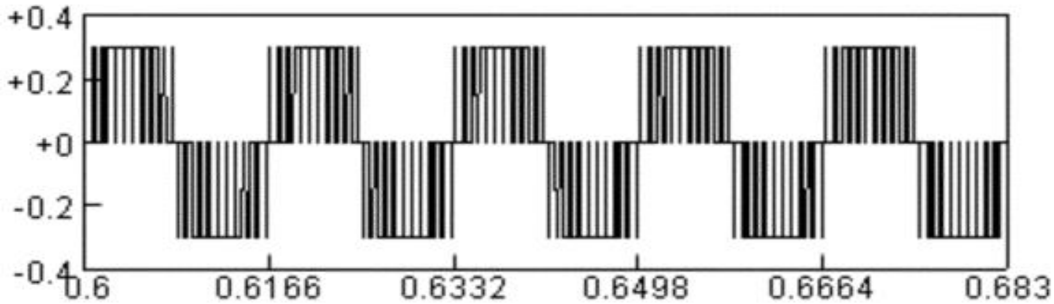


Figure 3.10 Per-phase output voltage waveform of FCMC [33].

3.5.3 CMLC

CMLC has been considered to be more expensive and have more losses when compared to other types of converters [36]. The reason is that the CMLC needs many transformers to supply electrically isolated active DC sources for the H-bridge or NPC converter cells instead of negative DC sources. The CMLC is considered as a suitable and favored one in reactive power compensation and active power filtering applications [16], [35]. The reason is that when the CMLC is compared to other converters in reactive power compensation and active power filtering, the CMLC can generate large number of voltage levels in spite of a fewer number of cells. Figure 3.11 shows the circuit configuration of single-phase seven-level CMLC.

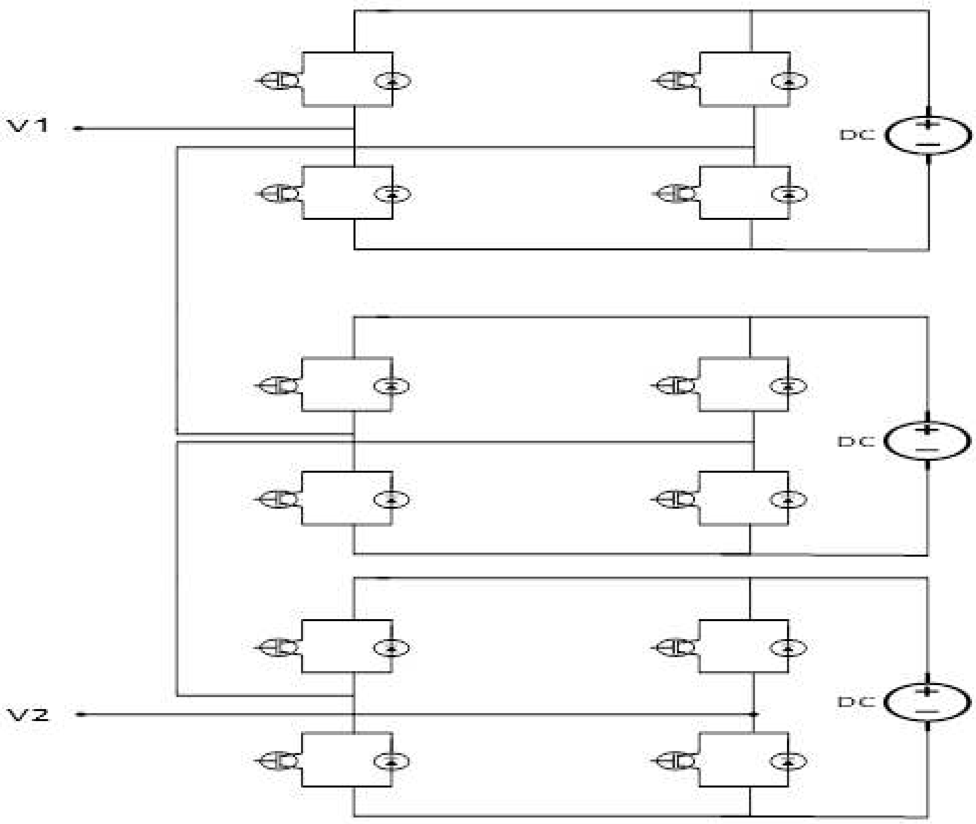


Figure 3.11 Circuit configuration of single-phase seven-level CMLC [35].

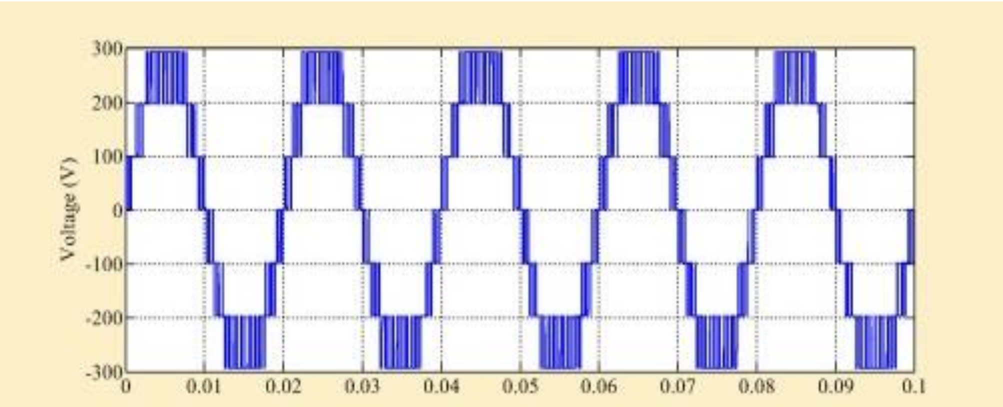


Figure 3.12 Output voltage waveform of CMLC [37].

3.5.4 MMC

As mentioned above, the MMC is preferred in the application of PMSG WECS due its advantages. Some important highlights of MMCs are as follows: 1) The construction is easier and flexible unlike other multi-converter topologies, 2) MMC is extendable to any number of voltage levels and capacitor voltage balancing is achievable with some methods, 3) Despite the increment in the number of voltage levels, MMC is able to generate higher voltages with diminished voltage stress on each power electronic switching device, 4) The cost is reduced significantly when compared to other multi-level topologies because a coupling transformer may not be needed, 5) Harmonic levels are significantly decreased thanks to increased number of voltage levels. As a result of this, filtering requirements are becoming less, 6) The MMCs have fault management capability and better fault ride through capabilities [21], [16], and 7) Due to its many advantages and popularity in recent years, a BTB-MMC topology is considered in this work. Because it allows obtaining high-quality current and voltage without using the filters. These features increase the efficiency and decrease the cost [18], [19].

3.5.4.1 Topologies of MMC

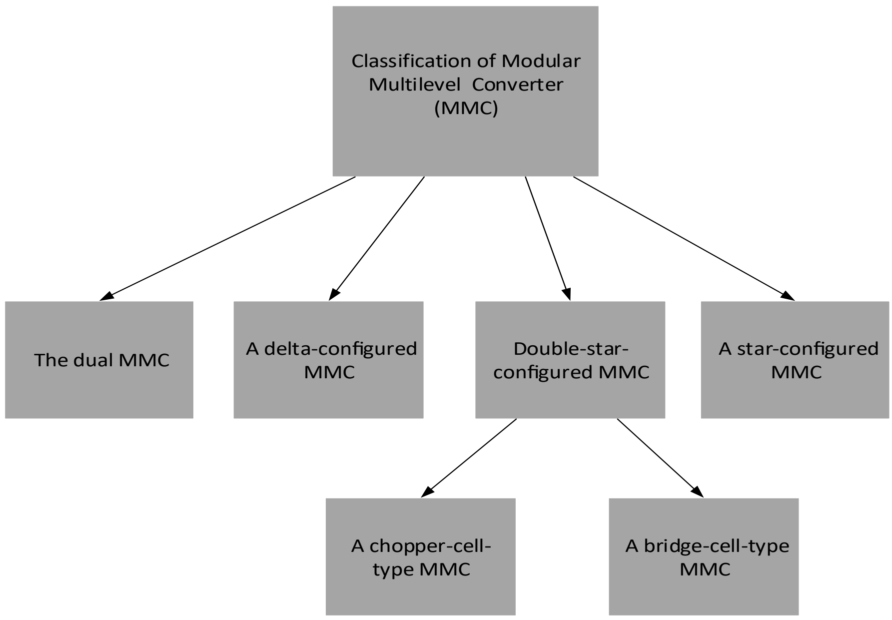


Figure 3.13 Topologies of MMC [21].

The star-configured MMC topology and the delta-configured MMC topology are not suitable and efficient for regenerative power sources [40]. Because the star-delta configured MMC does not has the ability to work as inverter, which cannot handle AC-DC-AC power conversion. As shown in Figure 3.14, these two kinds do not own a common DC-link. However, this topology is suitable for STATCOM applications.

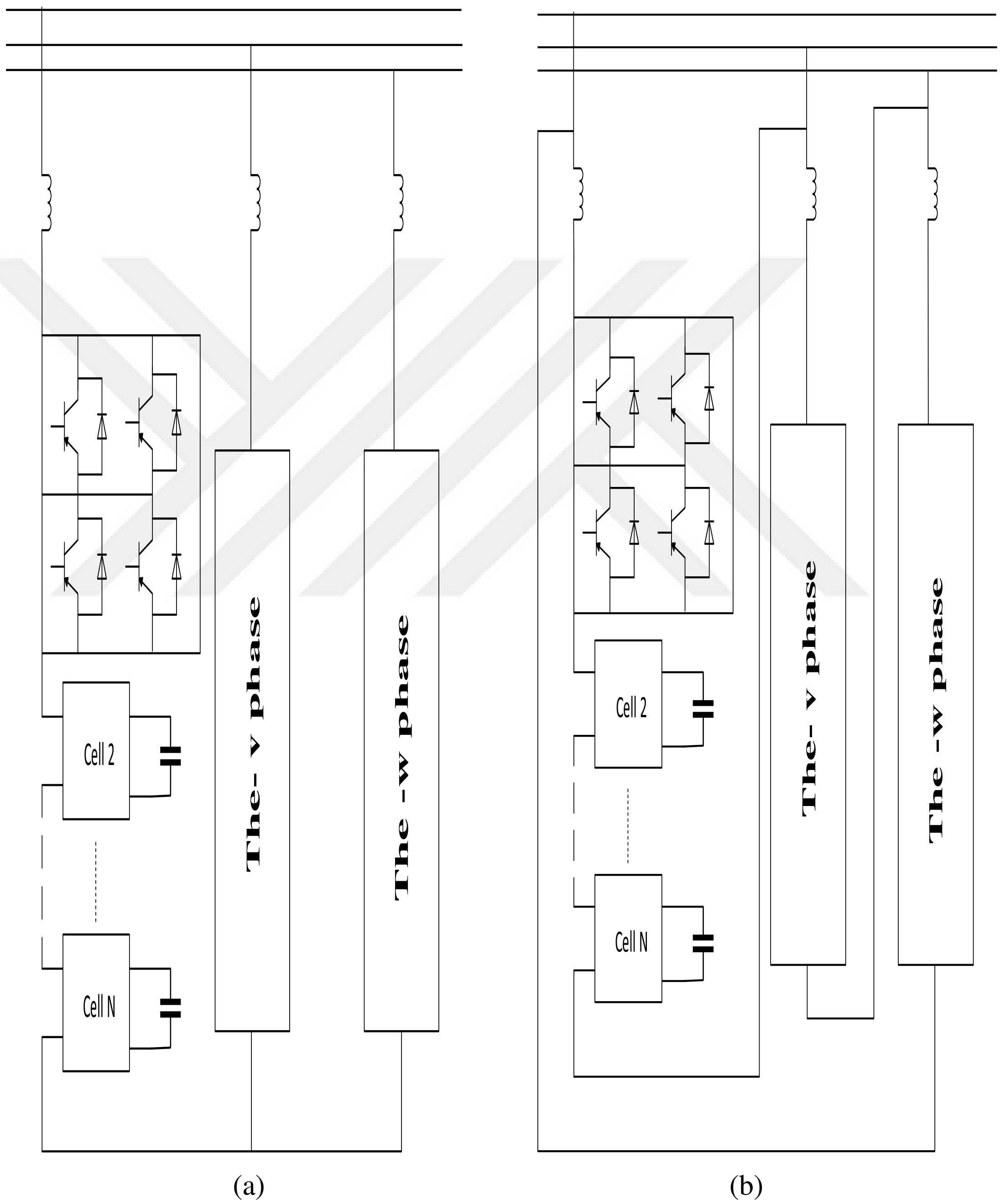


Figure 3.14 Circuit configuration of MMC: (a) Star-configured MMC, and (b) Delta-configured MMC.

In this thesis, the BTB system consists of two MMCs. The first MMC is working as AC-DC converter and the second MMC is working as DC-AC converter. As a result, the double-star-configured MMC topology is the most preferred choice in power conversion [40], [41]. Because the double star has a common DC-link that enables it to function like an inverter enabling AC-DC-AC power conversion as shown in Figure 3.15.
The topology of double-star configured MMC, shown in Figure 3.15, has a common DC-link that enables it to function like an inverter, which enables AC-DC-AC power conversion, as a result the double-star is preferred for regenerative power sources such as wind energy.

In contrast, the star-configured MMC topology and the delta-configured MMC topology are not suitable and efficient for regenerative power sources. Because the star-configured MMC does not have the ability to work as inverter which cannot handle AC-DC-AC power conversion.

3.5.4.2 Structure and Principle Operation of MMC

As shown in Figure 3.15, a three phase star-configured MMC has consists of three legs. Each leg contains an upper and lower arm. The upper arm consists of four sub-modules (SM). These SM are connected in series with one buffer inductor. The lower arm is the same as upper one as shown in Figure 3.15. The aim of using two non-coupled buffer inductor is to deal with the voltage difference between the upper and lower arm of the converter and limit the current when fault such as short circuit occurs.

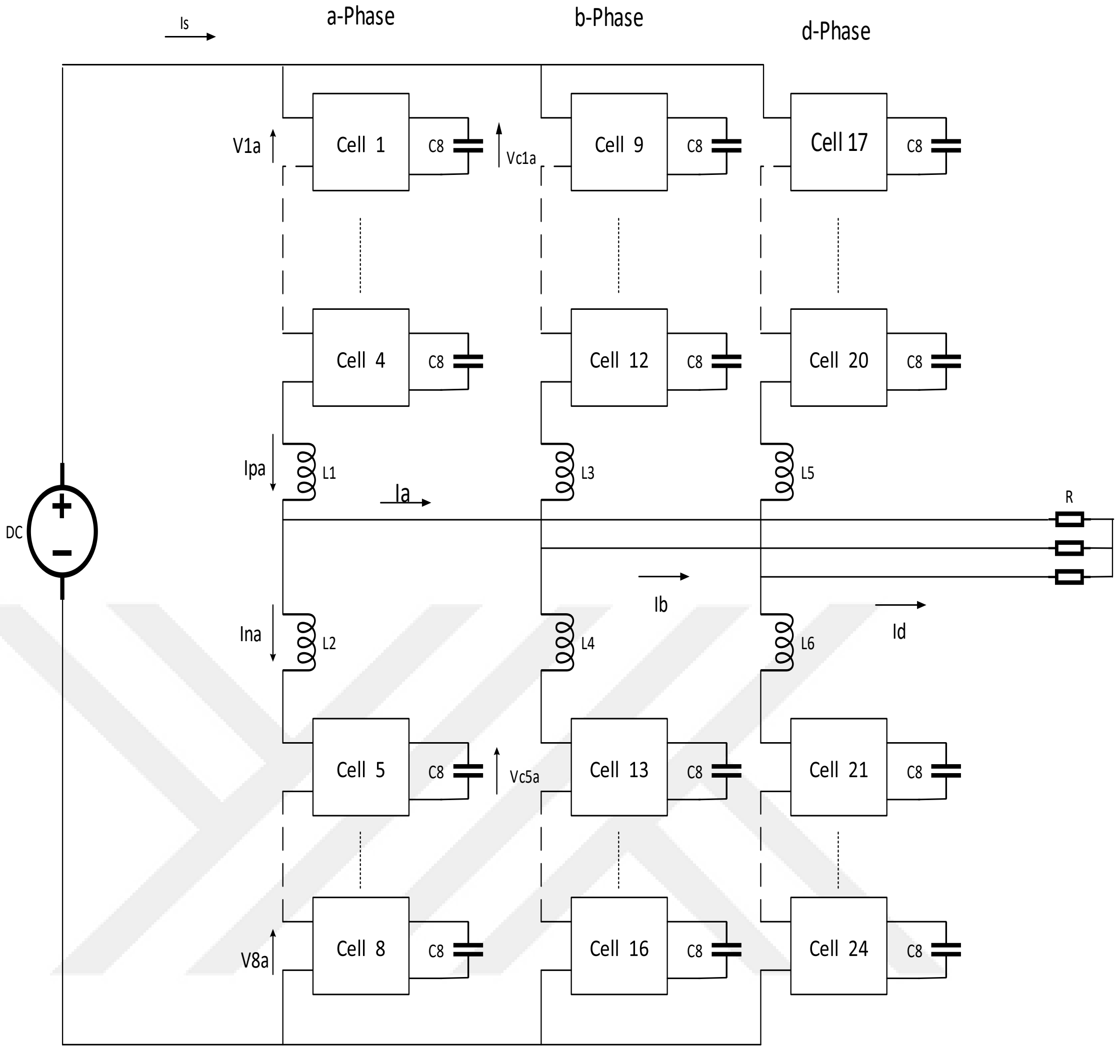


Figure 3.15 Three-phase double-star-configured MMC.

The SMs are divided into five types and they are as follows: (1) The half-bridge (HB) circuit, (2) The full-bridge (FB) circuit, (3) The clamp double diode (CDD) circuit, (4) The three-level converter (TC) circuit, (5) The five-level converter (FC) circuit.

- **Full Bridge Circuit**

Since the full bridge (FB) circuit (bridge cell) consists of four switches, the working principle of FB circuit builds on these four switches. As shown in Figure 3.16(a), if the state of switches is bypass state, the output voltage is zero. The FB circuit has twice the number of switches compared to the HB circuit. Thus, the losses and the cost of this circuit are larger [36].

- **Clamp Double Diode Circuit**

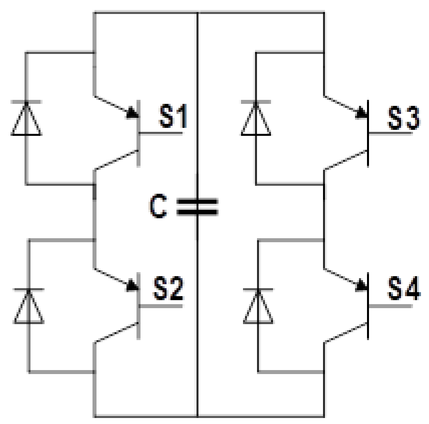
As shown in Figure 3.16(b), the clamp double diode circuit has more components compared to HB and FB. The structure of this circuit consists of: (1) two diodes, (2) two HBs, and (3) insulated gate bipolar transistor (IGBT). The losses of this circuit are greater than the HB, and the losses of (FB) circuit are greater than [43]. The clamp double diode circuit is working like two HBs.

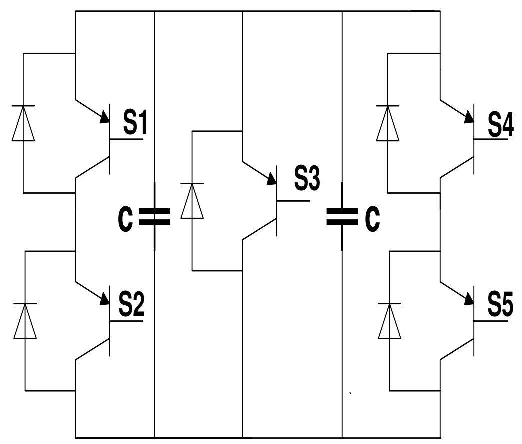
- **Three-Level Converter Circuit**

Figure 3.136(c) and (d) show the structure of three-level converter circuit. As shown in Figures 3.16(c) and (d), it consists of three-level FC or three-level NPC configuration. When three-level flying capacitor is compared to HB, the result is that both circuits have same semiconductor losses. In other hand, the HB has lower semiconductor loses when compared to three-level NPC configuration [44], [45].

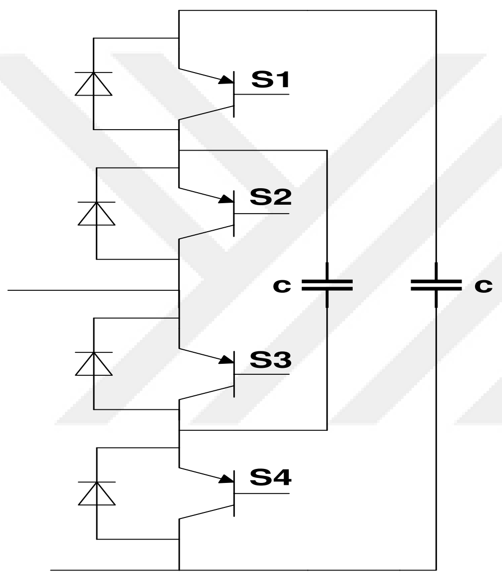
- **Five-Level Converter Circuit**

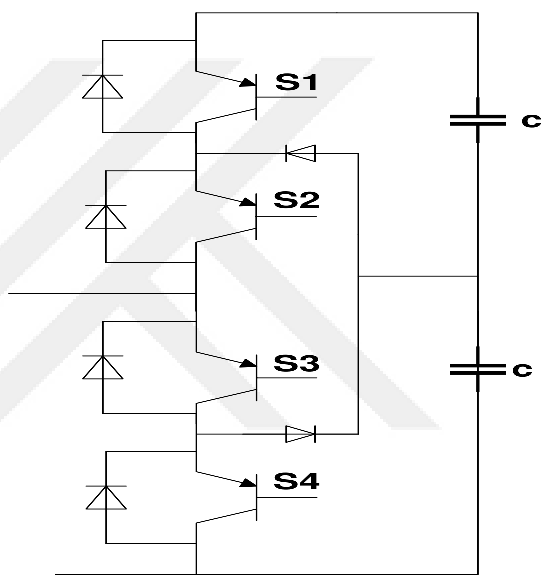
This circuit is similar to three-level converter circuit. As shown in Figure 3.16(e), its structure also contains two HBs and two IGBTs. The five-level converter circuit has more components when compared to other circuits. As a result, the losses of its semiconductors are lower than HB circuit. This circuit has the same losses of clamp double diode circuit [46].



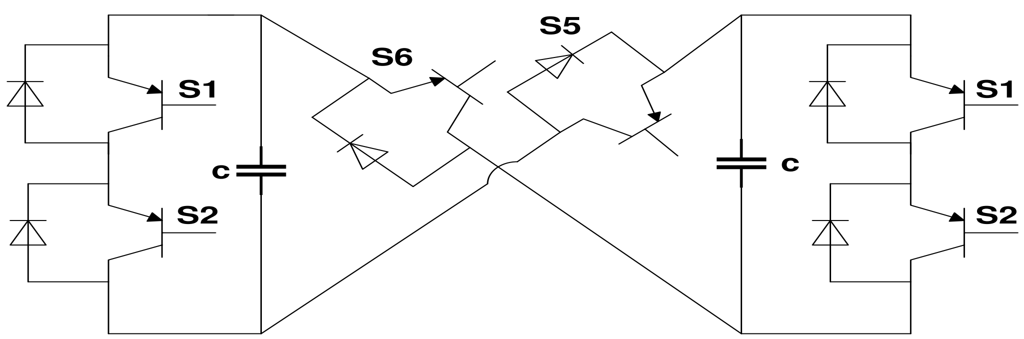


(a) (b)





(c) (d)



(e)

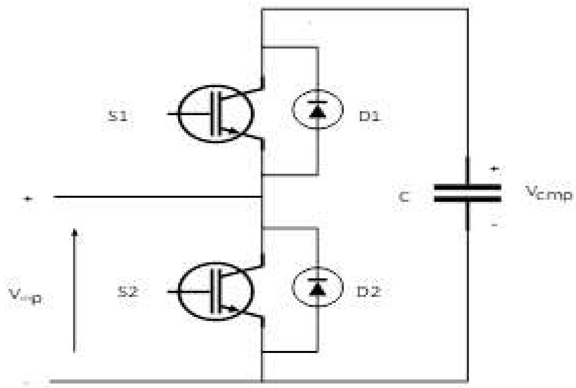
Figure 3.16 Types of SM of MMC: (a) FB circuit, (b) CDD circuit, (c) Three-level flying capacitor, (d) Three-level neutral-point clamped, and (e) Five-level converter circuit.

- **Half-Bridge Circuit**

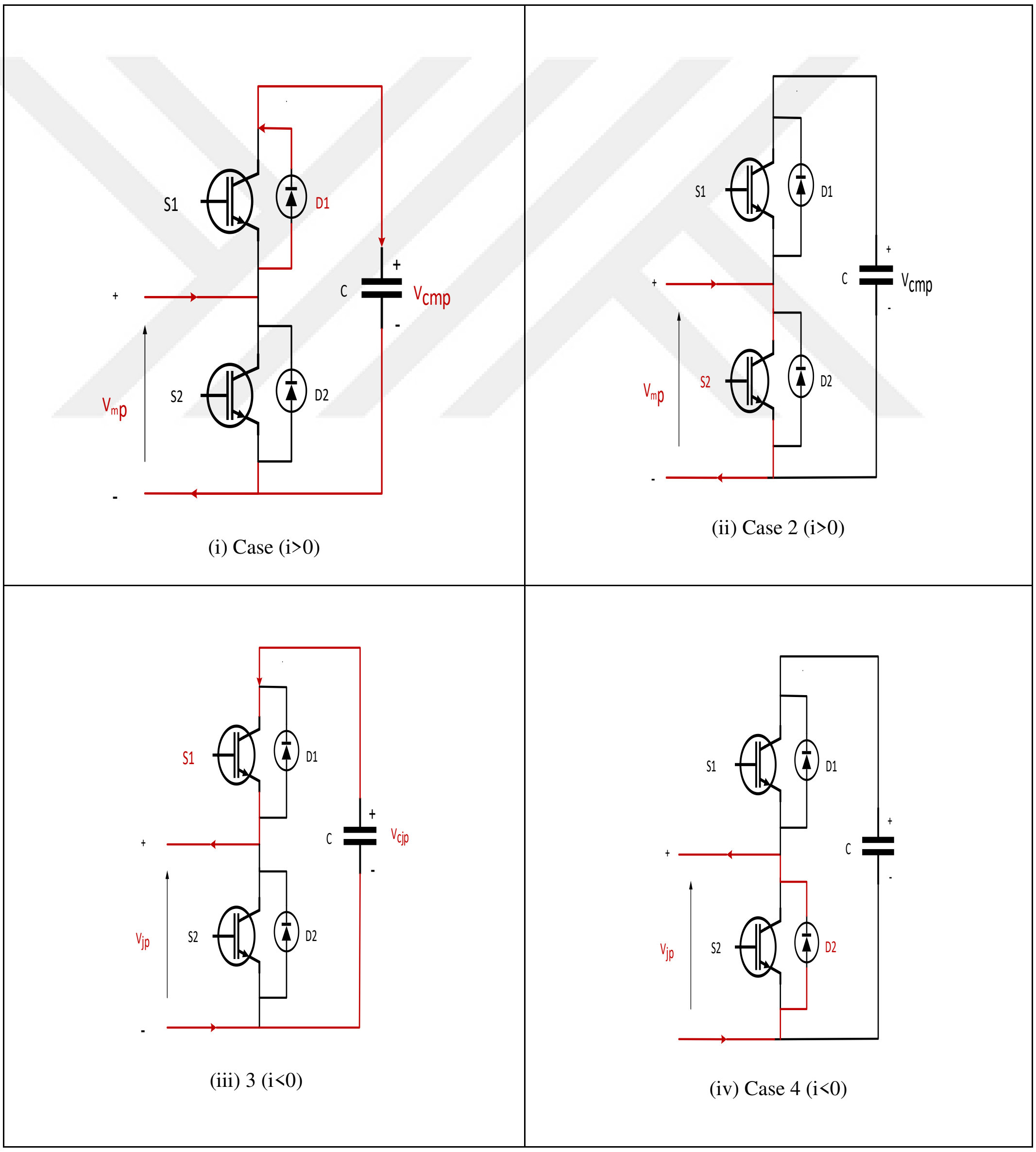
The half-bridge (HB) circuit is also called chopper cells circuit. The chopper cell has been considered as the most one that is preferred and suitable for MMC compared to other SM circuit. In HB circuit, there is no DC-side short circuit fault handling capability, it has lower losses, and HB has only two IGBT switches and one floating DC capacitor [50]. This thesis deals with HB circuit due to the advantages that are mentioned before. The structure of HB circuit is shown in Figure 3.17(a). The working principle of each SM will be on four cases as shown in the Table 3.4. The first and second cases are when the current is positive (i>0). The first case is when the switch (S1) is ON and the switch (S2) is OFF, as shown in Figure 3.17(b) (i), the current passing will be through (D1) to the capacitor. In this case, the capacitor charges and this case is called (inserted or switched ON).The second case is when the switch (S1) is OFF and the switch (S2) is ON, the current passing will be through (S2) in Figure 3.17(b) (ii), in this case the capacitor is unchanged and this case is called (bypassed or switched OFF). The third and fourth cases are when the current is negative (i<0), the third case is when the switch (S1) is ON and switch (S2) is OFF, the current passing will be through capacitor as shown in Figure 3.17(b)(iii), in this case the capacitor discharges and this case is called (inserted). The fourth case is when the switch (S1) is OFF and the switch (S2) is ON, in Figure 3.17(b) (iv) the current passing will be through (D2), capacitor is unchanged (bypassed or switched OFF).

Table 3.4 Capacitor cases

Current direction i>0 or i<0	**SM case**	**Capacitor case**
Positive i>0	ON	Charge
Negative i<0	OFF	Bypass
Positive i>0	OFF	Bypass
Negative i<0	ON	Discharge



(a)



(b)

Figure 3.17 (a) HB circuit, (b) Switching states of SM.

3.6 Modulation Technique

Each SM in MMC has a capacitor voltage, as a result, the control in MMC must be designed for balancing capacitor voltage. Many modulation techniques are used for MMC [41]. The principle of traditional PWM is to use carrier waveform with the reference waveform and compared each other in order to generate the required output signal [41], [42]. The comparison between two waveforms is realized according to the carrier waveform. If the reference waveform is higher than carrier waveform, the output is logic one or high and if the reference is lower than the carrier waveform the output signal is logic zero or low. Figure 3.18 shows the various PWM techniques that are used for MMC.

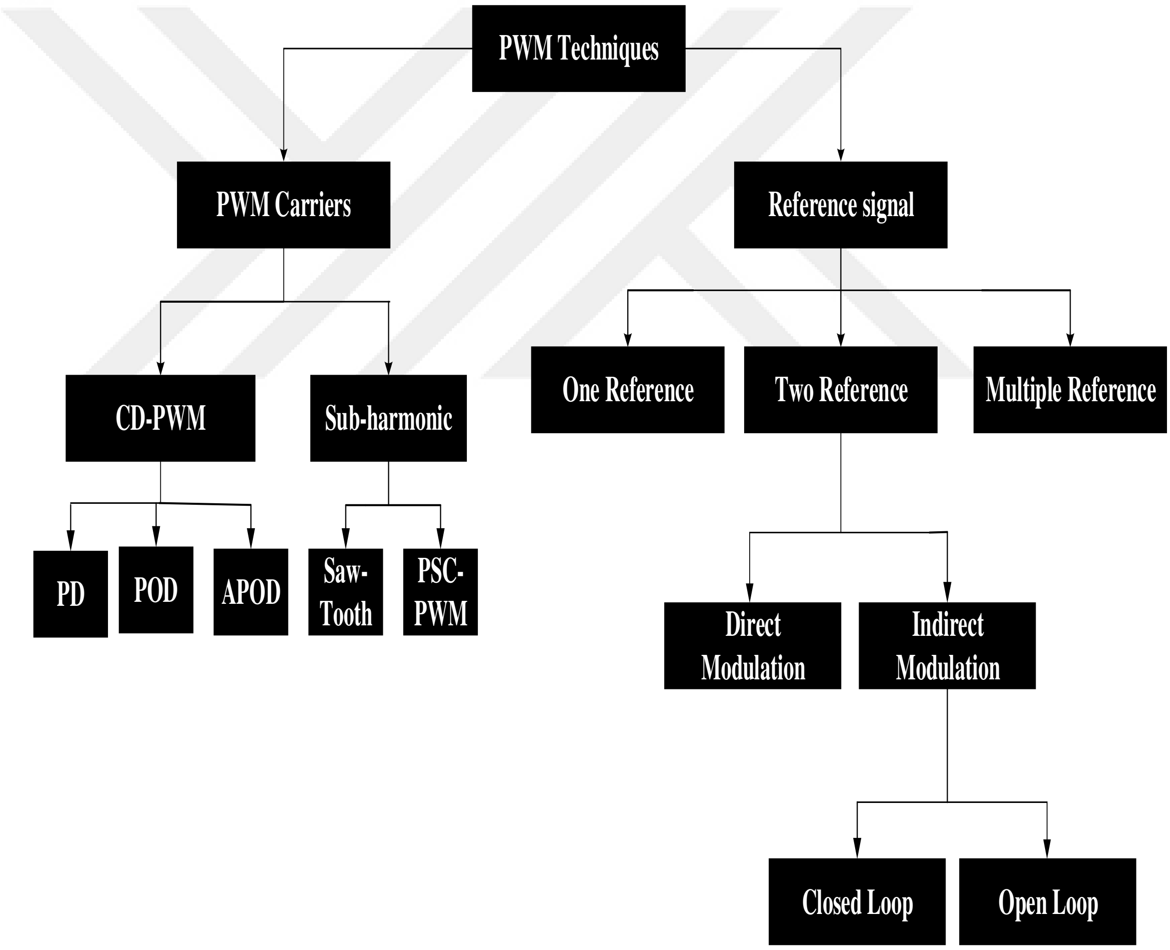
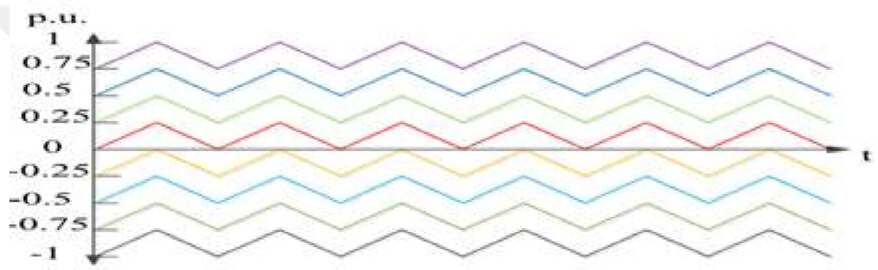


Figure 3.18 An overview of various PWM techniques for MMC [32].

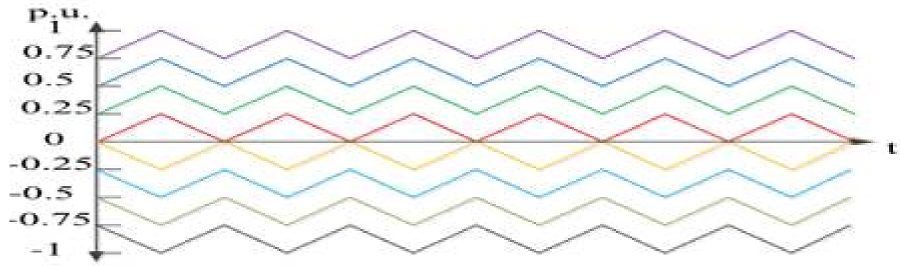
As shown in Figure 3.18, the modulation techniques that are based on PWM carriers are divided into two types:

3.6.1 Carrier Disposition PWM Technique (CD-PWM)

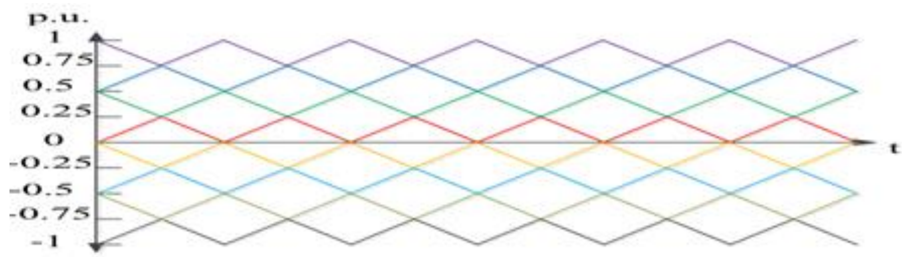
The CD-PWM needs N comparable triangular carrier waveforms. The working principle of this type is as follows: The carriers are compared with phase voltage reference for producing the required output signal [38], [49]. CD-PWM is divided into phase disposition (PD), phase opposition disposition (POD), and alternate phase opposition disposition (APOD). These techniques are shown in Figure 3.19 consecutively. These techniques have a drawback. The circulating current is larger compared to other techniques and the AC-side of converter suffers an effect in the harmonic and the voltage ripples in through the cells are distributed in not an equal way [38], [49].



(a)



(b)

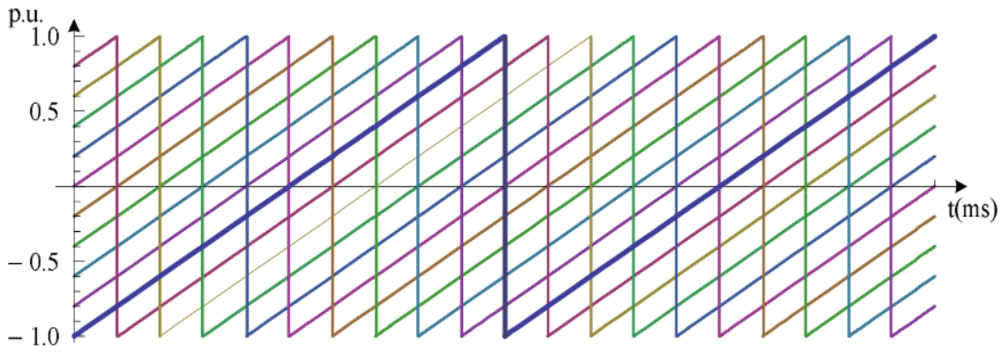


(c)

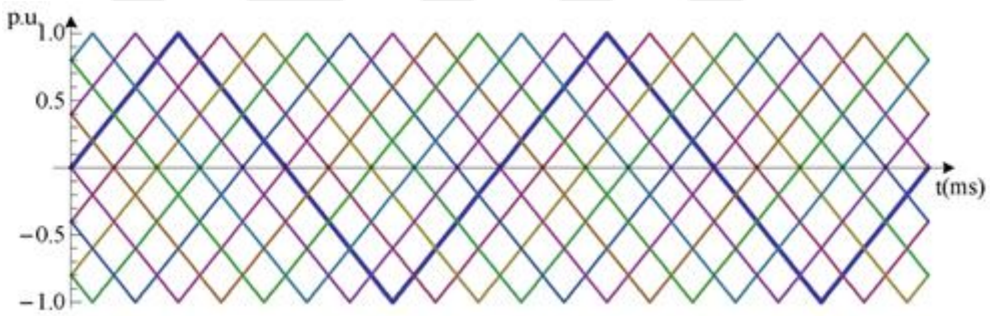
Figure 3.19 Multilevel carriers CD-PWM (a) PD technique [32] (b) POD technique [32], and (c) APOD technique [32].

3.6.2 Sub Harmonic PWM

As shown in Figure 3.20, the carrier waveforms in this technique should be triangular or sawtooth [50]. As a result, each leg of the converter in this technique requires $2N$ similar carrier. In [38], sub harmonic PWM technique has been proposed.



(a)



(b)

Figure 3.20 Multilevel carriers sub harmonic PWM (a) sawtooth carrier [50], and (b) phase shifted carrier [50].

3.6.3 Direct Modulation

As shown in Equation (3.2) and (3.3), there are two sinusoidal voltage references, which are required in this technique. The purpose of these voltage references is for controlling the arm voltages in the converter [38].

$$V_{p,ref,u} = \frac{V_{dc}}{2} [1 - \text{m} \cos(w_N t)] \tag{3.2}$$

$$V_{n,ref,u} = \frac{V_{dc}}{2} [1 + \text{m} \cos(w_N t)] \tag{3.3}$$

where m is the modulation index. The working principle this technique is as follows: The comparison is done between the carrier and the reference waveforms and this comparison produces the output voltage. Whereas, the number of cells that are inserted in both arms should be integral. As a result, the level of output voltage becomes $2N + 1$, where N is the number of inserted cell in the arm. If the carrier waveform that is used for upper and lower arm is the same carrier, the level of output voltage is $2N + 1$. Figure 3.21 shows the control scheme of direction modulation technique.

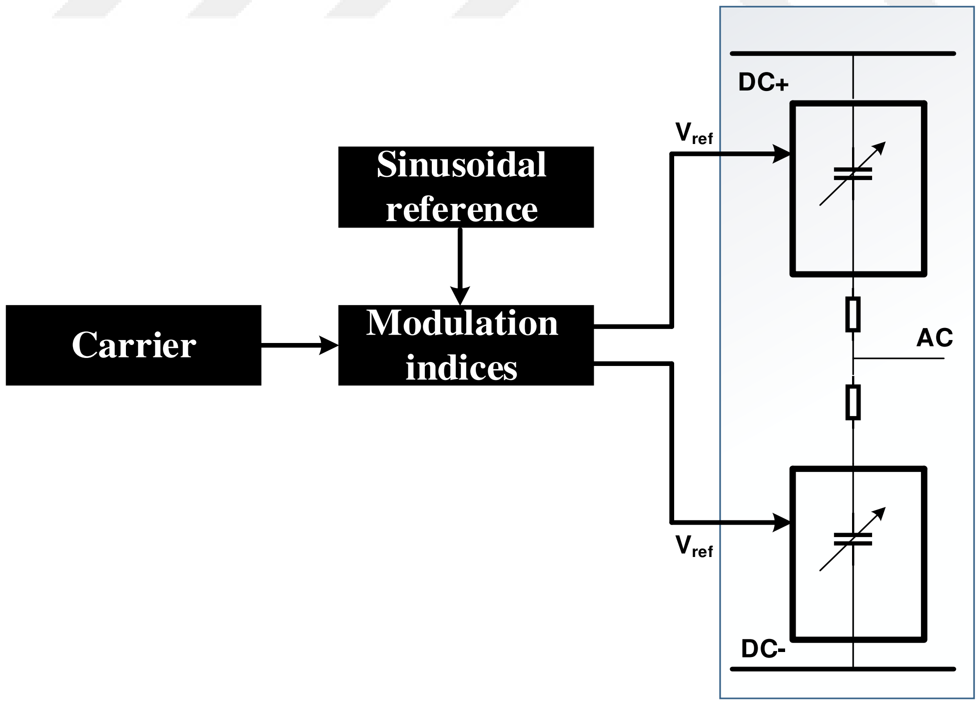


Figure 3.21 Direct modulation scheme.

3.6.4 Indirect Modulation

The working principle of this technique is not different from direct modulation. In this technique, an extra controller is necessary for the stability of the system [38]. The reference waveforms of arms are given by:

$$V_{p,ref,u} = \text{N} \frac{\frac{V_{dc}}{2} - v_{ref,u} \ \Sigma v_{ref,u} \ Circ_{v_{ref,u}}}{\sum_{i=0}^{N} v_{cp,i,u}} \tag{3.4}$$

$$V_{n,ref,u} = \text{N} \frac{\frac{V_{dc}}{2} - v_{ref,u} \ \Sigma v_{ref,u} \ Circ_{v_{ref,u}}}{\sum_{i=0}^{N} v_{cn,i,u}} \tag{3.5}$$

where i is the number of cell, and u is the first phase voltage in converter. Thus, $v_{cn,i,u}$ is a voltage of capacitors in each cell of lower arm, $v_{cp,i,u}$ is a voltage of capacitors in each cell of upper arm [38]. This technique is divided into two types:

3.6.4.1 Open Loop Control

In the working principle of this technique, the $\sum v_{ref,u}$ is evaluated to be equal to zero. The $Circ_{v_{ref,u}}$ is evaluated to reduce the harmonic of circulating current of the converter. In other words, it is evaluated to remove the harmonic completely [38], [51]. The major disadvantage of this technique is the delicate rating of the real parameters necessary to represent the dynamics of the system. Additional to that, the features of open loop control technique is a robust and simple technique, and there is no voltage sensor. Figure 3.22 shows the scheme of open loop control for capacitor voltages.

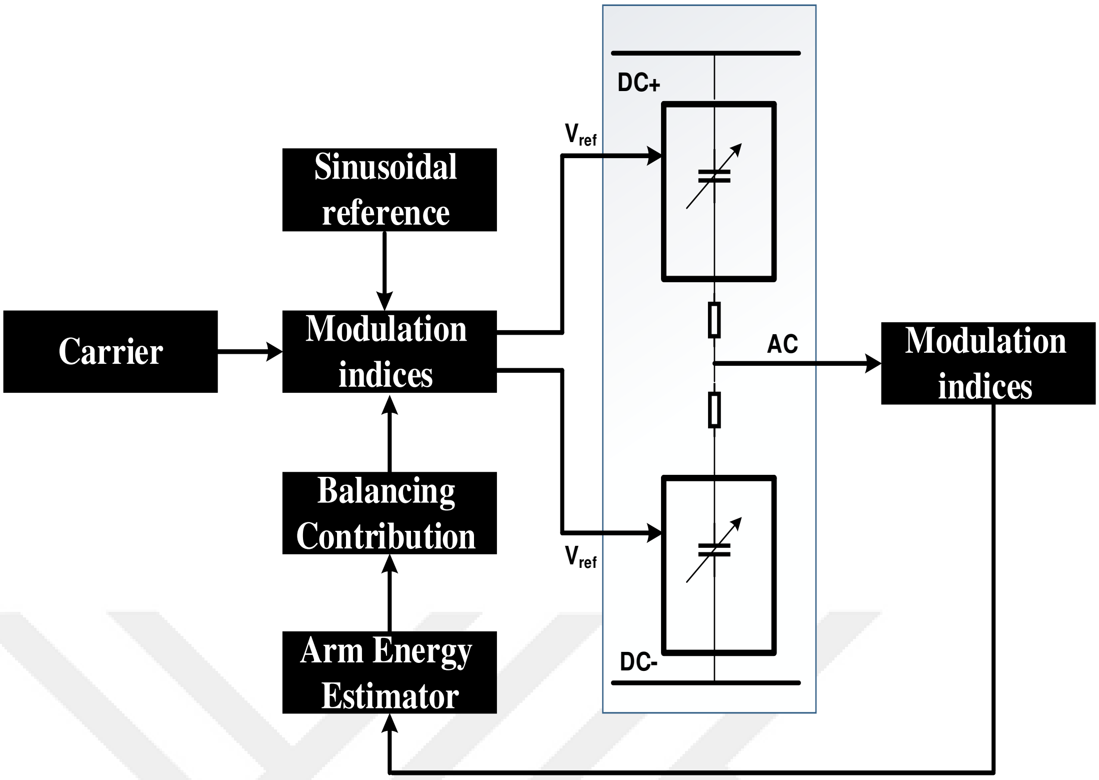


Figure 3.22 Open-loop control of the capacitor voltages for indirection modulation.

3.6.4.2 Closed-Loop Control

In this technique, the $\sum_{i=0}^{N} v_{cp,i,u}$ and $\sum_{i=0}^{N} v_{cn,i,u}$ are determined according to the real measured capacitor voltages [38], [51]. The $\sum v_{ref,u}$ is determined due to the closed-loop control of the entire energy saved in the capacitor of arms. Figure 3.23 shows the closed-loop control of the capacitor voltages. The benefits of this technique include that it is able to work with a high level of voltages under low output voltages [38]. In addition, this technique is able to achieve the control unit that is required for balancing of voltage between the arms in the three-phase of the converter.

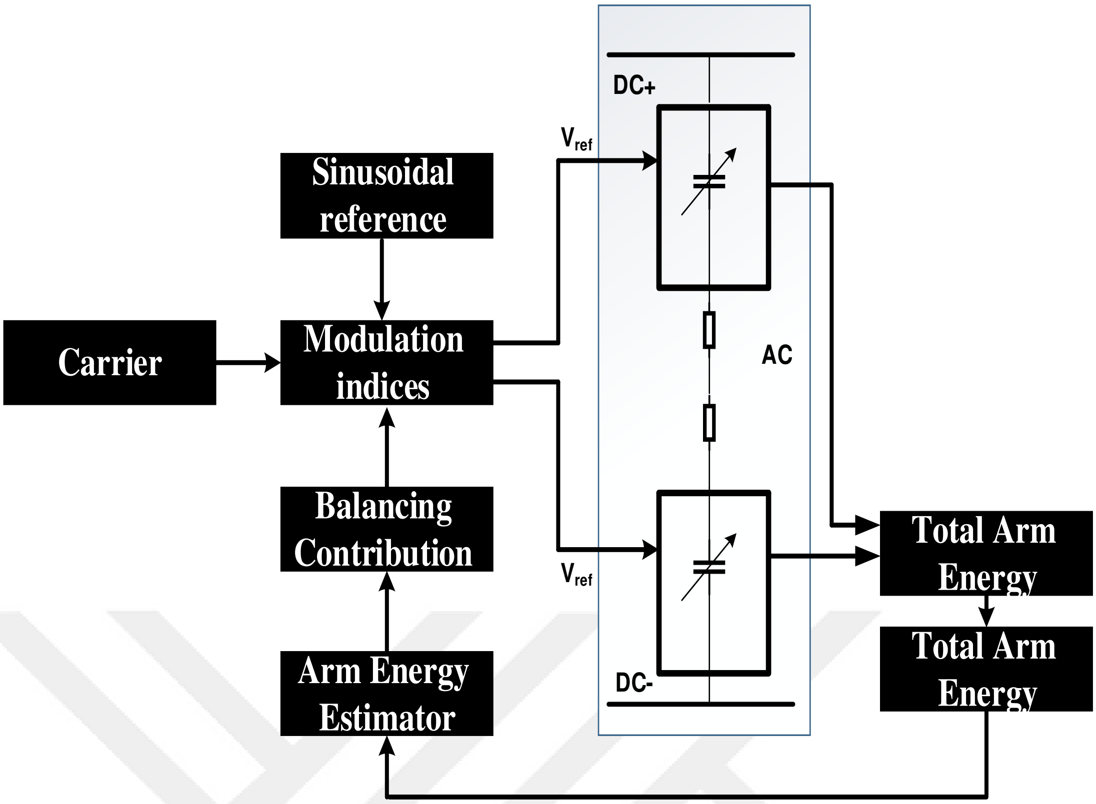


Figure 3.23 Closed-loop control scheme for indirection modulation.

Table 3.5 Comparison of modulation techniques

Property	**Modified PD-PWM**	**Direct Modulation**	**Indirect Modulation**	**PCS-PWM**
Number of reference waveforms	1	1	1	2N
Additional controllers required for stability	No	No	Yes	Yes
Presence of circulating current	Yes	Yes	No	No
Implementation effort	Moderate	Moderate	Low(open-loop) Moderate (closed-loop)	High as N

3.6.5 Phase-Shifted Carrier PWM Technique (PSC-PWM)

PSC-PWM has been considered in this work due to its attractive attributes such as:

1. Capacitor voltage balancing is easy to apply,
2. Switching frequency in each SM is equally distributed [38],
3. Low harmonic distortion at the MMC output,
4. Lower semiconductor losses [52].

In Chapter 4, the PSC-PWM technique is explained and examined in detail. In [53], [54], the techniques that are based on the fundamental frequency has been introduced briefly.

CHAPTER 4

MMC PMSG BASED WECS MODELING AND SIMULATION

4.1 Introduction

In this chapter, the modeling of MMC PMSG based WECS is proposed. This chapter also proposes the control strategy for three-phase BTB MMC with four SMs in upper arm and four SMs in lower arm. The control strategy that has been proposed in this chapter includes the modulation technique for BTB-MMC. The control of three-phase BTB-MMC with the method of capacitor voltage balancing issue is also proposed in this chapter.

4.2 System Design Method

The designed BTB-MMC topology is shown in Figure 4.1. It is a three-phase double-star configured MMC and consists of two MMCs, which are connected as BTB. Each MMC has three legs and each leg contains an upper arm and a lower arm [19], [35], [54]. In the proposed design, four SMs are connected in series. The aim of using two non-coupled buffer inductor is to deal with the voltage difference between the upper and lower arm of the converter and limit the current when fault occurs in a short circuit. The first MMC works as an AC-DC converter and its AC side is connected to the output of the PMSG. PSC-PWM method is used to trigger power semiconductors in each SM of MMCs.

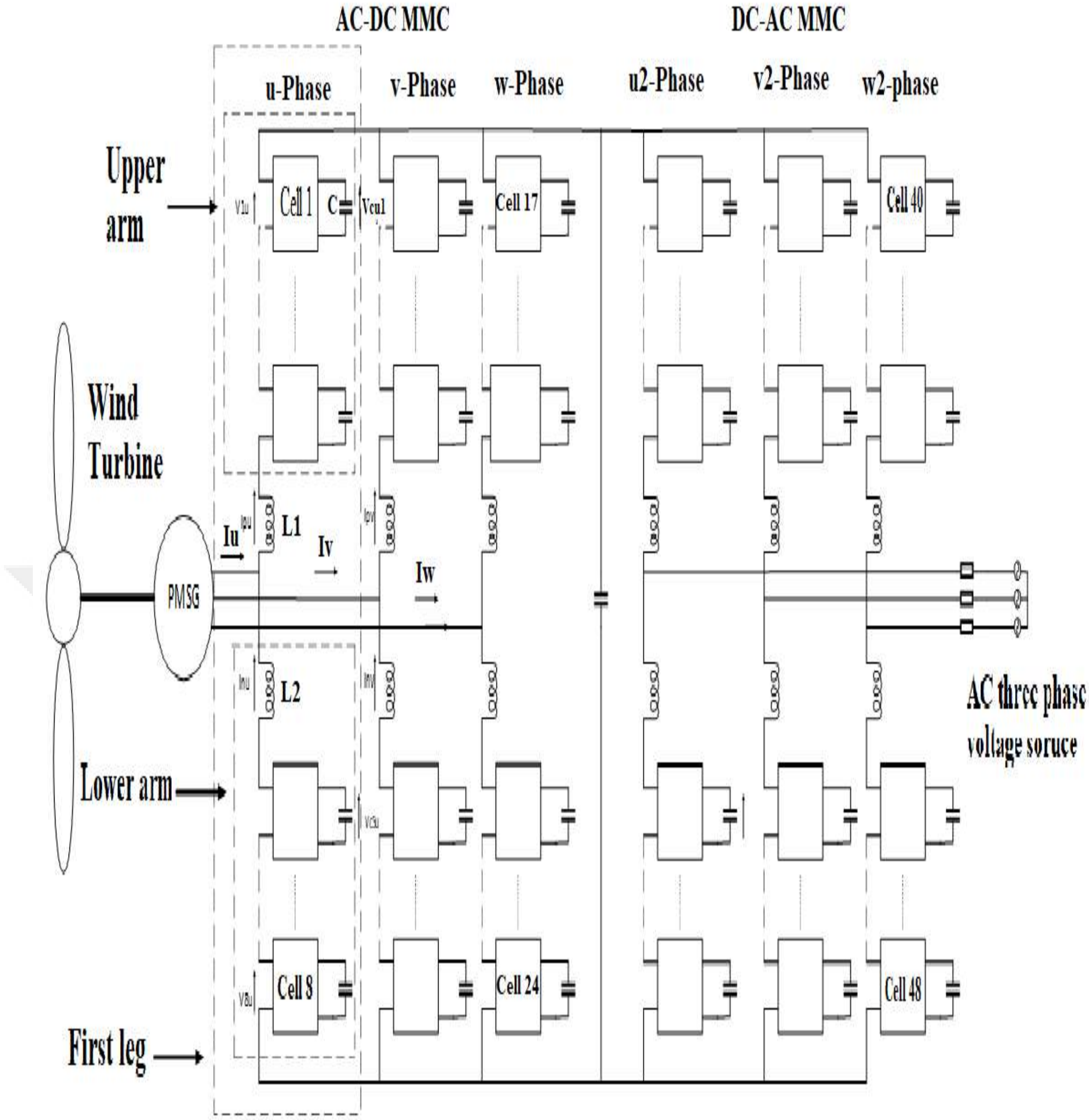


Figure 4.1 BTB-MMC based PMSG WECS.

The second MMC works as DC-AC converter and its AC side is coupled to the AC three-phase grid. The DC sides of each MMC are connected to each other via a common DC link consisting of a capacitor. The value of capacitor in each in each leg is 2.25 kV according to the number of SMs in each leg. Figure 4.2 shows the simulation model for wind turbine in PSCAD that has been used in the design of system [56]. However, the block is built and ready in the PSCAD program. Figure 4.3 shows the simulation model of the wind turbine which has been connected to the PMSG.

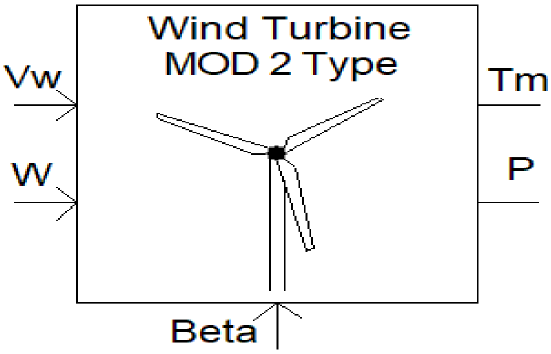


Figure 4.2 Wind turbine model in PSCAD [56].

As shown in Figure 4.2, the type of wind turbine model that is used in this thesis is a MOD 2 model. The equations of this model for modeling the blade dynamics are:

$$\lambda = \frac{w_m R}{V_w} \tag{4.1}$$

$$C_p = (0.44 - 0.0167\beta) sin \frac{\pi(\lambda - 2)}{13 - 0.3\beta} - 0.001845(\lambda - 2)\beta \tag{4.2}$$

$$P_m = 0.5\rho A C_p V_w^3 \tag{4.3}$$

$$T_m = \frac{P_m}{w_M} \tag{4.4}$$

where,

λ = Tip speed ratio

w_M = Angular mechanical speed [m/s]

R = Radius of turbine blade [m]

V_w = Wind speed [m/s]

C_p = Power coefficient [Per unit]

β = Pitch angle of blade [Electric degree]

P_m = Mechanical power for wind turbine blades [kW]

ρ = Air density [Kg/m^3]

T_m = Mechanical torque from wind blades [Nm]

The pitch angle (β), angular mechanical speed (w_M) and wind speed (V_w) are the inputs for wind turbine model [56]. The mechanical torque (T_m), and mechanical power (P_m) are the outputs from wind turbine block. The wind turbine is outputting a mechanical torque in order to run the PMSG as shown in Figure 4.3. The mechanical torque (T_m) is delivered to the PMSG which converts mechanical power into electrical power.

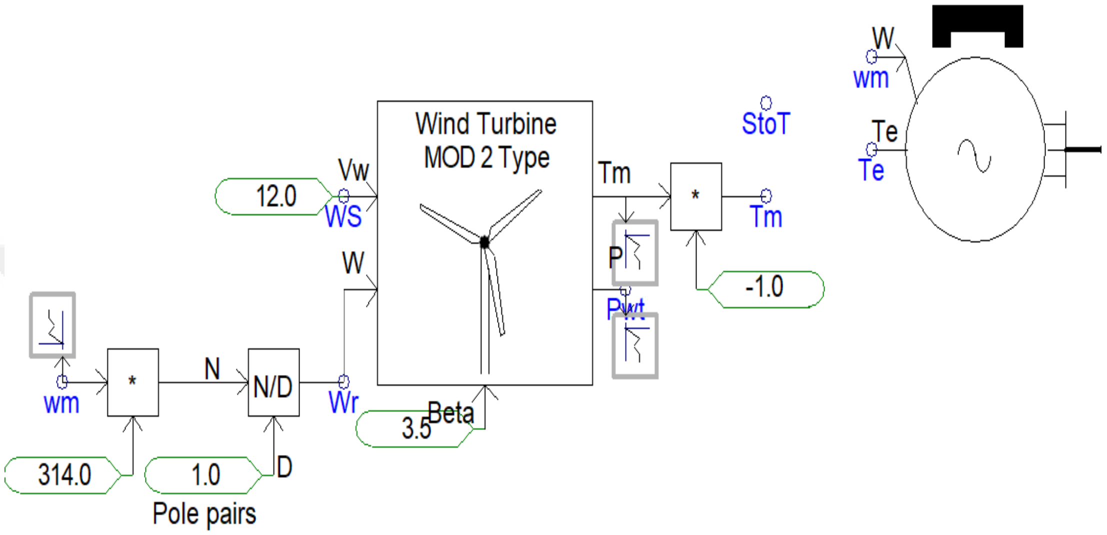


Figure 4.3 PSCAD wind turbine model with PMSG.

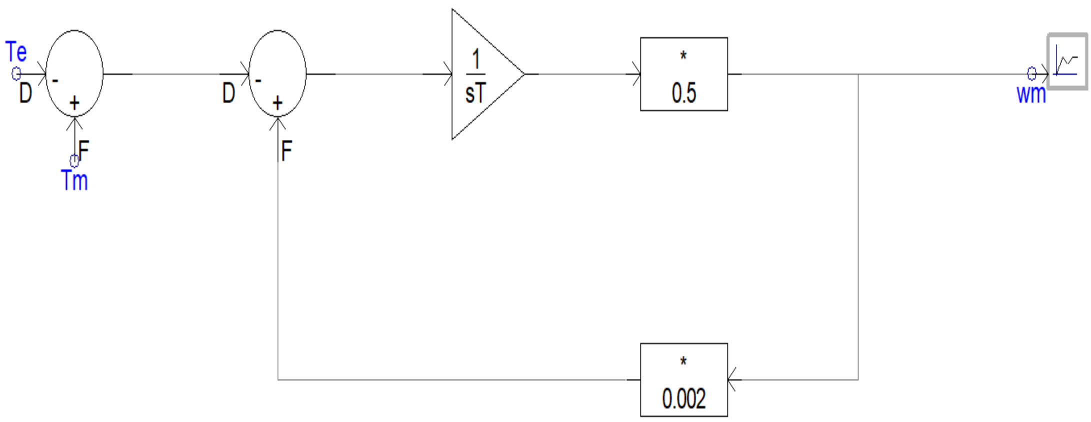


Figure 4.4 Block diagram of torque control.

As shown in Figure 4.3, the wind turbine is connected to the PMSG. Figure 4.4 shows the block diagram of torque control. The working principle of this block diagram is to compare the mechanical torque and the electrical torque (T_e). The "Linear Turbine Model" block is simply an implementation of Equation (4.5) relating net torque to angular acceleration and then integrates acceleration to obtain angular velocity, where

(J) is the moment of inertia. For a large turbine operating with fairly high efficiency, the effects of the rotor inertia are far more important from a modeling perspective than the effects of damping, so damping terms are neglected in this model.

$$W_m = \frac{1}{J}(T_m - T_e) \tag{4.5}$$

4.3 PMSG Based WECS Design

Two MMCs can be connected from their DC link to form a BTB arrangement. Thus, BTB-MMC can be used in a WECS. The MMC near wind generator operates as an AC-DC converter, while the other one is connected to AC three-phase voltage source that represents three-phase grid and operates as a DC-AC converter. By this way, the real power generated by the wind turbine is transferred to the AC grid in a controllable way. The SM or cell is the fundamental building block of an MMC. Each SM can be constructed by a HB that has two power semiconductors (IGBT) and a capacitor [57]. The PMSG based WECS design using a BTB-MMC arrangement in PSCAD is shown in Figure 4.5. Each MMC has three legs and each leg contains an upper and a lower arm [57], [58]. Four SMs or cells are connected in series in each arm. With this design, line-to-line AC voltage of each MMC has $2n + 1 = 17$ levels, where n is the number of cells per arm.

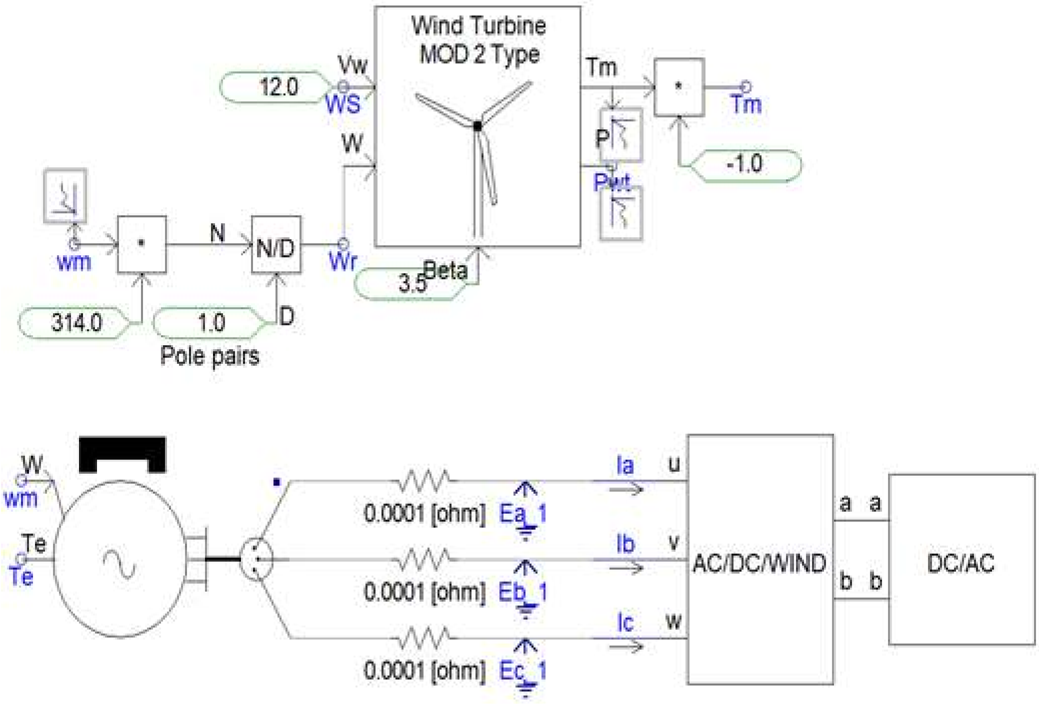
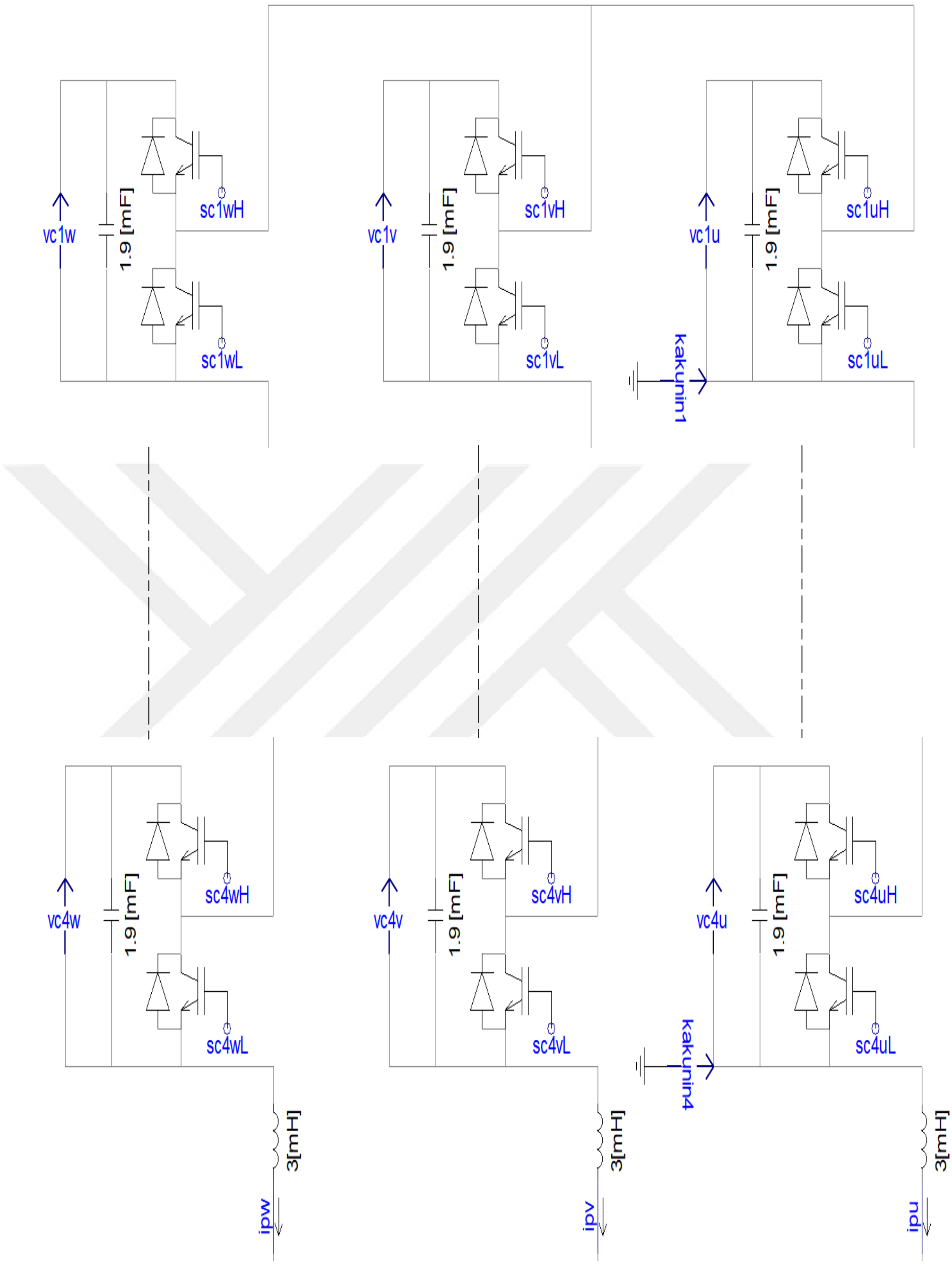
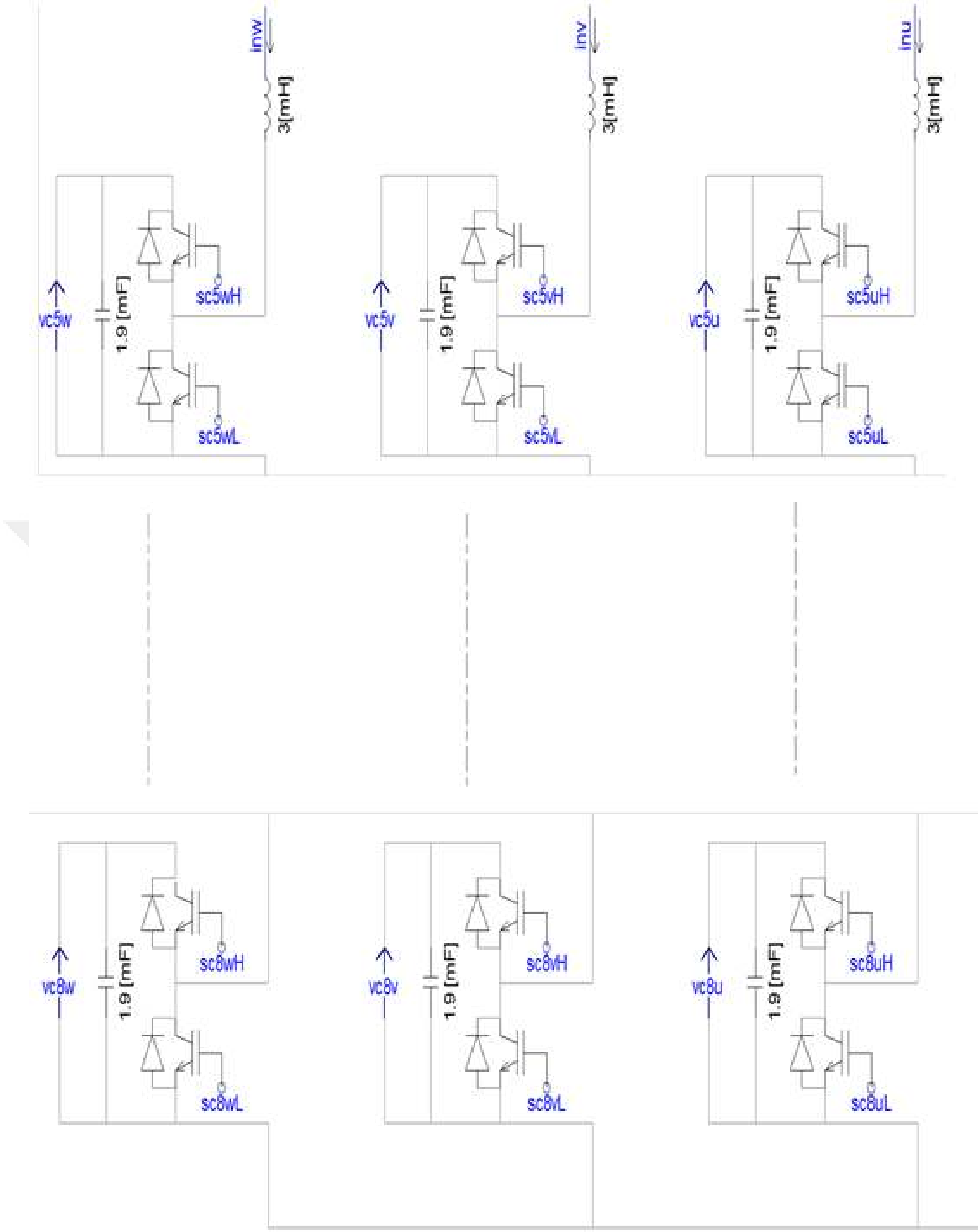


Figure 4.5 PSCAD model of BTB-MMC and PMSG based WECS.

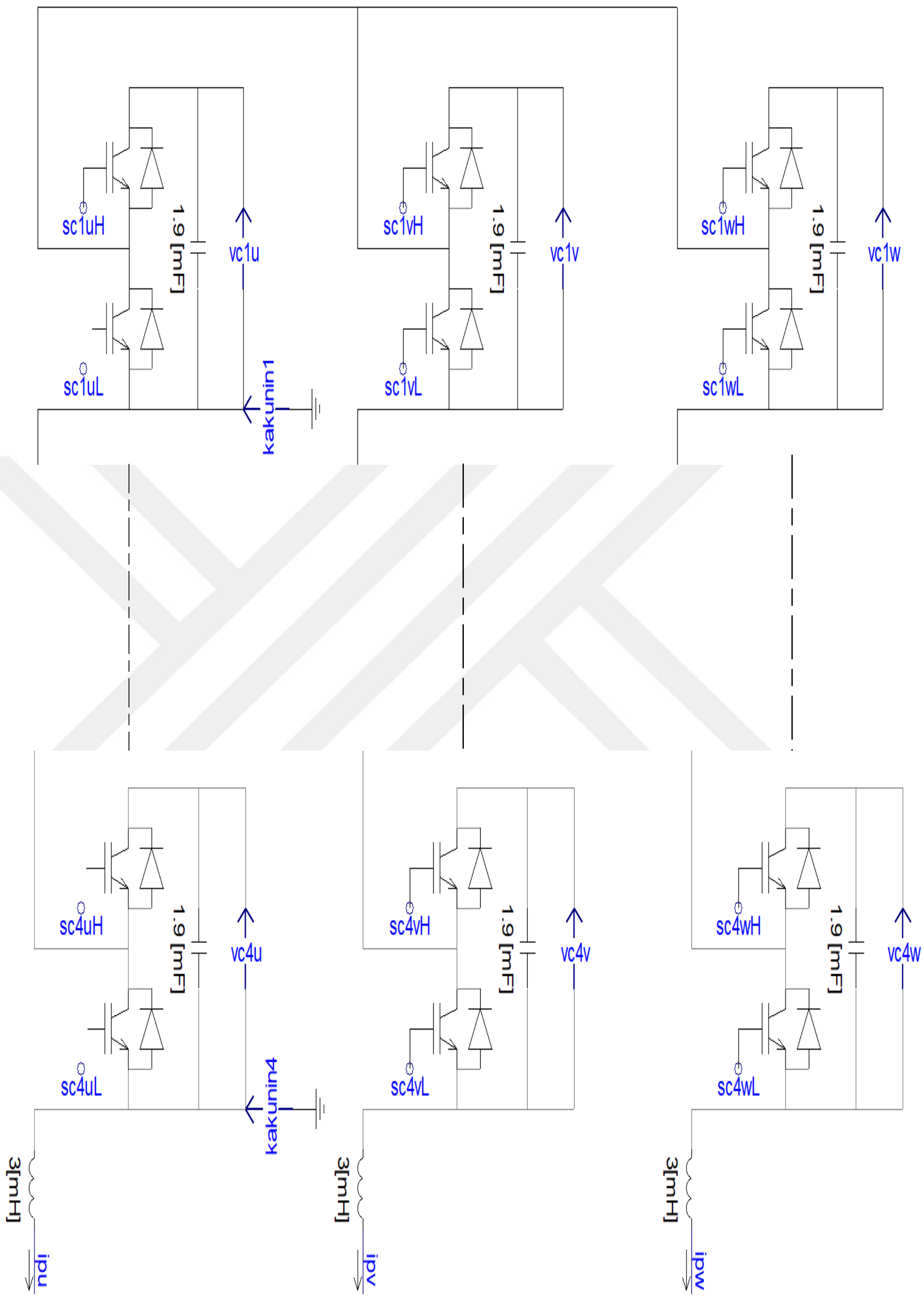

vc1w
1.9 [mF]
sc1wH
sc1wL
vc1v
1.9 [mF]
sc1vH
sc1vL
vc1u
1.9 [mF]
sc1uH
sc1uL
kakunin1
vc4w
1.9 [mF]
sc4wH
sc4wL
vc4v
1.9 [mF]
sc4vH
sc4vL
vc4u
1.9 [mF]
sc4uH
sc4uL
kakunin4
3[mH]
ipw
3[mH]
ipv
3[mH]
ipu

(a)

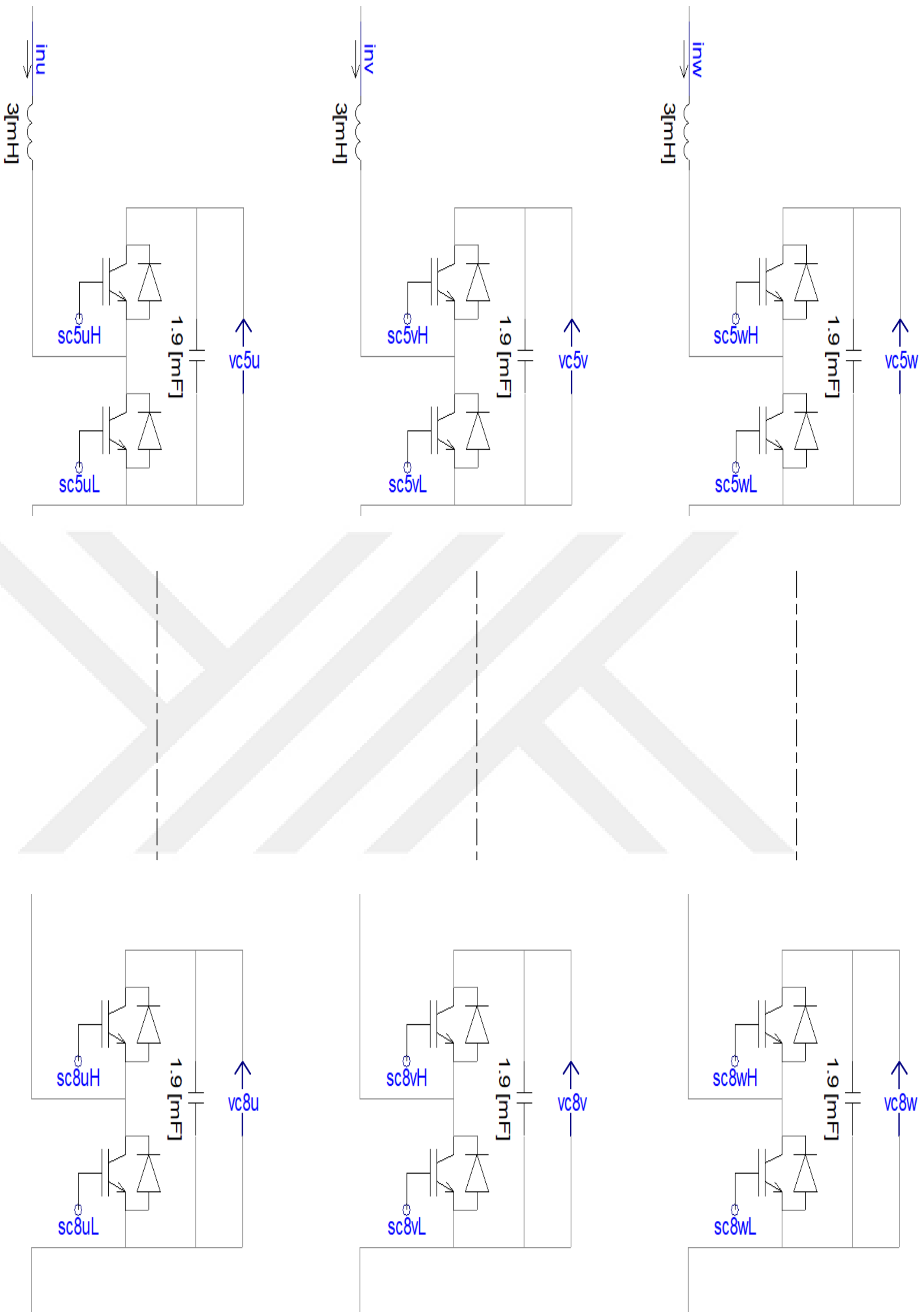


(b)

Figure 4.6 PSCAD model of MMC based AC-DC converter (a) upper arms, and (b) lower arms.


sc1uH
1.9 [mF]
vc1u
sc1uL
kakunin1
sc1vH
1.9 [mF]
vc1v
sc1vL
sc1wH
1.9 [mF]
vc1w
sc1wL
sc4uH
1.9 [mF]
vc4u
sc4uL
kakunin4
sc4vH
1.9 [mF]
vc4v
sc4vL
sc4wH
1.9 [mF]
vc4w
sc4wL
3[mH]
ipu
3[mH]
ipv
3[mH]
ipw

(a)



(b)

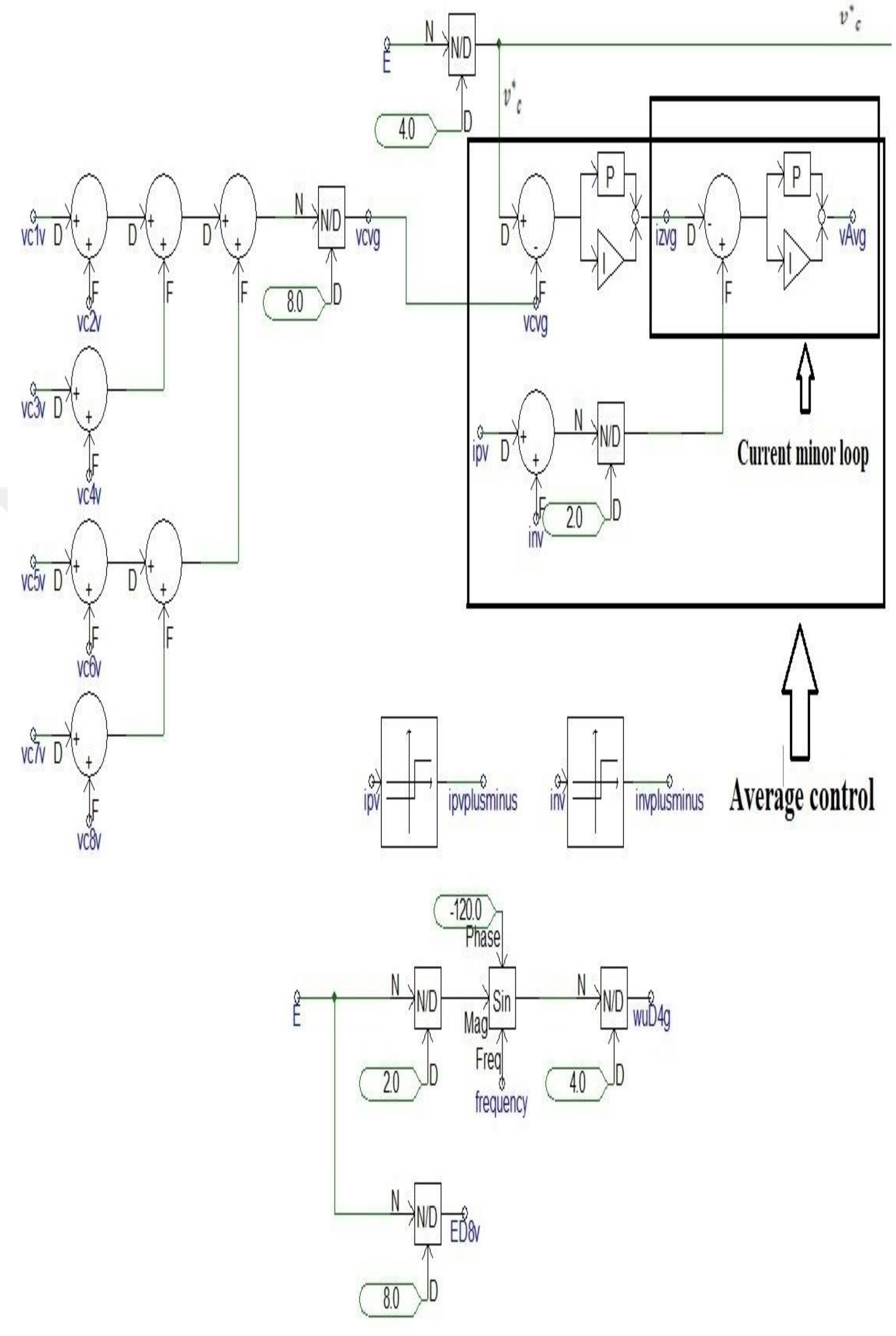
Figure 4.7 PSCAD model of MMC based DC-AC converter (a) upper arms, and (b) lower arms.

4.4 MMC Control Scheme

As shown in Figure 4.1, each SM has a capacitor of 1.9μf. The control design of the MMC must also consider the capacitor voltage balancing problem for proper operation of the BTB-MMC. The working principle of PSC-PWM as follows: If the triangular carrier is higher than the reference waveform, the SM is bypassed, on the other hand, when the triangular carrier is lower than the reference waveform, the SM is inserted. The phase shift between these two waveforms has to be $2\pi/N$, where N is the number of SMs in each arm. The reason here is to make the harmonic generation of the output voltage as low as possible. PSC-PWM technique needs to accomplish two tasks (average control and balancing control) in order to complete its function completely. These tasks depend on the capacitor voltage balancing issue of each MMC.

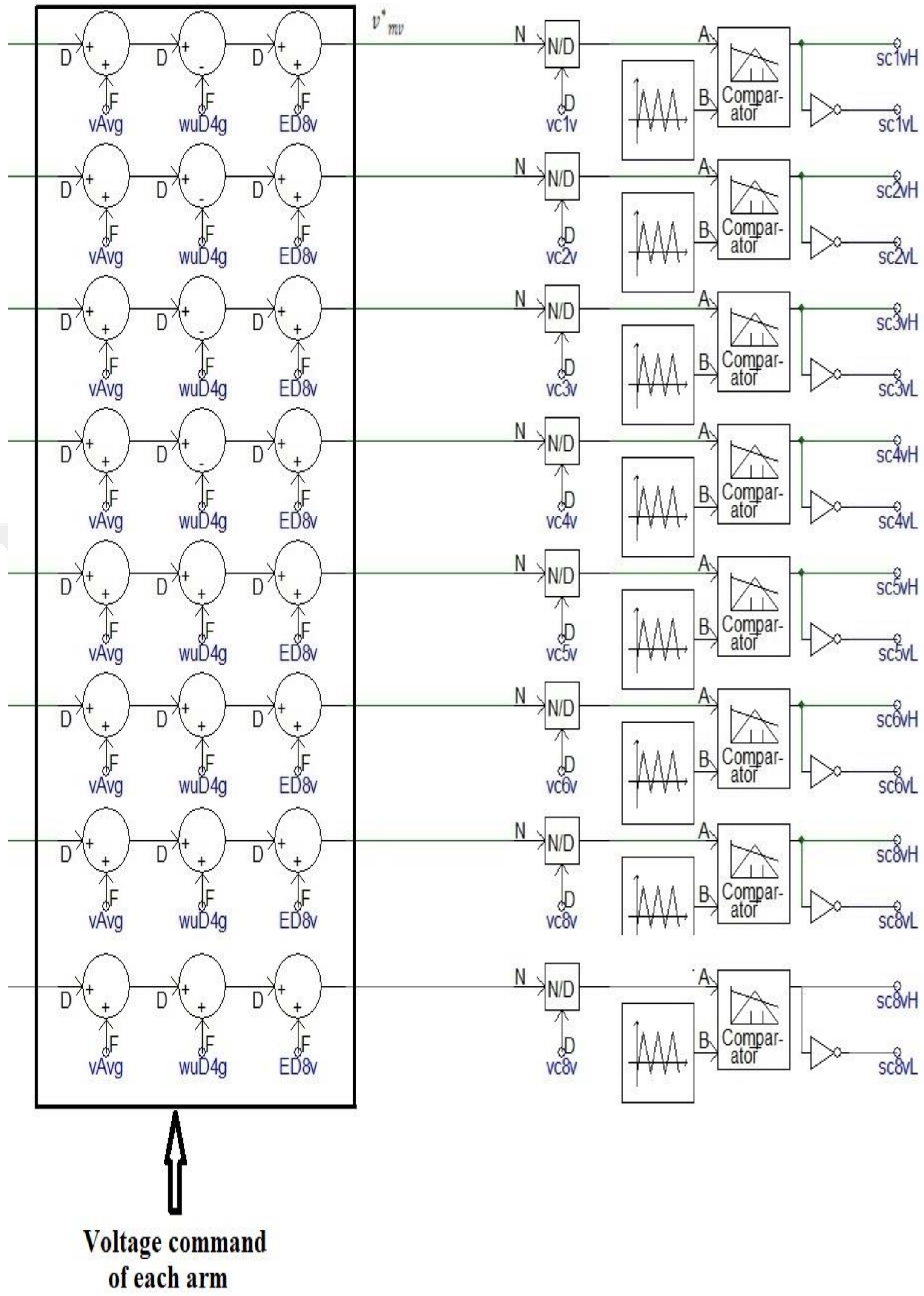
4.4.1 Average Control

The circulating current occurs due to the imbalance of the average capacitor voltages between the phases of the MMC [18], [54]. The circulating current has no influence on the AC or DC side; it only flows through the phases of the MMC. Consequently, the circulating current causes power losses and ripples observed in capacitor voltages of the SMs [19], [38]. The arm inductors shown in Figure 4.1 are designed to lower the circulating current. Figure 4.8 shows the overall control scheme of each MMC, including DC capacitor voltage control and circulating current control for v-phase in AC-DC MMC. The control scheme for other phases is the same.



v*c
N/D
4.0
8.0
vc1v
vc2v
vc3v
vc4v
vc5v
vc6v
vc7v
vc8v
vcvg
izvg
vAvg
P
I
ipv
inv
2.0
Current minor loop
ipvplusminus
invplusminus
Average control
-120.0
Phase
Sin
Mag
Freq
frequency
wuD4g
ED8v

(a)



(b)

Figure 4.8 The control scheme of each MMC (a) capacitor balance control, and (b) pulses control.

Figure 4.8(a) shows the modelling blocks of the averaging control in PSCAD. The v_{cvm} is the DC voltage across capacitor of SMs. The averaging control forces the *v*-phase average voltage v_{cvg} to follow its reference command $v^*{}_c$, where v_{cvg} is given by:

$$v_{cvg} = \frac{1}{8}\sum_{m=1}^{8} v_{cvm} \tag{4.6}$$

As shown in Figure 4.8(a), i_{pv} is a positive current of phase-*v*, and i_{nv} is a negative current of phase-*v*. From the block of the averaging control shown in Figure 4.8, the circulating current i_{zv} can be defined as:

$$i_{zv} = i_{pv} - \frac{i_v}{2} = i_{nv} + \frac{i_v}{2} = \frac{1}{2}(i_{pv} + i_{nv}) \tag{4.7}$$

where i_{zv} is a loop current that is impossible to measure directly [18]. As shown in Figure 4.8(a), the i_{zvg} is the current command of the i_{zv}, and can be defined by

$$i_{zvg} = k_1(v^*{}_c - v_{cvg}) + k_2 \int (v^*{}_c - v_{cvg})dt \tag{4.8}$$

The driving voltage v_{Avg} acquired from the averaging control is shown in Figure 4.8 and given by

$$v_{Avg} = k_3(i_{zv} - i_{zvg}) + k_4 \int (i_{zv} - i_{zvg})dt \tag{4.9}$$

The current minor loop is used to force the actual DC-loop current i_{zv} to follow the i_{zvg}. As result, the feedback control is used for making $v^*{}_c$ which is able to follow its command v_{cvg}. The proportional gain are $k1 = 0.5, k3 = 1.5$ and the integral gains $k2 = 1$, $k4 = 1$.

4.4.2 Balancing Control

Figure 4.8(a) also shows the balancing control block for phase−v in AC-DC MMC. The balancing control is used to force the individual DC voltage to follow its command V_C^* [18]. As shown in Figure 4.8(a), the gained output voltage from the balancing control is v_{Bmvg}. The balancing control is based on the phase current that is either positive or negative. The polarity of v_{Bmvg} must be due to i_{pv} or i_{nv} [19]. When V_C^* is greater than or equal v_{cvm} $(m: 1-4)$ in the upper arm, the positive active power has to be taken from the DC-link into the four SM. When i_{pv} is positive, the product of v_{Bmv} and i_{pv} generates positive active power. When i_{pv} is negative, the polarity of v_{Bmvg} must be reversed to occupy the positive active power. At last, v_{Bmvg} for m =1~4 is represented as:

$$v_{Bmvg} = \begin{cases} K5\,(v^*_c - v_{cvm}) & (i_{pv} > 0) \\ -K5(v^*_c - v_{cvm}) & (i_{pv} < 0) \end{cases} \qquad (4.10)$$

where m is the number of cells. The equation of v_{Bmvg} for m = 5 ~ 8 can be written as:

$$v_{Bmvg} = \begin{cases} K5\,(v^*_c - v_{cvm}) & (i_{nv} > 0) \\ -K5(v^*_c - v_{cvm}) & (i_{nv} < 0) \end{cases} \qquad (4.11)$$

The voltage command of every sub-module v^*_{mv} is shown below for positive-arm and negative-arm commands, respectively:

$$v^*_{mv} = v^*_{Av} + v_{Bvmg} - \frac{v^*_v}{4} + \frac{E}{8} \quad (m\text{: } 1 \sim 4) \qquad (4.12)$$

$$v^*_{mv} = v^*_{Av} + v_{Bvmg} + \frac{v^*_v}{4} + \frac{E}{8} \quad (m\text{: } 5 \sim 8) \qquad (4.13)$$

As shown in Figure 4.8(b), v^*_{mv} is the AC-voltage that is gained from the balancing control after passing through positive and negative command arm. Every SM capacitor voltage v_{cvm} normalizes voltage command v^*_{Av} [18], [19].

4.5 Summary of Chapter

In this Chapter, the simulation of MMC has been discussed. A brief review of control schemes for sub-module capacitors voltage of PMSG based MMC has been presented. The performance of MMC, in terms of active and reactive power, was described when it is connected with grid. On basis of simulation study, it was highlighted to the MMC controller for both "PWM" technique and voltage control of sub-module capacitors.

CHAPTER 5

SIMULATION RESULTS

5.1 Introduction

This chapter presents the simulation results of BTB-MMC and PMSG based WECS under three cases to examine the dynamic performance of the control strategy proposed in this thesis. The modelling blocks of PSCAD has been invoked to implement the model.

5.2 Simulation Results

Full-scale BTB-MMC based PMSG WECS presented in Figure 4.7 is simulated in PSCAD environment. The simulation results provide support to the stability of the overall control strategy. The wind turbine is outputting a mechanical torque in order to run the PMSG, while it is connected with BTB MMC whose parameters are shown in Table 5.1. In this chapter, the controllers of the BTB-MMC based PMSG WECS are examined under three cases: 1) Under rated conditions, 2) DC-link voltage drop condition and 3) Third case is proposed to see what happens to active power generation of PMSG when the wind speed reference is changed. Table 5.2 summarizes the parameters of wind turbine, while Table 5.3 summarizes the parameters of three-phase grid where the real power of the PMSG is injected. The HB has only two IGBT switches and one floating DC capacitor. The IGBT switching frequency in the PSC-PWM technique is chosen as 2 kHz.

Table 5.1 MMC parameters used for simulation

Rated active power	5 MW
Rated frequency	50 Hz
DC link voltage	9 kV
Inductance of each arm	3 mH (6.4%)
DC capacitor voltage	2.25 kV
Load inductance	6 mH
Capacitance of each arm	1.9 mH

Table 5.2 Wind turbine parameters

Wind speed	12 m/s
frequency	50 Hz
Rotor radius	35 m
Active power	5 MW

Table 5.3 Three-phase grid parameters

Frequency	50 Hz
Rated voltage L-L rms	5.5 kV

The duration of run in this thesis is selected as 0.2s in order to verify the proposed circuit as well as the control technique under various scenarios

5.2.1 Simulation Results Under Steady-State Conditions

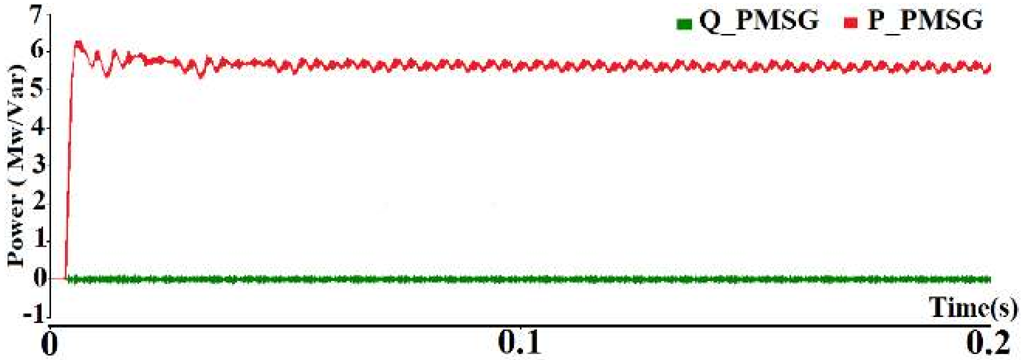
Figure 5.1(a) shows the active and reactive power of PMSG in steady-state conditions. The active and reactive power are calculated using *d* and *q* frames:

$$P = V_d I_d + V_q I_q \tag{5.1}$$

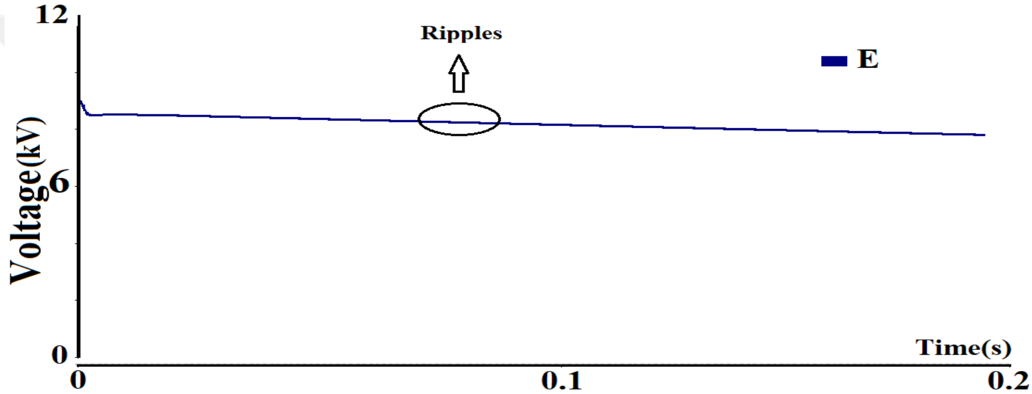
$$Q = V_d I_q - V_q I_d \tag{5.2}$$

The $V_d I_q$ and $V_q I_d$ are the *d-q* components of the three phase voltages and three-phase current that are obtained by using Park transformation.

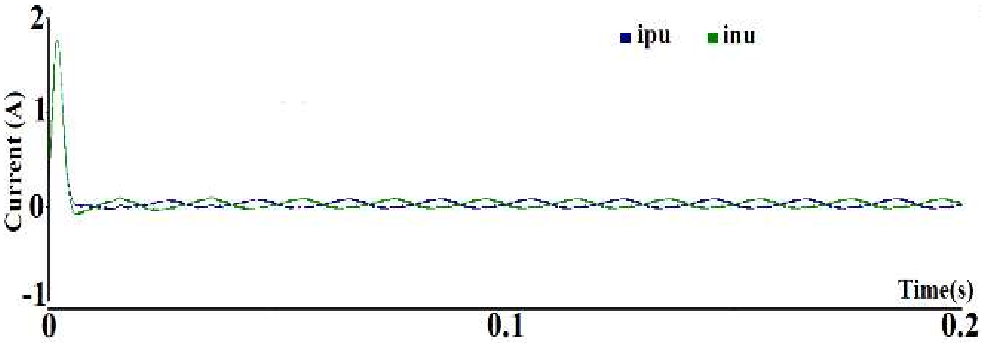
Figure 5.1 shows the active and reactive power output of the PMSG, DC-link voltage of BTB-MMC, and circulating current, respectively under steady-state condition.



(a)



(b)

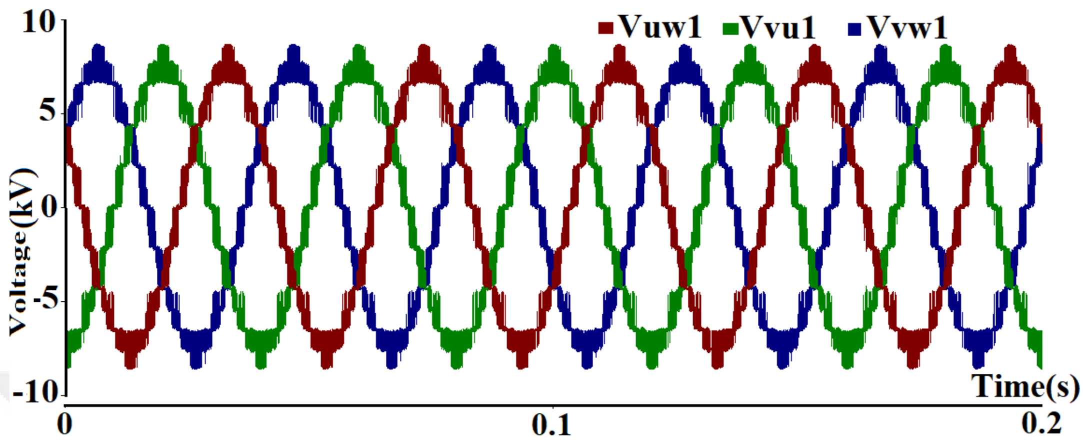


(c)

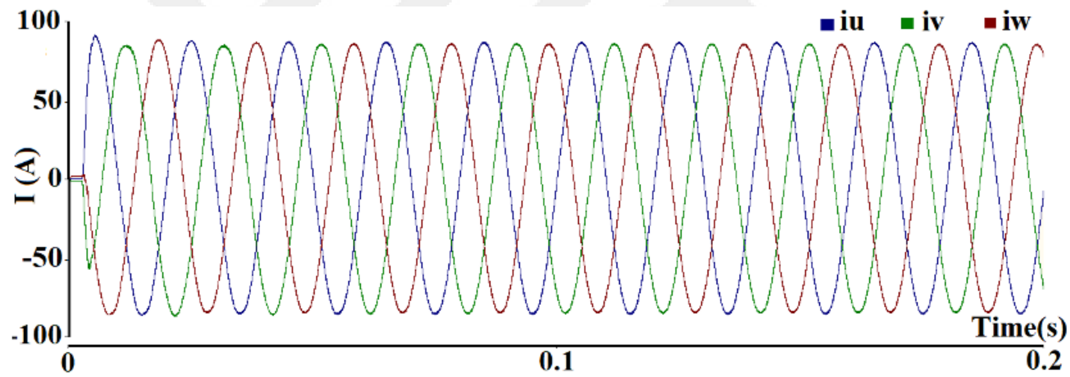
Figure 5.1 Simulation results under steady-state condition: (a) Active and reactive power of PMSG, (b) DC-link voltage, and (c) Circulating current.

Figure 5.2 shows the simulated waveforms of line-to-line voltages, phase currents, and line-to-neutral voltages of AC-DC MMC under steady-state condition. Figure 5.2(a) shows three-phase line-to-line voltages of AC-DC MMC under steady state conditions.

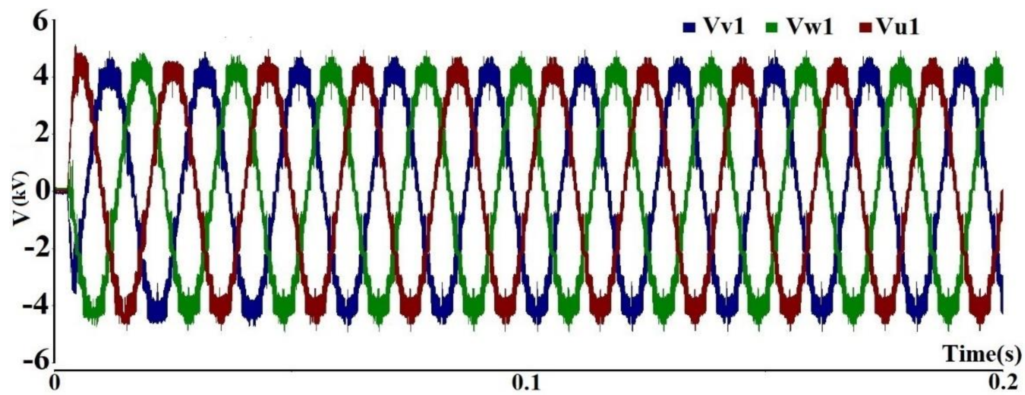
The rated voltage of PMSG is 5.5 kV. This rated voltage is converted to 9 kV DC as shown in Figure 5.2(a). Figure 5.2(b) shows the three phase current of AC-DC MMC side under steady-state condition. Figure5.2(c) shows the three-phase line-to-neutral voltage of AC-DC MMC side.



(a)



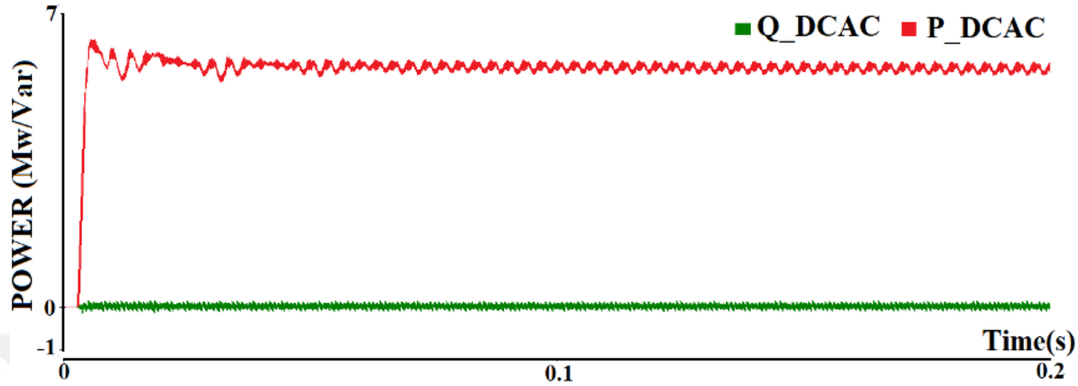
(b)



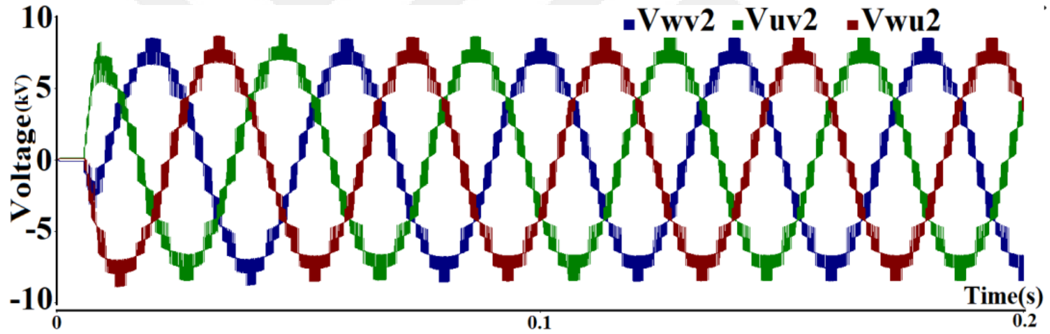
(c)

Figure 5.2 Simulation results under steady-state conditions. (a) Line-to-line voltages of AC-DC MMC, (b) Phase currents of AC-DC MMC, and (c) Line-to-neutral voltages of AC-DC MMC.

Figure 5.3 shows the active and reactive power of DC-AC MMC and line-to-line voltage of DC-AC MMC, respectively. From these waveforms, we can see that the DC-AC MMC side is able to output 17 levels at the line-to-line voltage, converted from the DC-link voltage that has been delivered by AC-DC MMC.



(a)



(b)

Figure 5.3 Simulation results under rated conditions. (a) The active and reactive power of DC-AC MMC, and (b) Line-to-line voltage of DC-AC MMC.

Figure 5.4 shows the DC capacitor voltages of eight SMs of phase-*u1*. The (SM1-SM4) refer to upper arm side while the (SM5-SM8) refer to lower arm side of AC-DC MMC. Figure 5.5 shows the DC capacitor voltages of eight SMs of DC-AC MMC side. It obviously seen that the voltages of SMs are close to each other with uniform shape and low ripple; these are due to the PWM technique which is efficient to eliminate the effect of ripples.

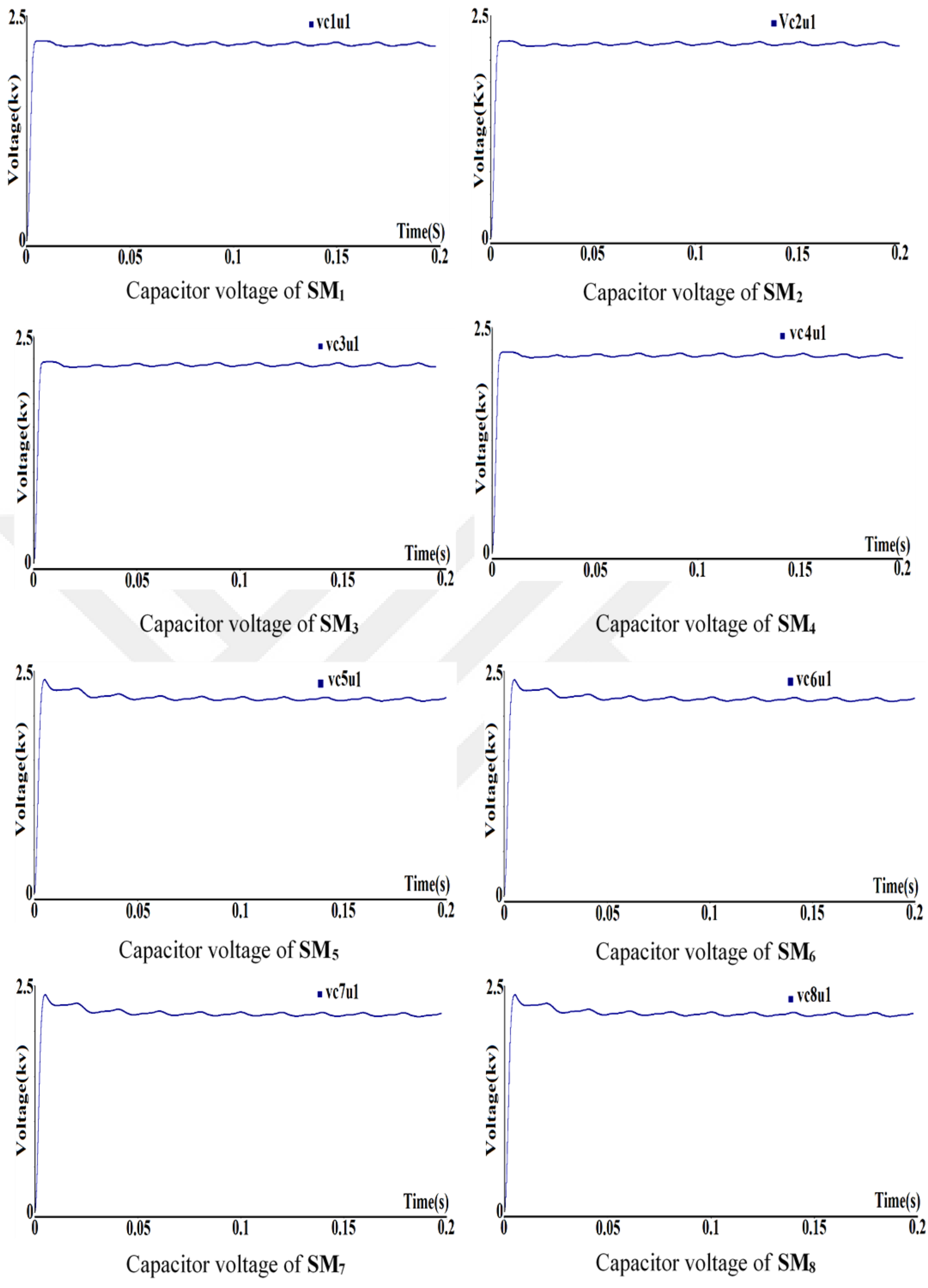
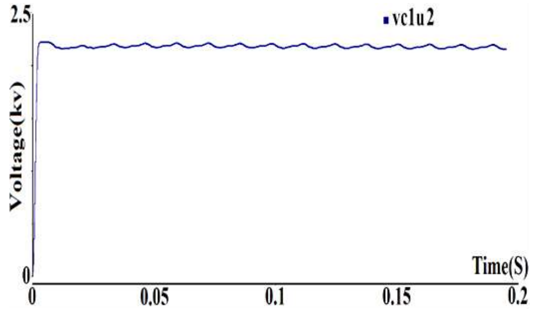
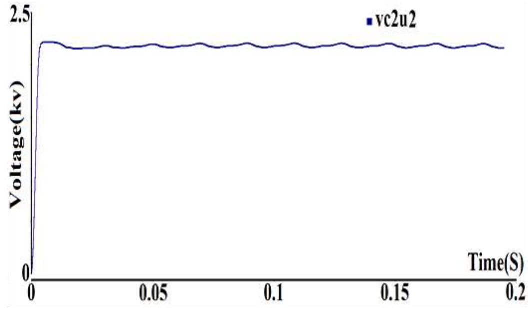


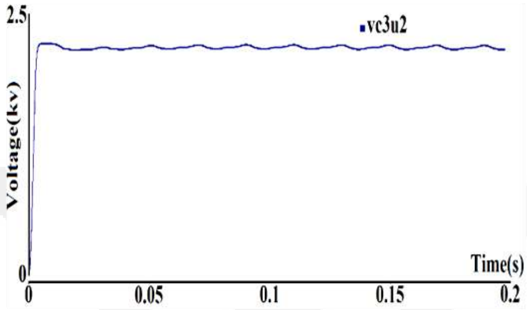
Figure 5.4 Individual DC-capacitor voltage of each SM for single arm of the AC-DC MMC.



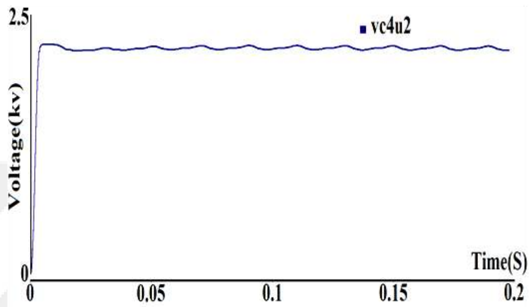
Capacitor voltage of **SM**$_1$



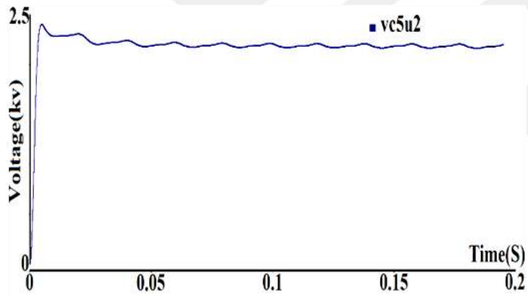
Capacitor voltage of **SM**$_2$



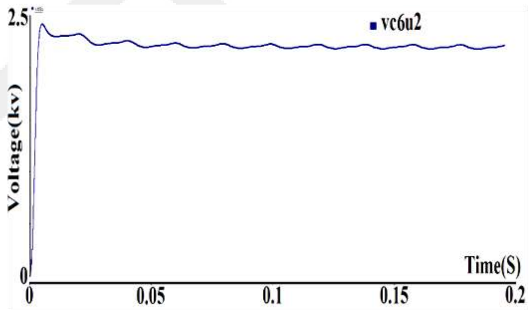
Capacitor voltage of **SM**$_3$



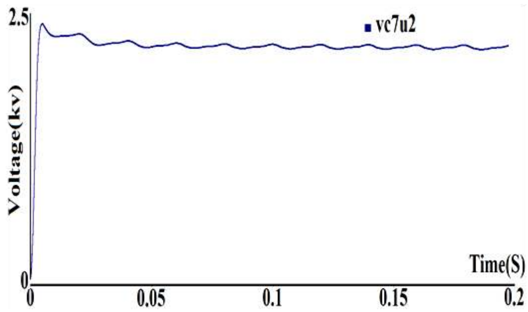
Capacitor voltage of **SM**$_4$



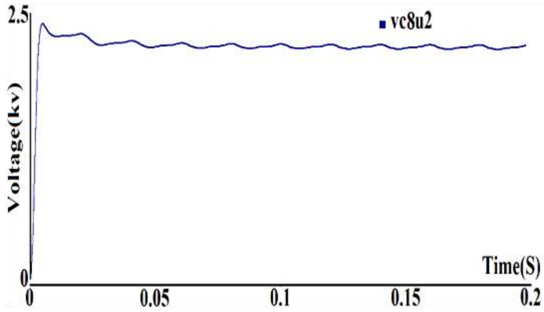
Capacitor voltage of **SM**$_5$



Capacitor voltage of **SM**$_6$

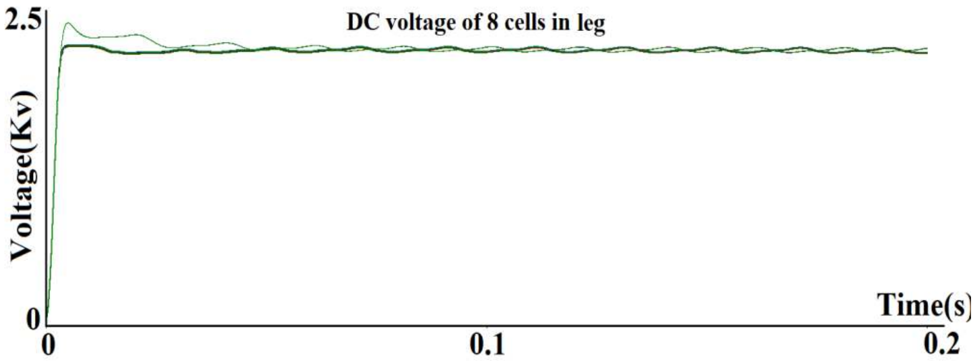


Capacitor voltage of **SM**$_7$

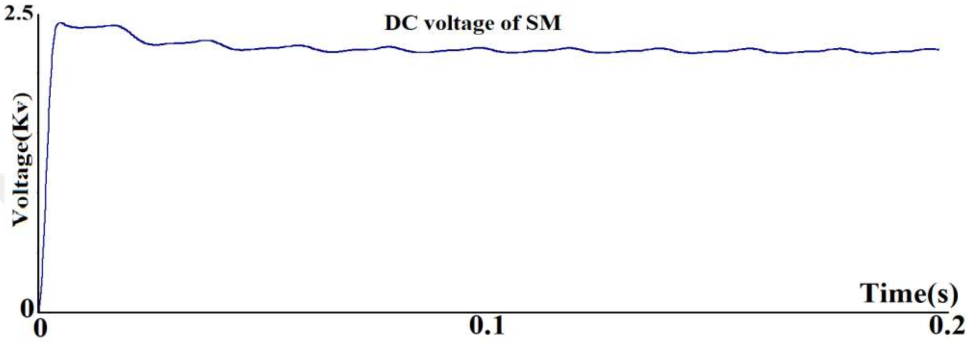


Capacitor voltage of **SM**$_8$

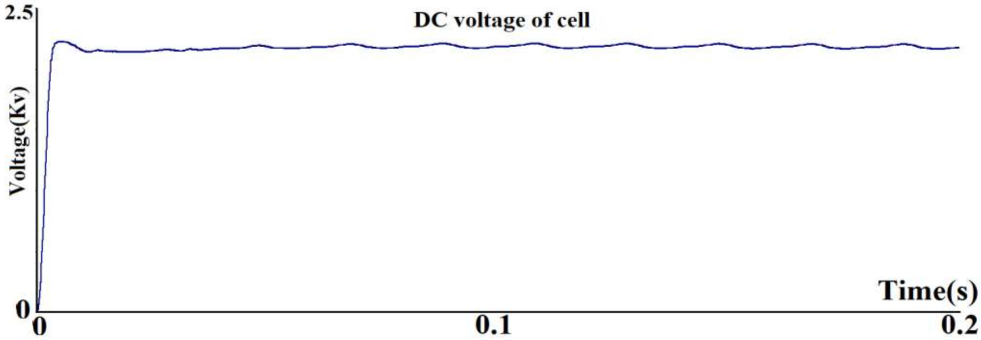
Figure 5.5 Individual DC-capacitor voltage of each SM for single arm of the DC-AC MMC.



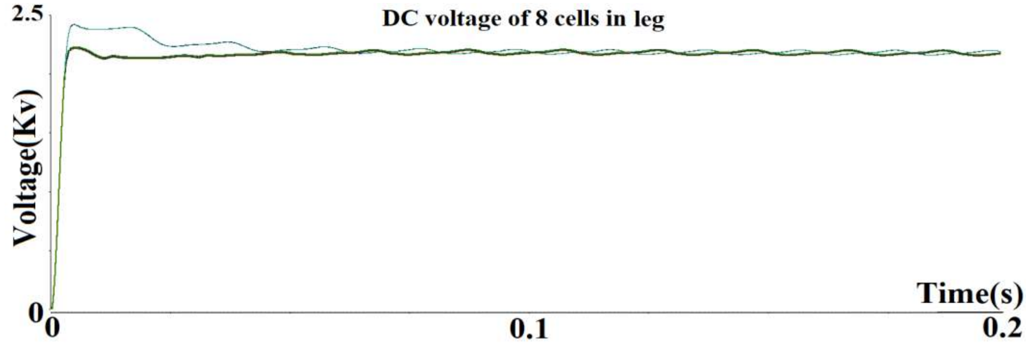
(a)



(b)



(c)



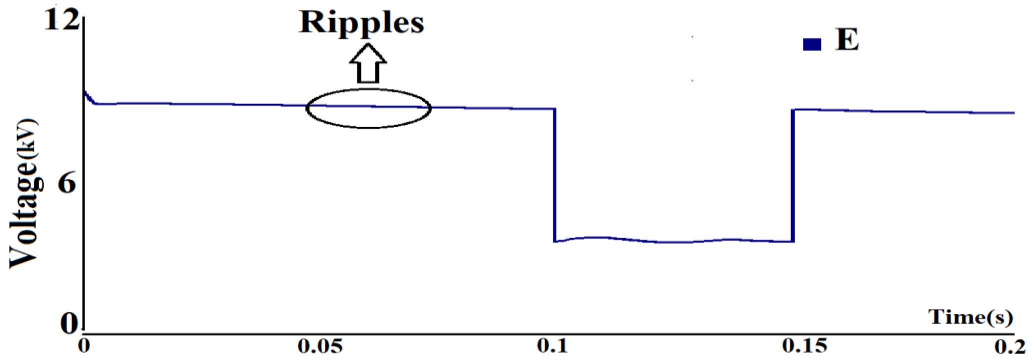
(d)

Figure 5.6 Simulation results of individual DC capacitor voltage of (a) eight SMs in phase-$u2$ of DC-AC MMC side, (b) SM1 in phase-$v2$ of DC-AC MMC side, (c) SM5 phase-$v2$ of DC-AC MMC, and (d) eight SMs in phase-$v2$ of DC-AC MMC.

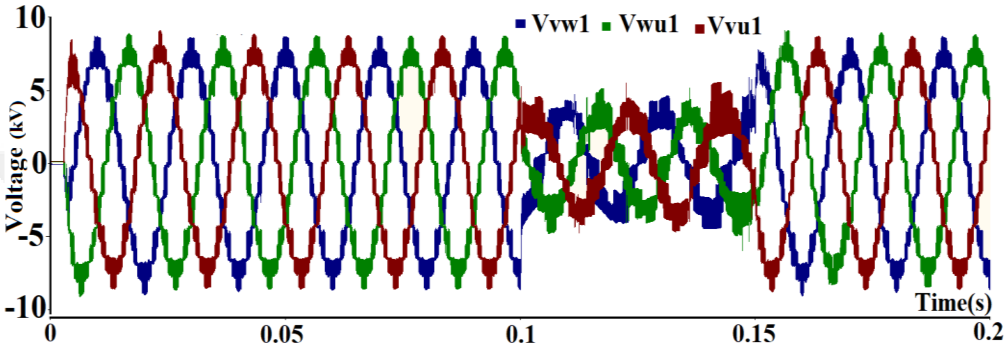
From Figure 5.4, 5.5, and 5.6 it is shown that DC capacitor voltages of each SM has reached to steady-state after time reaches to less than 0.05s. According to these small ripples and uniform shape in DC capacitor voltage waveforms, this means that the capacitor size of each SM is selected as good choice, which is 1.9 mF.

5.2.2 Simulation Results Under Dynamic Case

In this case study, the dynamic performance of the control scheme of MMC is examined when DC link voltage set point is dynamically changed at t = 0.1s for a duration of 0.05s as shown in Figure 5.7(a). As observed from the simulated waveforms presented in Figure 5.7, the DC-AC and AC-DC MMCs were able to ride through these dynamic states smoothly. After the drop of DC link voltage, three-phase AC voltages of both MMCs are also diminished. Since, the DC link voltage is used as reference voltage in the controller for both MMCs. Figure 5.7(b) shows the line-to-line voltage of AC-DC MMC. Figure 5.7(c) shows the active and reactive power output of the PMSG under dynamic case. Figure 5.7(d) shows the three phase current of DC-AC MMC under dynamic case. Figure 5.7(e) that shows the three-phase voltage of AC voltage source under this dynamic case. It is apparent in Figure 5.7(e), that the MMC module has highly approved in the output voltage even with DC-link drop.



(a)



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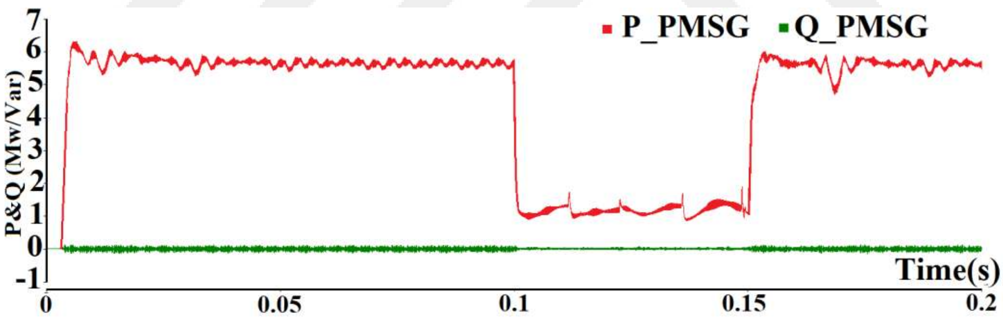

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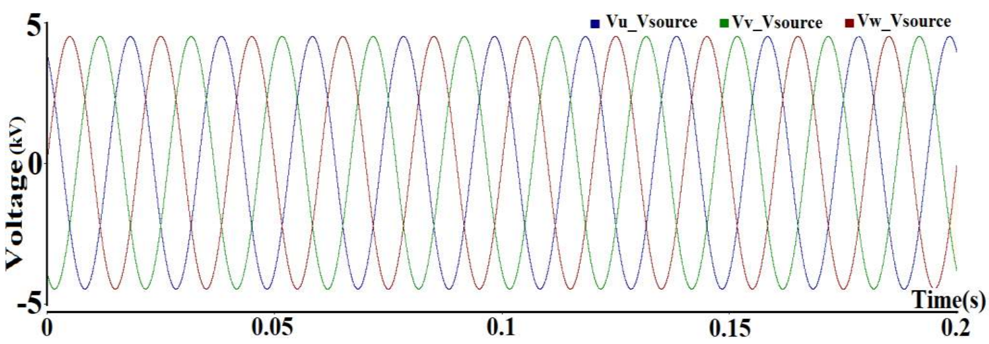
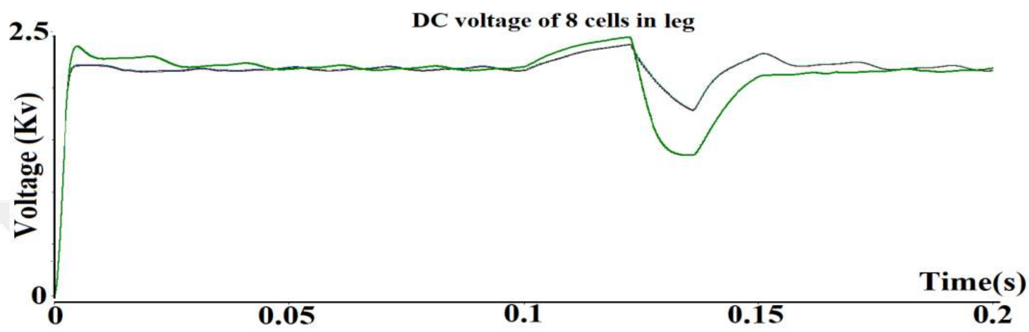


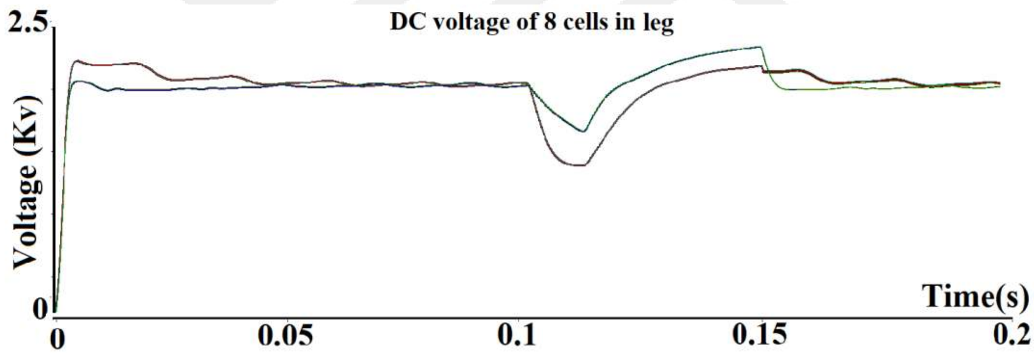
(d)

Figure 5.7 (a) DC link voltage set-point change, (b) Line to line voltage of AC-DC MMC, (c) Active and reactive power of generator, and (d) Three-phase voltages of AC voltage source.

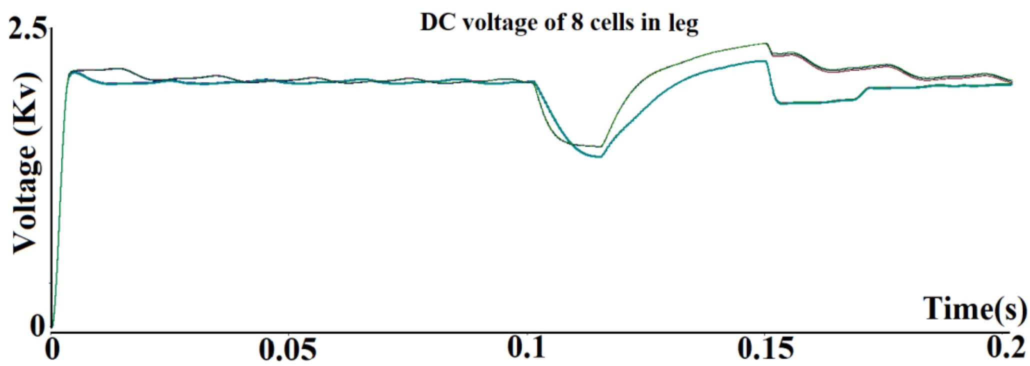
Figure 5.8(a) shows the voltages of eight SMs in phase-*u1* of AC-DC MMC when DC link voltage set-point change is applied. The voltages of each SM have returned to their nominal values after some disturbances. Figure 5.8(b) shows the voltages of eight SMs in phase-*v* of AC-DC MMC. Figure 5.8(c) shows the voltages of eight SMs in phase-*w1* of AC-DC MMC shows the three phase line-to-line voltage of three-phase voltage source. Figure 5.9(a), (b), and (c) show the voltages of eight SMs in phase-*u2*, phase-*v2* and phase-*w2* of DC-AC MMC converter respectively.



(a)

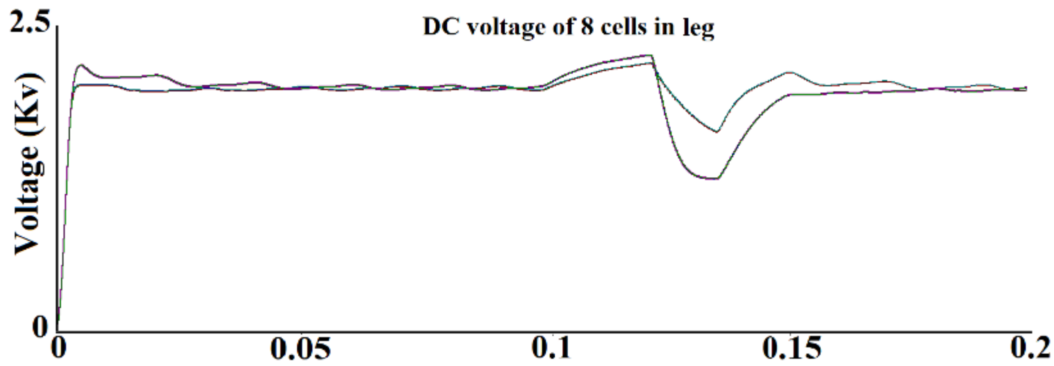


(b)

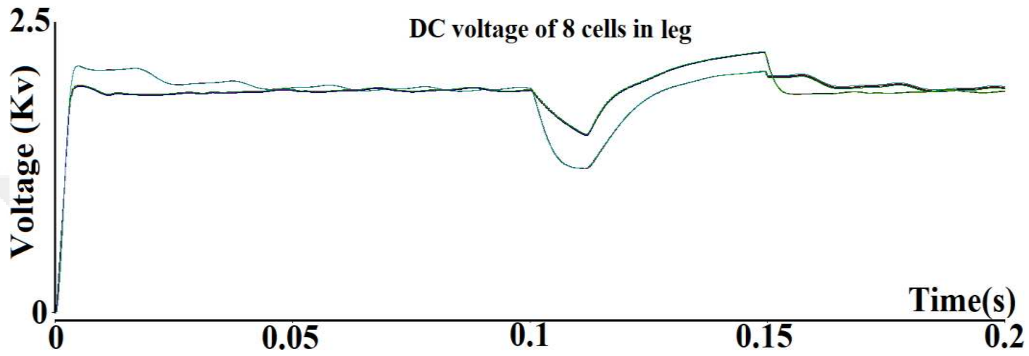


(c)

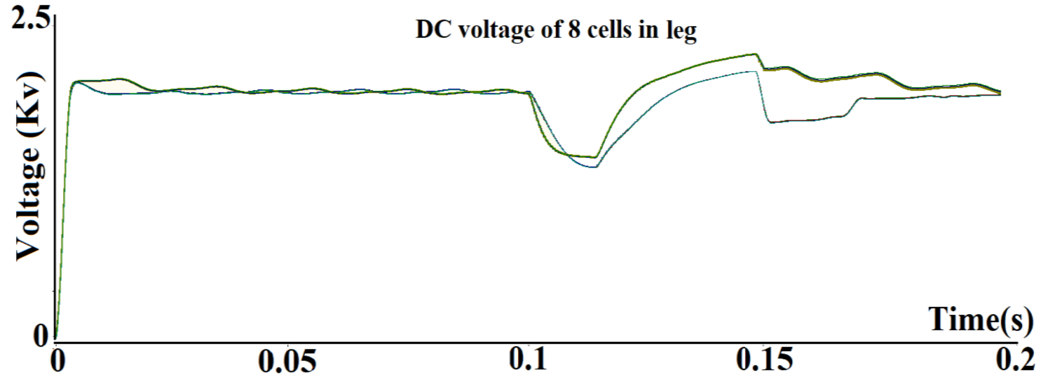
Figure 5.8 Simulation results of DC-capacitor voltages of AC-DC MMC (a) phase-u1, (b) phase-v1, and (c) phase-w1.



(a)



(b)

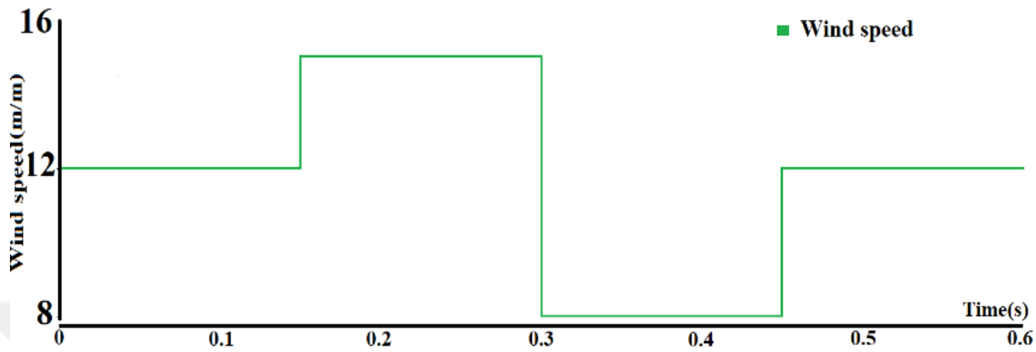


(c)

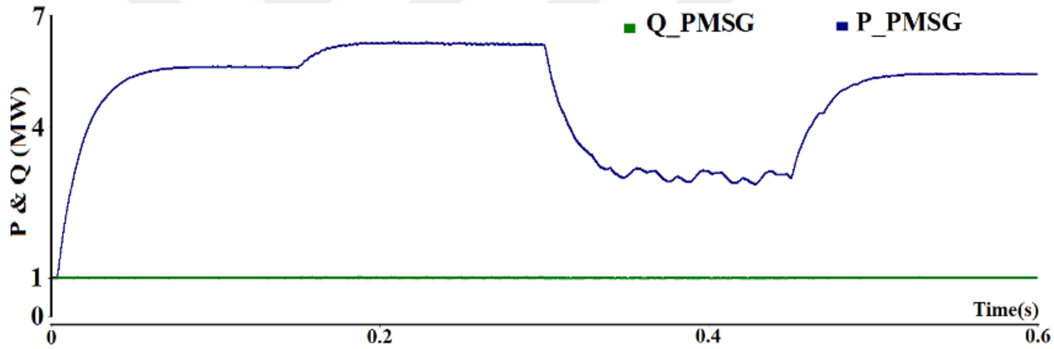
Figure 5.9 Simulation results of DC-capacitor voltages of DC-AC MMC (a) phase-u2, (b) phase-v2, and (c) phase-w2.

5.2.3 Simulation Results Under Variable Wind Speed

Figure. 5.10(b) shows active power of generator is changed according to the changing in wind speed reference. As shown in Figure 5.10(a) the changing in wind speed can be explained as follows: from 0.1s to 0.15s, the wind speed is 12m/s, at *t*=0.15s, the wind speed is increased to 15m/s for a duration of 0.15s. At *t*=0.3s, the wind speed is suddenly decreased to 8m/s, and the wind speed is restored to 12m/s at *t*=0.45s. As shown in Figure 5.10(b), the active power of PMSG is changed according to the changing in wind speed reference. Because the changing in wind speed leads to a change in mechanical torque and thus leads to a change in the active power of PMSG [59].



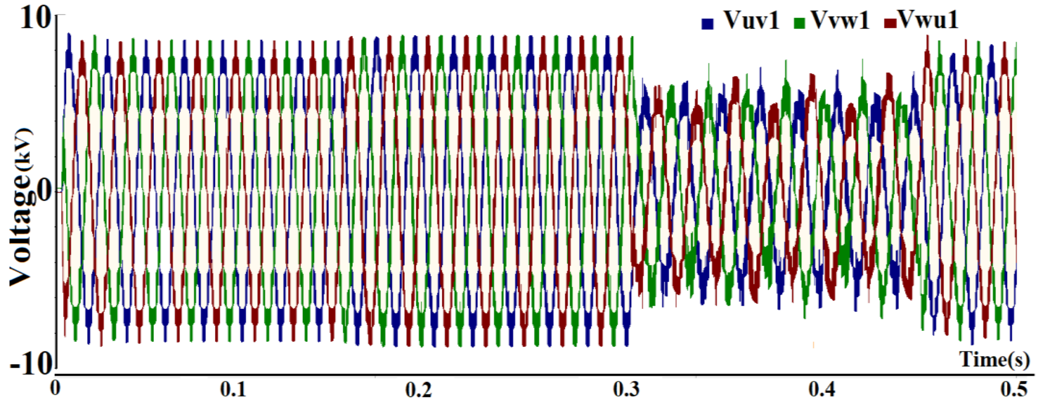
(a)



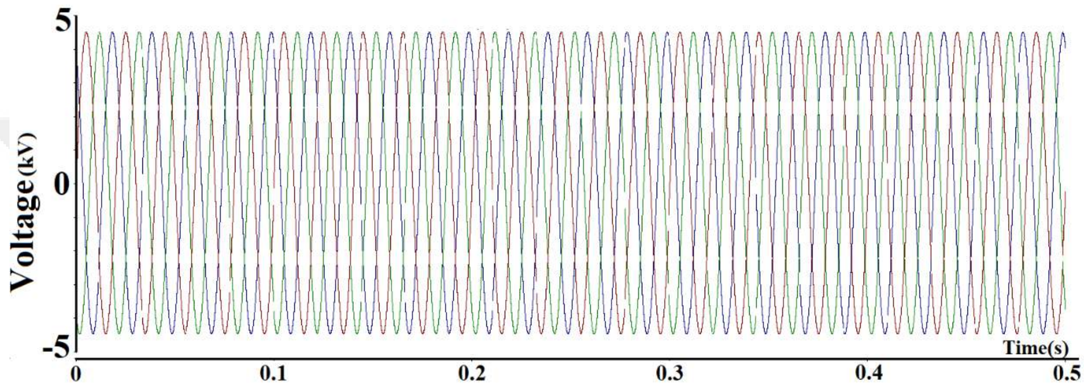
(b)

Figure 5.10 Simulation results of (a) Variable wind speed, and (b) Active and reactive power of PMSG.

Figure 5.11(a) shows the line-to-line voltage of AC-DC MMC. As shown in Figure 5.11(a), line-to-line voltage of AC-DC MMC is changed according to the changing in wind speed reference. At t=0.15s, line-to-line voltage is increased according to the rising in wind reference for a duration 0.15s. As shown in Figure 5.11(a), line-to-line voltage of AC-DC MMC is decreased at t=0.3s according to wind speed that is suddenly decreased. At t=0.45s wind speed is restored to 12m/s, therefore, line-to-line voltage is returned it its normal value. It is apparent in Figure 5.11(b) that the MMC module has highly approved in the output voltage even with changing in wind speed, this is due to the 17-level MMC design.



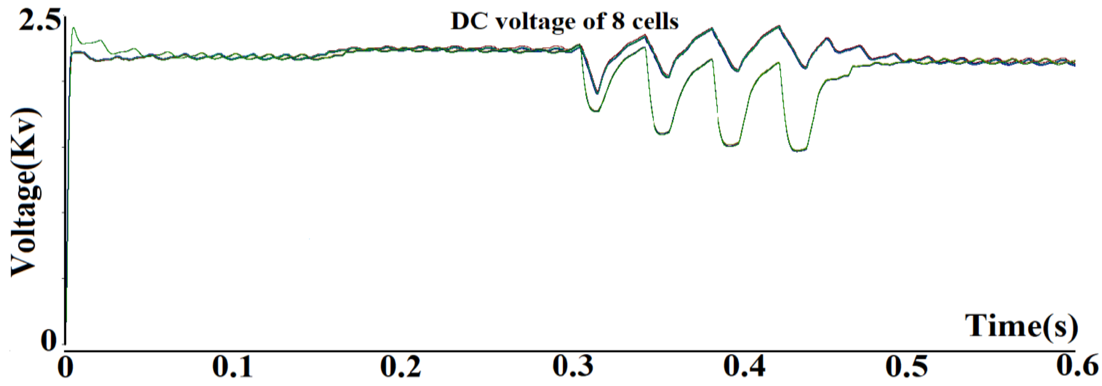
(a)



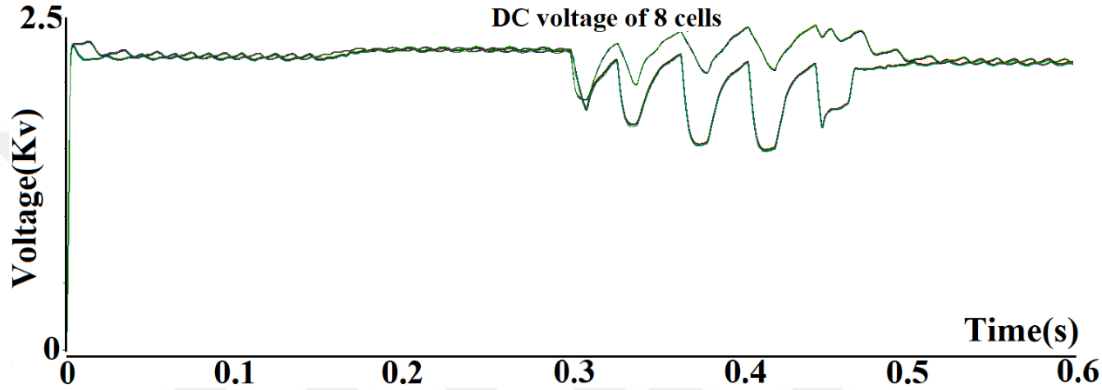
(b)

Figure 5.11 Simulation results of (a) Three-phase voltage of AC-DC MMC, and (b) Three-phase voltages of AC voltage source.

Figure 5.12(a) shows the DC-capacitor voltage of eight cells of phase-*u1* in AC-DC MMC. As shown in Figure 5.12, the DC-capacitor in its normal value until t = 0.15s. In t = 0.15s, the DC-capacitor voltage of eight cells is increased according to the rising in wind speed. In t = 0.3s, DC-capacitor voltages is changing according to the suddenly decreased in wind turbine. At t = 0.5s, the DC-capacitor voltage has returned to its normal value. Figure 5.12(b) shows the DC-capacitor voltage of eight cells of phase-*v1* in AC-DC MMC. Figure 5.12(c) shows the DC-capacitor voltage of eight cells of phase-*w1* in AC-DC MMC. Figure 5.13(a), (b) and (c) show the DC-capacitor voltage of eight cells of each phase in AC-DC MMC respectively.



(a)



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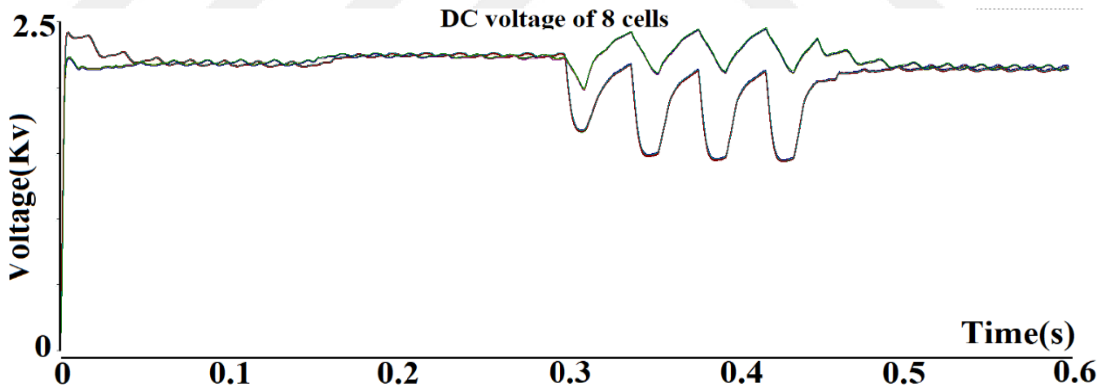
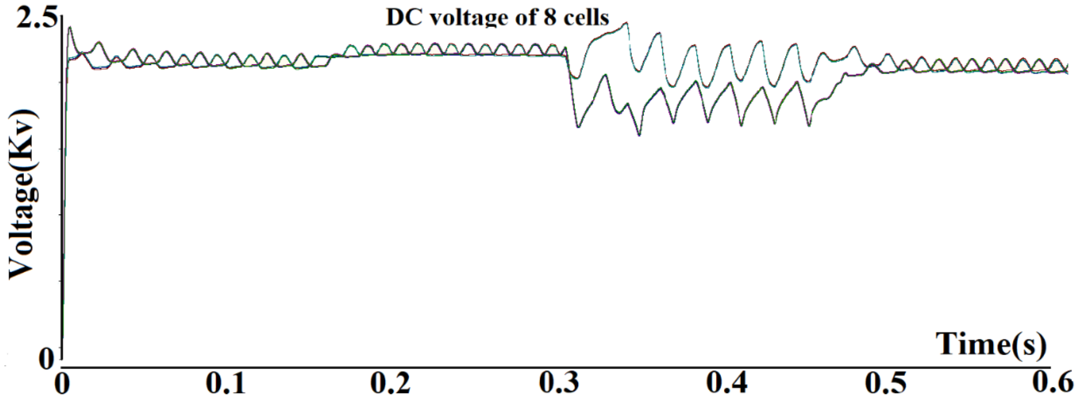
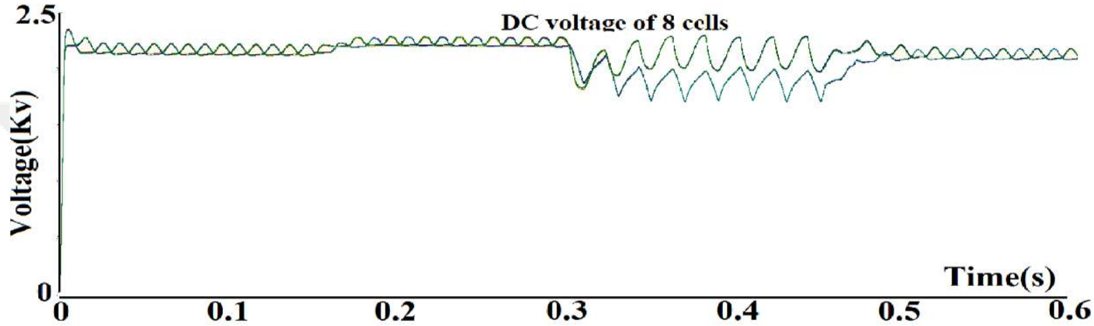


(c)

Figure 5.12 Simulation results of DC-capacitor voltages of AC-DC MMC in variable wind speed case (a) phase-$u1$, (b) phase-$v1$, and (c) phase-$w1$.



(a)



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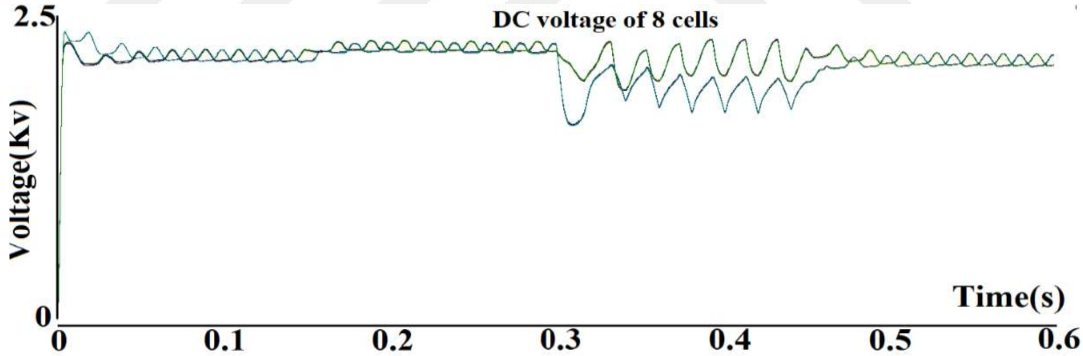

(c)

Figure 5.13 Simulation results of DC-capacitor voltages of DC-AC MMC in variable wind speed case (a) phase-$u2$, (b) phase-$v2$, and (c) phase-$w2$.

5.3 Summary of the Results

This thesis has described theoretical improvements on the capacitor voltage balance of the HB module. As observed form the simulation results, the AC-DC and DC-AC MMCs were able to ride through dynamic states smoothly. The MMC module has highly approved in output voltage even with changing in wind speed due to the 17-level MMC design. The results of the MMC PMSG based WECS have been verified by simulation, under the PSCAD computer simulation program.

The major contributions of the research can be summarized as follows:

- Modeling and simulation of PMSG based WECS system.
- Analysis and simulation of 17 levels MMC.
- Studying with a constant switching frequency for the 17 levels MMC.
- Proposal of the simulated case that includes constant and variable wind speed conditions.

CHAPTER 6

CONCLUSIONS

This thesis has described and modelled theoretical structure of MMC converter system based on a PMSG based WECS system consisting of BTB MMCs. The PMSG is the most preferred generator type among generators in wind turbine applications. The BTB method is very attractive since it has achieved the AC-DC-AC conversion. The construction and design of MMC has received great significance in recent years due to its of output waveform shape and it represents a high performance.

Each MMC has three legs and each leg contains an upper and a lower arm. Four SMs or are connected in series in each arm. Each cell has two IGBTs and a DC capacitor. As a result, each MMC unit has 6 inductors and 24 HBs. The aim of using two non-coupled buffer inductor is to deal with the voltage difference between the upper and lower arm of the converter and limit the current when fault occurs in a short circuit. Each MMC is connected from their DC link to form a BTB arrangement. The conclusion of this work can be listed as follows:

1. MMC is able to generate high voltages with diminished voltage stress on each power electronic semiconductor.
2. Harmonic levels can be significantly decreased thanks to the increased number of voltage levels. As a result, filtering requirements are becoming less.
3. MMCs have better fault ride through capabilities.
4. PSC-PWM method is used to trigger power semiconductors in each SM. Balancing and average control methods are designed to achieve the balancing of capacitor voltage in each SM in both MMCs.
5. In order to verify the efficiency of the proposed control scheme, different cases were performed in this work.
6. The generated power from this system can be adjusted according to the required power level. This is considered to be an attractive advantage

7. As observed from the simulation results, the dynamic performance of the proposed control scheme is satisfactory.
8. The 17-level MMC design is giving a high improvement even with changing in wind speed.

6.1 Future Work

The following subjects can be investigated further to contribute the project:

1. Evaluation of the converter performance under different modes of balanced and unbalanced faults,
2. Implementation of different control architectures using modern control techniques such as neural network and fuzzy logic,
3. Possible to extend this work to include the implementation for more than one wind turbine together with a grid connection,

Replacement all sub module cells, which are HB that has been considered in converter design by FB sub modules.

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