ABSTRACT

Integration of electric power generated from renewable energy sources into transmission and distribution sector of power system is a crucial component in the delivery of affordable, clean and sustainable power. Renewable energy can be described as the energy of today and the future; basically renewable energy will replace fossil fuels as the main source of energy generation for domestic and commercial purposes. Several methods can be used to achieve this goal of integrating generated energy. Matrix converters which are also known as cycloconverters are used to achieve power conversion from one medium to another. In our research, this technology is applied in achieving various power conversions from one medium to another and from one phase to another. An advantage of the cycloconverter is the ability to accept any type of voltage input; whether ac or dc voltage and also produce any type of output voltage. This type of converter eliminates the need for different types of converters for specific voltage type application

Keywords: renewable energy sources; Matrix converters; cycloconverters

ÖZET

Yenilenebilir enerji kaynaklarından üretilen elektrik enerjisinin enerji sisteminin iletim ve dağıtım sektörüne entegrasyonu, uygun fiyatlı, temiz ve sürdürülebilir gücün sağlanmasında önemli bir unsurdur. Yenilenebilir enerji bugünün ve geleceğin enerjisi olarak tanımlanabilir; temelde yenilenebilir enerji, fosil yakıtların yerini yerli ve ticari amaçlı enerji üretiminin ana kaynağı olarak kullanacaktır. Üretilen enerjiyi bu şekilde birleştirmek için çeşitli yöntemler kullanılabilir. Aynı zamanda, devir dönüştürücüler olarak da bilinen matris dönüştürücüler, bir ortamdan diğerine güç dönüşümü sağlamak için kullanılır. Araştırmamızda, bu teknoloji bir ortamdan diğerine ve bir fazdan diğerine çeşitli güç dönüşümleri elde etmek için uygulanmaktadır. Döngü konvertörünün bir avantajı, herhangi bir voltaj girişini kabul etme yeteneğidir; ac veya dc voltaj olup olmadığını ve ayrıca herhangi bir çıkış voltajı ürettiğini. Bu tür dönüştürücü, belirli voltaj tipi uygulamaları için farklı türdeki dönüştürücülere duyulan ihtiyacı ortadan kaldırır

Anahtar Kelimeler: yenilenebilir enerji kaynakları; Matris dönüştürücüler; cycloconverterler.

ABULQASEM AHMED JBRIL ABDO

MATRIX CONVERTERS FOR RENEWABLE ENERGY SOURCES

NEU

2019

MATRIX CONVERTERS FOR RENEWABLE ENERGY SOURCES

ATHESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY

By
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In Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical and Electronic Engineering

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Approval of Director of Graduate school of

Applied Sciences

Prof.Dr. Nadire CAVUS

We certify this thesis is satisfactory for the award of the degree of the Masters of Science in Electrical and Electronic Engineering

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To my parents…

ABSTRACT

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LIST OF ABBREVIATIONS

ESS:	Energy Storage Systems
AC :	Alternate current
DC:	Direct current
DVR:	Dynamic Voltage Restorer
PV:	Photovoltaic
CSP:	Concentrated Solar Power
CO2:	Carbon Dioxide
PT:	Parabolic Trough
LER:	Linear Fresnel Reflector
CHP :	Combined Heat and Power
HAWT:	Horizontal Axis Wind Turbines
VAWT:	Vertical Axis Wind Turbines
DER :	Distributed Energy Resources
LV:	Low Voltage
MV:	Medium Voltage
FC :	Fuel Cell
MG :	Microgrid
DG:	Distributed Generation
D:	Diode
L:	Inductor
C:	Capacitor
OWIM:	Open Winding Induction Motor
PWM:	Pulse Width Modulation
IGBT:	Insulated Gate Bipolar Transistor
MPC :	Model Predictive Control
ISVM :	Indirect Space Vector Modulation
SPWM:	Sinusoidal Pulse Width Modulation
QZSIMC:	Quasi Z Source Indirect Matrix Converter
RB-IGBT :	Reverse Blocking Insulated Gate Bipolar Transistor

CHAPTER 1

INTRODUCTION

The significance of energy in today's world cannot be underestimated; gradually in all forms (petrochemical, renewable, solar, wind, hydro ,wave and etc) energy have become very important commodities that helps smooth running of affairs in our daily activities such as: transportation, aviation, railways, automobile, ships, construction, health delivery, education, communication etc. The absence of energy will have a crippling effect on the socio-economic development of any society. Conventional utilization of Electric power and energy applications is changed to new application such as electric vehicle. Disadvantages (such as environmental pollution, emission of CO_2 gases, depletion of ozone layer, conflicts etc) of conventional method of using fossil fuel for electric power generation has paved the way for rapid utilization of renewable energy resources for electric power generation. Renewable energy resources usage is a principal component in the development of microgrid and distributed generations.

A microgrid is an isolated or localized discrete electrical energy system composed of distributed generations, energy storage systems (ESS) and loads which have the capability of self-operations, island mode and grid-tied operations. Distributed generations are electric power generation systems which consist of ESS capabilities supplied by a number of small generating sets usually using renewable energy resources. Microgrids and distributed generations make usable the multiple renewable energy sources for electrical power generation such as: conditioning of these energy sources to a suitable level for gird integration. One of the necessary operations of renewable energy sources rectification/inverting (changing ac power to dc power or changing dc power to ac power). This process is necessary because most grid systems are either purely ac or dc hence we need rectifier and inverter.

Rectifier and inverter circuit is required in electric power conversion processes, recently efficiency and cost are important indices that drive the supply and demand of most commodities. The application of these components will have added cost and reduce efficiency in energy generation systems. To over these difficulties where multiple generating sources are applied, matrix converter is the solution. Matrix converter has numerous advantages such ac to dc, ac to ac power, dc to ac and dc to dc power conversion.

1.1. Thesis Problem

Energy conversion processes have an important task in today's energy generation systems because of the various methods of electric power generation and the different types of loads. Some applications of energy conversion in electrical systems are dynamic voltage restorer DVR, static synchronous compensator STATCOM, static VAR compensator, electric vehicle and etc.

In the energy conversion processes, the number of conversion devices increase because separate devices are required for specific functions such as rectifier for changing ac to dc, inverter for changing dc to ac and cycloconverter changes ac to ac, buck, boost, buck-boost converter for changing dc to dc. These elements increase losses, reduced efficiency and high cost of generating systems hence high cost of electric power.

Also rigid in terms of input power IE they are designed to accept only dc power for buck-boost converter and inverter and ac power for rectifier and cycloconverter as input power. If the input power should change, then combinations of conversion devices are required to produce the desired power. Specific inverter, buck-boost converter, cycloconverter and inverter have specific output phase voltage IE the phase voltage is limited to one, two or three phases.

1.2 The aim of Thesis

Main purpose of this thesis is to apply energy conversion device having the requisite qualities to solve the problems enumerated above. The applied energy conversion device should have the ability to accept either ac power or dc power as input power without the addition of extra energy conversion devices, also the output phase voltage should be versatile, the device should be able to produce single phase, two phases or three phases voltage at the output.

This will be achieved by the application of matrix converter and simulation carried out in EMTDC/PSCAD software environs to produce results for analysis.

1.3 The importance of Thesis

The significance using of renewable energy sources for electric power generation has an added impetus of protecting and conserving the environment for the next generations; also renewable energy resources are cheap and in abundance.

Application with useful and appropriate technology need more works and years to be efficient for energy generating systems thereby reducing cost of energy which has direct correlation to the development of every society.

1.4 Limitation of study

Even though this research was conducted with outermost care, the possibilities of shortcomings and limitations are unavoidable. First and foremost the research was conducted using EMTDC/PSCAD software hence the ability to control the research is limited to the structure of the software. Although research based simulation results have become an acceptable standard in academia, the disadvantage of not having experimental results due cost of components, proper practical knowledge and conducive environmental cannot be ignored.

1.5 Overview of the Thesis

This thesis is categorized into five chapters:

Chapter 1: Introduction. This chapter is made of introduction, Thesis Problem, The aim of Thesis, The important of Thesis and overview of the thesis.

Chapter 2: Renewable Energy Sources

Chapter 3: Microgrid and Distributed Generations

Chapter 4: Matrix Converter

Chapter 5: Simulation of Matrix Converter

Chapter 6: Conclusion

CHAPTER 2

RENEWABLE ENERGY

2.1 Introduction

Renewable energy sources such as solar, wind, hydro and tidal energy have made tremendous impact in the generation of electricity for both personal and commercial purposes. It's an undeniable fact that world energy generation is gradually shifting from the use of fossil fuel for power generation to renewable source because of the great positive impact it has on the environment and the also naturally occurring commodity which is free. In this chapter, the following renewable energy sources; solar, wind, hydro, tidal, biomass, biofuel and geothermal energy will be will be investigated.

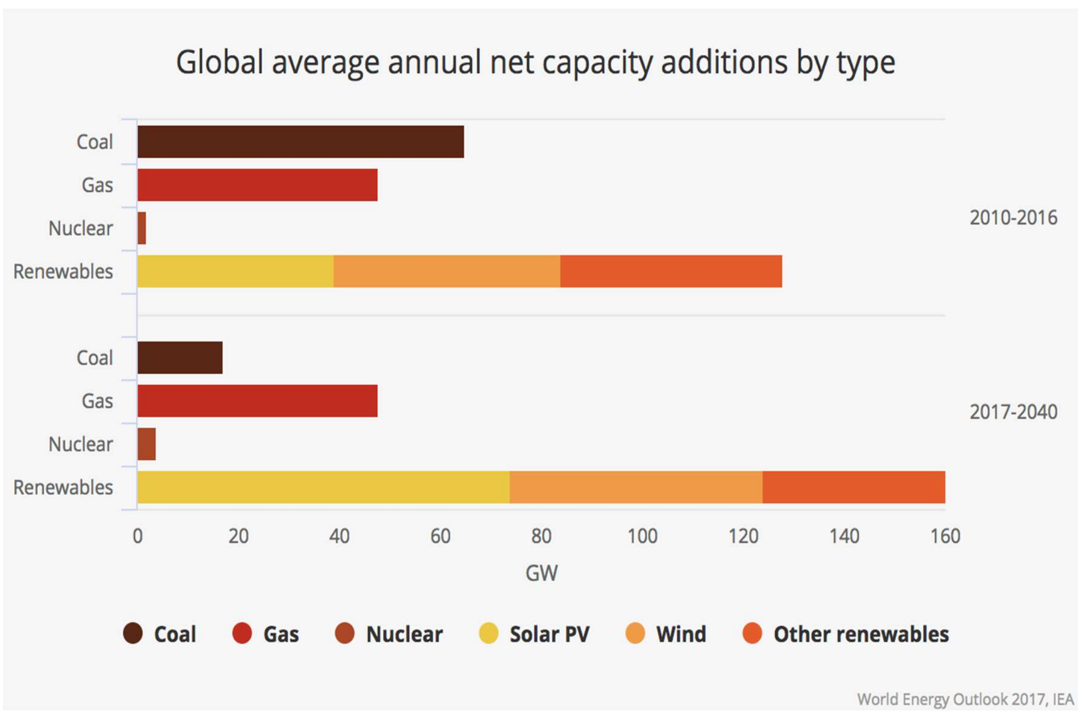


Figure 2.1: Electric power generation sources (Outlook, 2017)

2.2 Solar Energy

The Sun is source of solar energy radiates large amounts of solar energy in the atmosphere at a speed of 3.0 x 10^8m/s^2 (speed of light). The sun is able to produce this vast amount of energy by a method called fusion in which helium and hydrogen atoms are combined, this process release electromagnetic energy in the amounts of 3.8×10^{20} MW into space. Basically the sun is described as a blackbody because it's able to radiate enough energy into space to support life (Infobook, 2018). 4.3×10^{20} J of energy is the amount of solar energy that reaches the earth's atmosphere and this amount of energy is enough to provide the energy (4.1 × 1020 J) requirements for the earth's consumption in one year.

Energy from the sun provide an electromagnetic wave which is made up of different wavelengths of spectrum. The strength of the wavelength is dependent on its length in the spectrum, wavelength with longer spectrum have minimum amount of energy and wavelengths with shorter spectrum have maximum energy, among the various wavelengths visibles on the earth's surface are within the range 0.29µm to 2.3µm (Tiwari & Dubey, 2009).

Once these wavelengths or energy reaches the earth's surface, its usage is diverse such as agriculture and weather related applications. The next subsections of this chapter will investigate the various methods of electric power generation using solar energy.

2.2.1 Solar Energy History

Solar energy's history is very old just like human nature. Although in the early years solar energy was not used for electricity generation, its application by human included illumination, food preservation etc. One major breakthrough in solar energy application in the 7th century is the producing of fire by focusing the sun's rays onto a magnifying glass (Infobook, 2018). In 1839, Alexandre Edmond Becquerel unearthed that small amounts of volts of electricity could be generated when certain substances are exposed to solar energy (Masters, 2004). Upon this discovery, several attempts were made to maximize the generation of electricity from solar energy. Notable scientist who made very significant breakthrough in their researches is Charles Greeley Abbott and others.

2.2.2 Solar Collectors

Solar collectors are devices which absorb or collect radiations (solar energy) for various applications such as water heating, electric power generation and etc. solar collectors make use of the heat energy component of solar energy. The heat energy is used for heating in either passive or active solar heating (Consumption, 2008).

2.2.3 Photovoltaic Systems

The photovoltaic system is made up of the building block or element known as photovoltaic cell and it's responsible for converting solar energy in electric power. Photovoltaic can be broken down into two words; ***photo*** which is light and ***voltaic*** which voltage. Photovoltaic systems have other names such as PV system, PV solar array, solar photovoltaic system, and photovoltaic power systems (Infobook, 2018). The photovoltaic cell is the principal component for electric power generation, a number of PV cells are connected in series and parallel to produce a PV panel or module, these connections (series and parallel) are done to determine the voltage or power ratings of the module. Panels are also connected by the series and parallel arrangement to produce and array whose power is depended on the series and parallel connections. Photovoltaic effect causes the generation of electric power from solar energy. Photovoltaic system is made up of panels/modules, inverters and other components (mechanical and electrical) which efficiently converts solar energy into electrical power and also conditions it for use by the consumer.

Figure 2.2: Photovoltaic cell (Gaiddon, Kaan, & Munro, 2009)

2.2.4 Photovoltaic Effect

Electric field is produced in the PV cell when solar radiations hit the surface of the PV cell. This occurrence produces the breakup of the negative charge carrier (n type) and positive charge carries (p-type). Negatively charged electrons are separated from silicon atom which is used in producing the PV module and solar radiations (photons) transfer its energy to the electrons, this process is repeated several times to produce enough electrons, the flow of these freed electrons generates electric power or current. More photons and higher PV panel ratings are required to generate much large power.

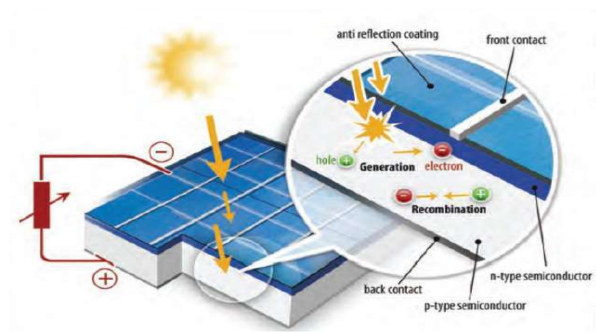


Figure 2.3: Solar cell cross-section (Gaiddon et al., 2009)

2.2.5 Types of Photovoltaic Cells

The most common material used for the production of photovoltaic cells is the silicon material due to its versatile properties and also similar characteristics to semiconductor materials. Examples of photovoltaic cells used for build PV panels are; Monocrystalline, Polycrystalline, Bar-crystalline silicon, Thin-film technology (Infobook, 2018)

Figure 2.4: Solar cell types (Tiwari & Dubey, 2009)

2.2.6 Types of PV Systems

Now a days the classification of photovoltaic systems is a complex task because of the varied ways of utilizing PV systems. Hence simple or complicated systems can be used to classify them. A simple photovoltaic system is an irrigation system which uses dc motor connected to photovoltaic panel to provide dc voltage to power the pump; this system is devoid of an inverter and storage units which are common in personal and mini commercial PV systems. Photovoltaic systems can be grouped into the following, standalone, grid connected and hybrid systems (Sieminski, 2014). The categorizes of photovoltaic systems are similar in terms of core functions i.e. to provide power from solar energy, however the difference lies in the magnitude of power produced, the type of consumer, and the components used in achieving the desired energy.

2.2.7 Standalone PV Systems

The standalone photovoltaic system is not connected to the grid or utility provider, the power produced in such a system is used directly by the consumer. PV modules/panels, energy storage units (batteries), charge controller and an inverter (where ac load are required) are the components which constitute standalone photovoltaic systems. Standalone photovoltaic systems are most useful in communities with erratic or without power supply from the utility provider, also when power from the grid becomes too expensive; standalone PV systems can be used to reduce cost (Sieminski, 2014).

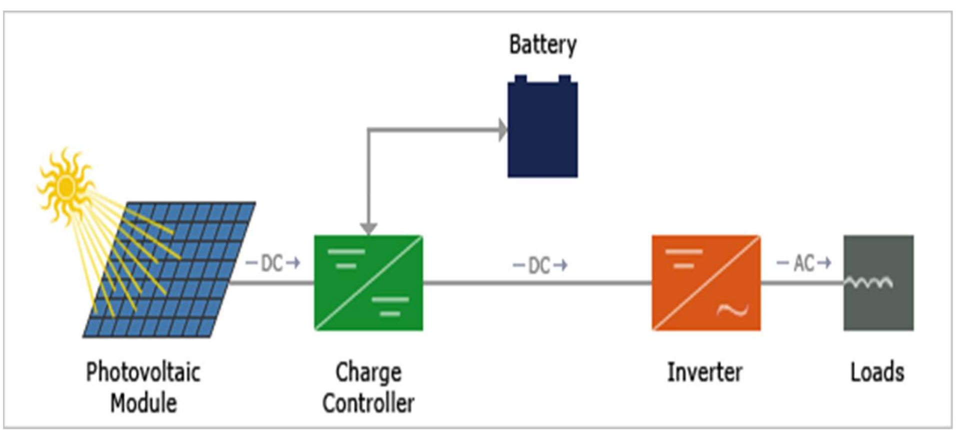


Figure 2.5: Standalone PV system (Sieminski, 2014)

2.2.8 Grid Connected PV Systems

The grid connected photovoltaic system is a PV system which is connected to the utility or grid by an inverter. Previously grid connected photovoltaic systems do not use energy storage units but with the advent of tesla megawatt battery units called ***Powerpack*** its possible now to store energy in megawatts for grid applications. Grid connected PV systems is made-up of commercial solar farms and standalone systems have grid integration due to favorable grid codes in mostly developed countries.

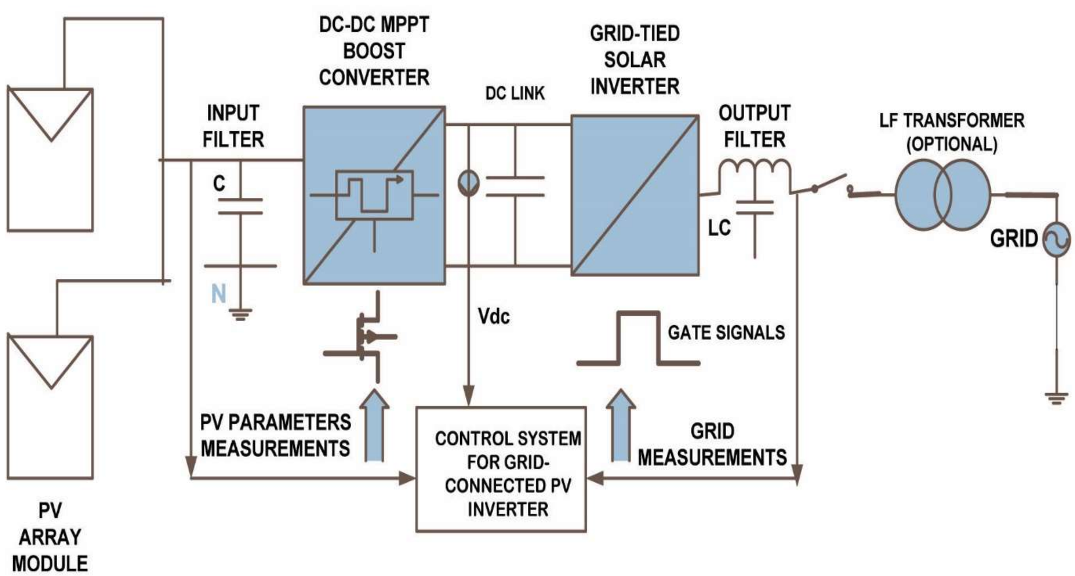


Figure 2.6: Grid connceted PV system(Tiwari & Dubey, 2009)

2.2.9 Hybrid PV System

The hybrid photovoltaic system combines solar energy and any other power production unit or energy storage units to provide power in case the PV systems is unable to deliver power. PV systems depend on solar energy as the fuel for electric power generation hence in situations of weather fluctuation or at night, power generation becomes problematic for PV systems. A typical example of the hybrid PV system is the PV/diesel generation units, other combinations are PV/wind, PV/energy storage unit etc.

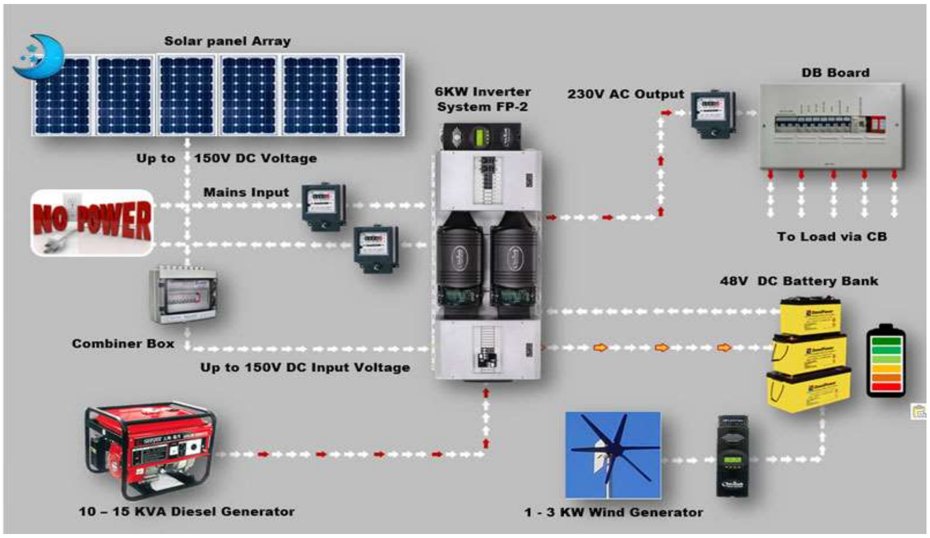


Figure 2.7: Hybrid PV system (Admin, 2016)

2.2.10 Applications of Photovoltaic systems

Photovoltaic systems have variety of applications. Due to its wide range applications its advantages are enormous and plays very critical role in the socio economic development of most countries. PV systems are useful in reducing CO_2 gas emission by avoiding fossil fuels as means of power generation. Some areas of PV system applications are:

a. Telecommunication and signaling. b. Space applications. c. Residential applications
d. lighting of highway and traffic e. health and agriculture

f. transport and Photovoltaic g. Special power systems.

2.2.11 Concentrated solar power (CSP)

Concentrated solar power or thermal power differs from photovoltaic system in terms of methodology but they utilize solar energy as the fuel for electric power generation. Thermal power prefers the heat component of solar energy. In Concentrated solar power, highly polished surfaces or mirrors are used to focus radiations of the sun on devices known as solar collectors; these solar collectors transfer their heat energy from the sun onto substances such as water, salt etc. within their core. Depending on the type of concentrated solar power technology, water is heated to steam which is used to power steam turbine (Poole, 2001). Unlike PV systems which can be located at almost anywhere in the world, concentrated solar power has limitations in terms of site locations. Hence the best locations for building concentrated solar power technology are areas with at least 2000KWh/m^2 of yearly solar radiation but locations 2800KWh/m^2 and above of yearly solar radiations are the best locations for concentrated solar power technology. Iran middle and near east, Australia, North and South Africa, United States, Soviet Union, India and Pakistan are very suitable locations for the building of concentrated solar power (Power, 2009). One major disadvantage of concentrated solar power is the large volumes of water required for cooling purposes; it the absence of water air cooling is applied which raises the cost of the systems by more than five percent but below ten percent. Hybrid cooling can be utilized to reduce the cost of the system. There are four types of concentrated solar power technology; ***Solar Dish, Solar Tower, Parabolic Trough, Linear Fresnel Reflector.***

2.2.12 Parabolic Trough (PT)

The parabolic trough (PT) uses curved mirrors or highly polished surfaces which are curved to concentrate solar energy onto a tube containing fluids located in at the center of parabolic trough but at an elevated level. The fluid in the tube (say water) is heated to desirable temperatures of 400 degrees Celsius and above which is used to produce steam to power steam turbines. Among the types of concentrated solar power, parabolic trough technology is the most advanced and most utilized method for power generation (Poole, 2001), (Power, 2009).

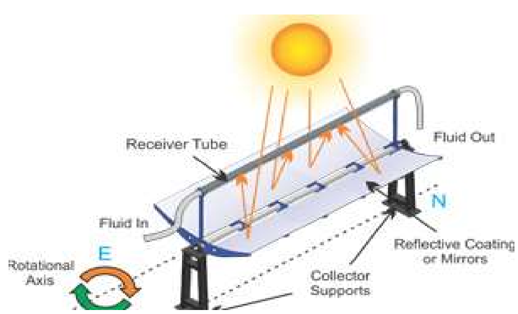


Figure 2.8: Parabolic trough (Power, 2009)

Table 2.1 Parabolic Trough in USA (Power, 2009)

Plant Name	Location	1st year of operation	Output power MW	Dispatchability Provided by
SEGS I	Dagget, CA	1985	13.8	3-hrs TES
Nevada solar 1	Boulder City, NV	2007	64	None
SEGS II	Dagget, CA	1986	30	Gas Boiler
APS Saguaro	Tucson, AZ	2006	1	None
SEGS IV	Kramer Junction CA	1987	30	Gas Boiler
SEGS V	Kramer Junction CA	1988	30	Gas Boiler
SEGS VI	Kramer Junction CA	1989	30	Gas Boiler

2.2.13 Linear Fresnel Reflector

The Linear Fresnel Reflector (LFR) technology uses the same method as the parabolic trough, instead of curved mirrors; flat surfaced mirrors are used in the linear Fresnel reflector technology. An inverted linear collector located at an elevated level above the flat surfaced mirror containing water receives solar radiations which are reflected onto it by the mirrors. Also water is converted to steam by the solar energy which is used to drive a steam turbine to produce electric power. When compared to parabolic trough, this method is new and has reduced system cost and also installation area is reduced (Environmental and Energy Study Institute (EESI), 2009).

Figure 2.9: Linear Fresnel Reflectors
(Environmental and Energy Study Institute (EESI), 2009)

2.2.14 Central Receiver

The central receiver also known as solar tower uses a collection of mirrors known as heliostat which has the attributes of sun tracking centralizes solar radiation onto a receiver at apex of a tower. The receiver is known as central receiver and it transfers the heat energy into another substance; water, oil or salt, the thermal energy in solar radiation is converted to a suitable state for electric power generation. The state is dependent on the generation unit head. For example air at very high temperatures (1000^{o}C) can be used to power a gas turbine. Several components combined forms the solar tower; heliostats, receiver, thermal storage unit, controllers, heat exchange and transport medium (Poole, 2001; Power, 2009) (Environmental and Energy Study Institute (EESI), 2009).

Figure 2.10: Central receiver(Environmental and Energy Study Institute (EESI), 2009)

2.2.15 Solar Dish

The solar dish also known as the dish system has the same appearance as the satellite receiver used for communication purposes. The solar dish technology also use mirror which are designed into a dish form and used to concentrate solar energy onto a receiver as shown in Fig. 28. The components of the solar dish system are: engine, receiver and concentrator. The engine is located on the elevated point at the center of the dish where received solar radiations used by the engine to produce electric power. The mechanism of the engine is similar to that of car engine; an electric generator is used for the power generation.

The solar dish technology has the advantage of using dual axis tracking systems hence maximization of output power is possible at all times of the day hence efficiency of the system can be considered very high.

Figure 2.11: Solar dish technology (Environmental and Energy Study Institute (EESI), 2009)

They are other solar energy technologies such as concentrated photovoltaic systems which is similar to the conventional photovoltaic but combines part of the solar cell technology and part of concentrated solar technology with multi junction solar cells which are highly efficient. Some other applications of solar energy are cooling, desalination, energy storage, heating and etc.

2.3 Wind Energy

Until the concept of generating electricity from wind energy, other applications of wind energy existed such water pumping, wood sawing, grain grinding, irrigation etc. the use of wind energy is over 300 years old. The term windmill was used to describe activities which used energy power as the prime mover. Also during the early stages of wind energy based electricity generation, the generation systems description fell under windmill technology but not anymore. Basically windmills provided mechanical power which was used in various applications. An example of windmill is shown in Fig. 2.11(Manwell, McGowan, & Rogers, 2010),(Spera, 1994).

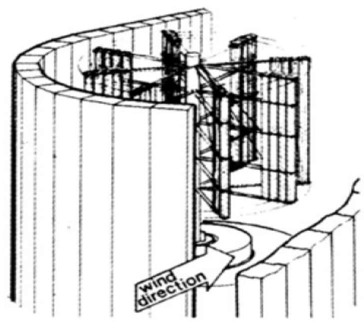


Figure 2.12: Windmill of Persian origin (Manwell et al., 2010)

The concept of windmill gave birth to wind turbines which were developed for the generation of electric power. The initial concept where windmills provided mechanical power to move heavy loads is still visible in the wind turbines. In the case of the wind turbine, the mechanical power is used to move the rotor of a generator thereby producing electricity. Basically windmills provide mechanical power whiles wind turbines generate electric power. Examples of the pioneering wind turbine rotors are: Savonius and Darrieus. Wind turbines are put into two categories; vertical axis wind turbines known as VAWT and horizontal axis wind turbines also known as HAWT. By their nomenclature, the difference lies in the rotation of the turbines about the axis. In the case of VAWT, the rotation is about vertical axis whiles the rotation is about the horizontal axis for the HAWT (Duran, 2005).

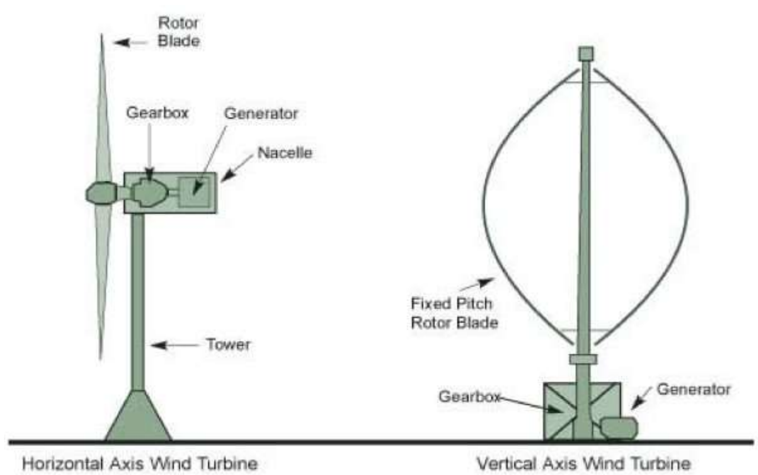


Figure 2.13: HAWT and VAWT (Duran, 2005)

The horizontal axis wind turbine is the most common type of wind turbine being used currently for most wind energy related projects. One major characteristics of the modern HAWT is that most of them come in three blades forms although the number of blades can vary. The horizontal axis wind turbine can be divided into two groups based on the orientation of the rotor; upwind tower HAWT and downwind tower HAWT. There are other classifications based on the following:

a. Articulation of the blade; is it teetering form or rigid form.
b. Wind alignment; is the active yaw type or free yaw.
c. Blade number; is the number of blades 3 or 2.
d. Control of the rotor: is the control stall type or pitch type.

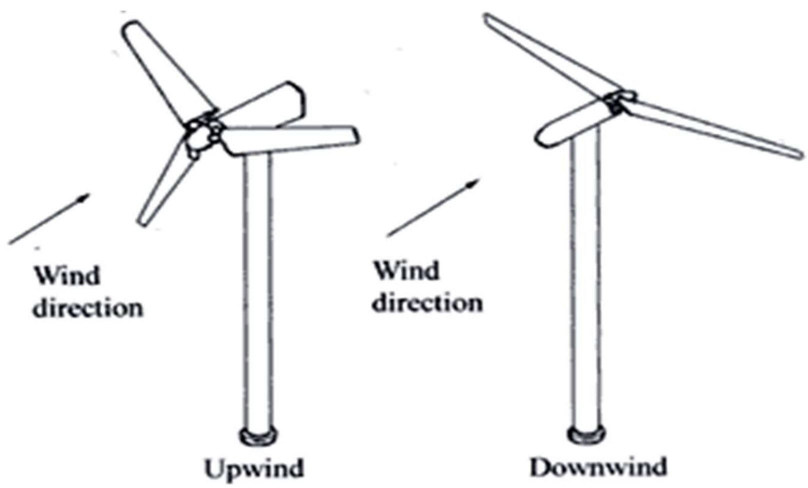


Figure 2.14: upwind and downwind HAWT turbines (Duran, 2005)

Two basic mathematical parameters which define the performance of the horizontal axis wind turbine are shown in (2.1) and (2.2).

$$C_p=\frac{P}{\frac{1}{2}PU_{\infty}^{2}\pi R^{2}} \tag{2.1}$$

$$C_T=\frac{T}{\frac{1}{2}PU_{\infty}^{2}\pi R^{2}} \tag{2.2}$$

Wind turbine capacity and size has evolved over the years with the introduction of bigger blades which corresponds to bigger megawatts of output power hence higher efficiency with reduced noise. Fig. 2.14 shows the capacity of wind turbines from the 19th century to 2025. As 2015, a single wind turbine had the capacity to produce 9 megawatts of output power.

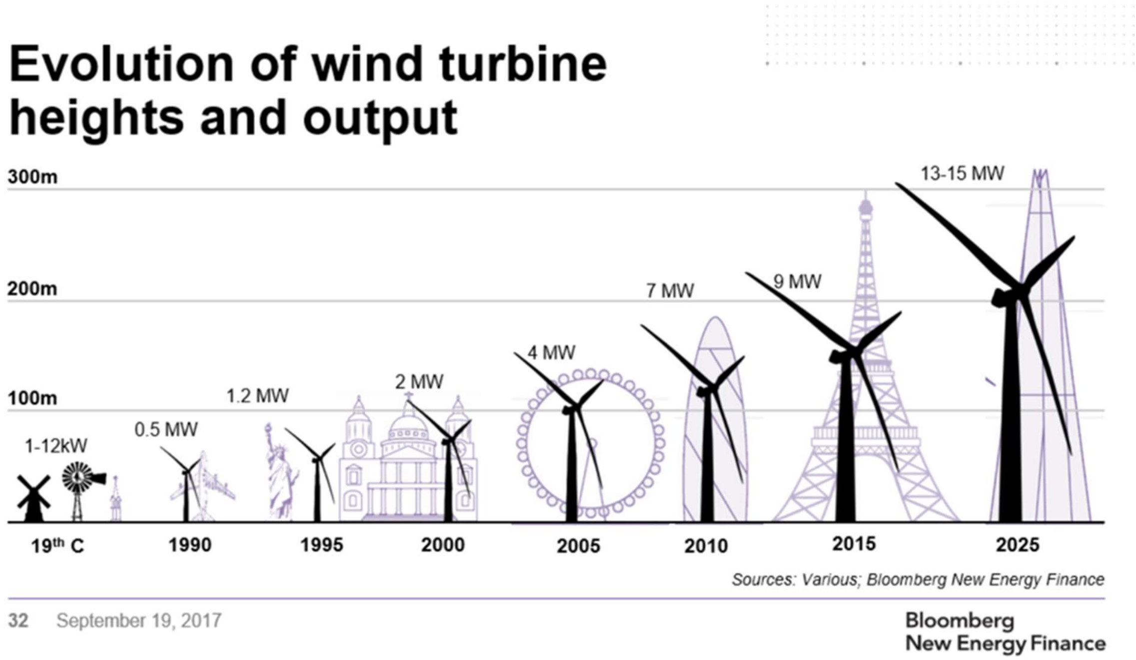


Figure 2.15: Wind turbine size and power evolution (Liebreich, 2017)

2.3.1 Advantages of Wind Energy

Wind energy is a renewable resource which means that it's environmentally friendly and will never run out compared to fossil fuels used for electric power generation. Advantages of wind are enormous. For example:

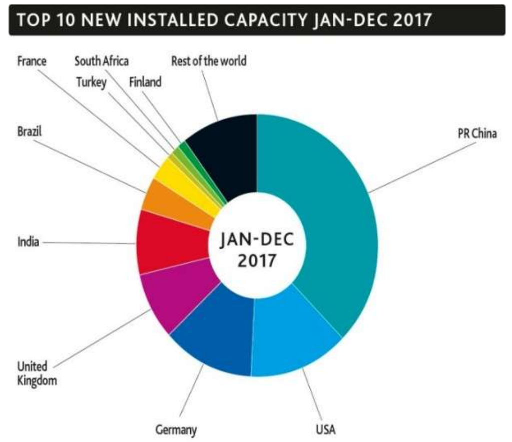
1. It's a renewable energy source which means it will always be available.
2. Does not cause negative effects to the environment.
3. Increased use of wind energy will reduce the use of fossil fuel hence protection of the environment.
4. Wind energy as a 'fuel' is free, no cost buildup for fuel purchase

5. Installation capacity is dependent on the customer; private and commercial installations are possible.
6. One major advantage is job creation for manufacturers, installers, and repairers.
7. Providing electric power to remote communities.
8. Requires minimum maintenance and least cost of running.

2.3.2 Disadvantages of Wind Energy

1. The wind speed is not constant, it varies.
2. Initial cost of installation is costly.
3. The rotation of the blades causes noise pollution.
4. The rotation of the blades also kills birds and other wildlife.
5. The beauty of the environment is destroyed.

Fig. 2.15 shows the installed capacity of wind energy from January to December of 2017, from the chart, China PR leads with 37% of the global installed capacity.



Country	MW	% Share
PR China	19,660	37
USA	7,017	13
Germany	6,581	12
United Kingdom	4,270	8
India	4,148	8
Brazil	2,022	4
France	1,694	3
Turkey	766	1
South Africa	618	1
Finland	535	1
Rest of the world	5,182	10
Total TOP 10	**47,310**	**90**
World Total	**52,492**	**100**

Source: GWEC

Figure 2.16: Wind turbine size and power evolution (Sawyer, 2017)

2.4 Hydro Energy

Hydro energy is a renewable obtained from water flowing at great gravity or force which is used to rotate the turbines of generators to produce electric power. Both wind and hydro energy are forms of solar energy because the sun's radiations help in producing wind and water (hydro). Basically water in motion has powerful force which can be channeled into driving the turbines of generators to produce electricity. One of the most common forms of hydro energy is the hydropower hydroelectric power plants. These hydroelectric power plants come in various sizes and locations. Megawatts of hydropower plants usually require dams to store water for longer years of generation; streams and rivers may have small kilowatts of hydropower for private or mini-commercial applications. In Fig. 2.17, a dam based hydroelectric power plant is shown; water stored in the dam (headwater) is released through the penstock at an appreciable height and in a controlled manner, the force of the water turns the blade of the generator to produce electric power, the tail-water is released downstream. In the case of private or mini-commercial hydropower plants, suitable converters like ***matrix converter*** can be used to efficiently condition the power before transmitting to the consumer. Hydroelectric power plants have several advantages such as; renewable energy, non-pollutant, very reliable and requires minimum maintenance but some disadvantage's in the case of megawatts facilities is the need for dam which requires land and also heavy rains causes flooding of adjacent areas [d] .

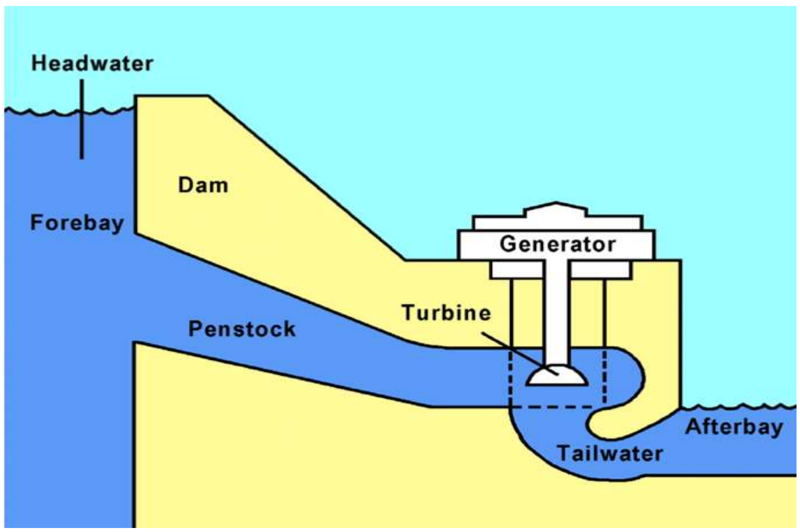


Figure 2.17: Hydro-electric power plant. (Office, 2005)

2.5 Tidal/Wave Energy

Tidal and wave energy occurs at the same location; at sea or at the beach. Tidal wave is caused by the difference in gravitational force which exist between these three bodies; earth, moon and sun. The moon creates diurnal tide and ebb cycles because it applies much force on the tides, basically tidal energy is harnessing the power of the rise and fall of tides. Canada has one the best tides in the world which is located at Fundy bay, with amplitude measurements of 16m – 17m close to the shore. Examples of locations with very good tides are shown in Table (2.2).

Table 2.2: Examples of locations with very good tides (Gorlov, 2001)

Country	Location	Range of tide (meters)
Russia	Penzhinskaya Guba (Sea of Okhotsk)	13.4
Russia	Bay of Mezen (White Sea)	10.0
Argentina	Puerto Rio Gallegos	13.3
France	La Rance	13.5
France	Port of Ganville	14.7
England	Severn Estuary	14.5
Canada	Fundy Bay	16.2

Tidal energy has two components; potential and kinetic energies. Potential energy is the energy required to raise a kilogram of water aloft the surface of the ocean. Mathematically, the potential energy of tidal energy is given by (2.3) where: E is the energy, h is the amplitude or height of the tide, A is the area and ρ is the density. The kinetic energy represented by T is given by (2.4) where the mass and velocity are represented m and V respectively. Some examples of installed Tidal power plants are shown in Table (2.3).

$$E=0.5g\rho Ah^2 \tag{2.3}$$

$$T=0.5mV^2 \tag{2.4}$$

Table 2.3: Tidal energy installed capacity around the world (Gorlov, 2001)

COUNTRY	LOCATION	INSTALLED CAPACITY MW
France	La Rance	240
Russia	Kislaya Guba	0.4
Canada	Annapolis	18
China	Jiangxia	3.9

2.6 Biomass Energy

Biomass is any matter or substance on the surface of the earth which is produced by the process called photosynthesis. Basically they are trees, shrubs, vegetation’s etc. Also biomass refers to all waste produced by living organisms such as human waste which can be categorized into sewage and solid waste, there are forms of waste such as animal waste, vegetation waste and waste produced by industrial factories.

Until the discovery of fossil fuels, energy generated from biomass help the human race to live with comfort, an example is the use of wood for fire to cook and also warm ourselves during winter season. Even in today’s fast paced and developed world, biomass plays an important role in the lives of under developed countries and countries under conflict (Sriram & Shahidehpour, 2005).

Although the use of biomass produce carbon dioxide, this is not a problem because growing of biomass substances absorbs carbon dioxide from the atmosphere hence the process is a recycling one and also biomass is renewable (Sriram & Shahidehpour, 2005). The process of releasing energy from biomass can be put into 5 categories;

a. Combustion
b. Gasification
c. Pyrolysis
d. Digestion
e. Fermentation

Figure 2.18: Cycle of biomass energy (Sriram & Shahidehpour, 2005)

The combustion method of releasing energy from biomass can be considered as the not too technical one, this process involves the burning of biomass materials to produce heat which is used in various ways to generate electric power. The heat produced from biomass can be used to boil water to steam to turn steam turbines or the heat can be used in other forms of thermal power plants for electricity generation (Sriram & Shahidehpour, 2005). The gasification process involves changing biomass into gas which can be used as fuel to generate electricity. The gasification process is simplified in Figure 2.19.

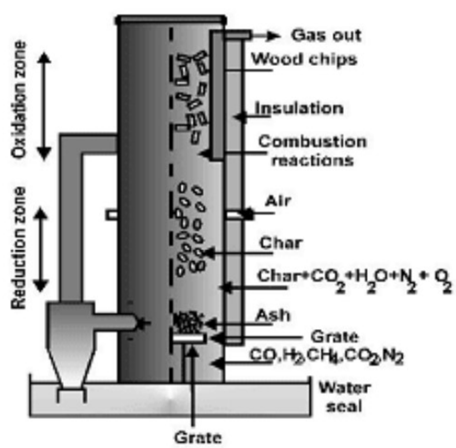


Figure 2.19: Gasification method. (Sriram & Shahidehpour, 2005)

The pyrolysis method involves the production of charcoal from biomass which is considered a healthy form of energy and can last much longer than product from which it was derived. Digestion process can be natural or artificial and this leads to the production of methane or hydrogen which can be used as fuels. Fermentation process leads to the production of biofuels, ethanol, methanol and biodiesel (Sriram & Shahidehpour, 2005).

2.7 Geothermal Energy

Actually Geothermal energy name is derived (geothermal) from the combination of two words from the Greek language. Earth and heat stands for ***geo*** and ***therme*** respectively in Greek. So basically, geothermal energy is the heat or thermal energy derived from the crust of the earth. This type of energy is considered renewable because it's a natural replenishing substance. The process of geothermal energy is illustrated in Fig 2.20

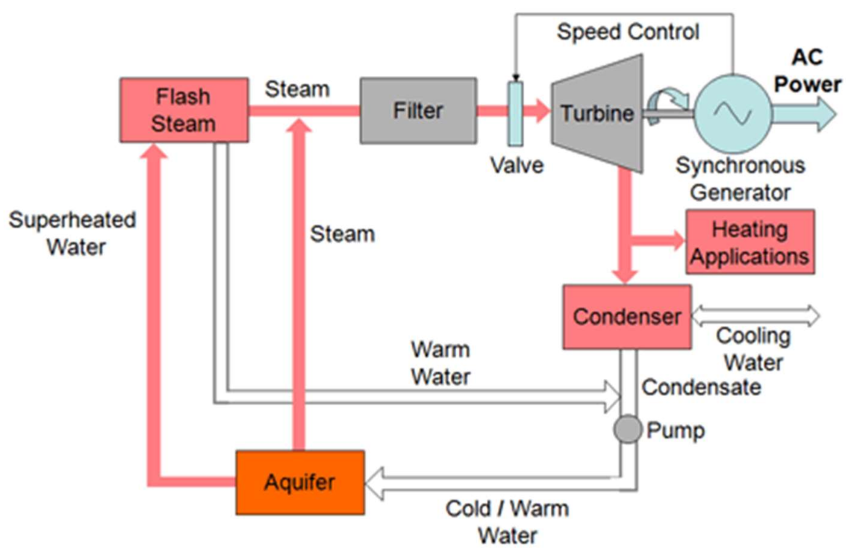


Figure 2.20: Geothermal energy (DiPippo, 2016)

CHAPTER 3

DISTRIBUTED GENERATION AND MICROGRID

3.0 Introduction

Increase in electric power demand across the globe has resulted in reduced supply leaving most countries categorized as ***third world countries*** with poor generation and distribution capacities. This can be linked to increased resources needed to establish generations which mainly use fossil fuels; causing serious havoc to the environment. Renewable energy sources have off recent attained much attention, developed countries like Germany, China, USA and Japan have made serious investment in generations stations which are whole renewable energy such wind, hydro, photovoltaic system etc. Projections in Figure 3.1 made by world energy outlook predicts solar energy, wind energy and other forms of renewable energy going to account for most of newly installed generating stations. Distributed generation (DG) is an electric power generating facility which comes with energy storage systems discharge by a combination of small capacity units mostly called DER (distributed energy resources). Distributed generation can be grid connected or standalone units, DGs are also referred to as:

a. On-site generation
b. Distributed energy
c. Localized energy

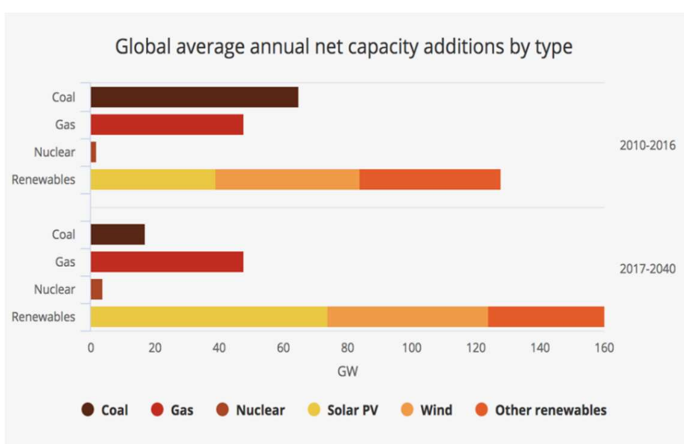


Figure 3.1: Electric power generation sources (Outlook, 2017)

3.1Distributed Generation

Basically distributed generation uses small capacity generation sets to generate electric power and the facility is sited close the load or consumer. Distributed generations are mostly localized, flexible to install, modular and have generating capacities not exceeding 100MW. Distributed generations are classified as ***hybrid*** when two or more forms of generating units are combined to produce power, examples are PV together with wind, PV together with diesel generators, PV, wind together with diesel generator. Renewable energy sources are major units distributed generation setups, some examples of renewable energy sources mostly used in DG setups like wind, hydro, biomass, biofuels, solar, geothermal and tidal/wave energy. Grid Connection of power from Distributed generation units is done on two levels: low voltage (LV) levels or medium voltage (MV) levels, what is most preferable currently is to connect the DG on the same voltage level as the load as to minimize conversion losses (Barker & De Mello, 2000). Table 3.1 shows the classification of distributed generation units (González-Longatt, 2008).

Table 3.1: Classification of DGs (González-Longatt, 2008)

CATEGORY	**SIZE**
Large DG	50MW – 300MW
Medium DG	5MW – 50MW
Small DG	5kW - 5MW
Micro DG	1W – 5kW

3.1.1. Advantages of Distributed generation (Vu Van, Driesen, & Belmans, 2004)

1. Distributed generation units provide guaranty and reliable electric power to consumers and provide value-for-money to utility providers due to minimize losses.
2. Distributed generation units provide the following factors; stable power, quality power and the noise in power are hugely minimized.

3. Installation period is less when compared to traditional power generation units and payback periods are less.
4. Most distributed generation units are environmentally friendly due to the application of renewable energy sources and efficiencies are really high.

3.1.2.Disadvantages of Distributed generation (Vu Van et al., 2004)

1. AC to AC power electronic converters are not able to reduce harmonic contents in the power system.
2. Grid connection of DGs could possible introduce the following drawbacks in power system; power fluctuations, over voltage and unbalance conditions when grid tying conditions are not properly met.
3. Circuit problems usually arise when distributed generation units are connected to the grid.

Due to the nature of distributed generation unit in many countries, classification of DGs is done using different criteria per the country involved. In (González-Longatt, 2008), distributed generations are grouped into two categories: DGs based on rotating devices and converter/inverter based DGs. Also using distributed energy resources as the criteria for categorization, the following DGs will be obtained. One major disadvantage of DER is that the initial capital (Friedman, 2002) tends to expensive:

a. PV system
b. Concentrated PV system (sterling engines)
c. Fuel cells
d. Micro-turbines
e. Combined heat power
f. Hybrid DGs
g. Wind turbines

Photovoltaic systems is a typical example of inverter based distributed generation unit and micro-turbines together with wind turbines constitute the rotating machine based DGs. Most DERs have been explained in previous chapters hence only fuel cells, combined heat power and micro-turbines will be explained in this chapter. These types of distributed energy resources will be compared to each other and their advantages and disadvantages enumerated.

3.2. Combined Heat and Power

Combined heat power (CHP) which is sometimes called total power or cogeneration is a crucial source of electric power generation for distribution networks of the utility. Combined heat and power can be defined as concurrent generation of electricity and productive heat. Basically CHP generate electric power and heat at the same time; the electric power generated is utilized by the load and the heat generated during the process of electric power generation is left to waste but it's put to good use such as heating of buildings or factories and also used for industrial applications. Typical example of the application of combined heat and power for heating purposes is located mostly in European countries such as Denmark, UK, Finland and Sweden (Horlock, 1987). In Denmark, the use of CHP for rural applications are achieved by building smaller combined heat and power units (Jorgensen, Sorensen, Chistensen, & Herager, 1997). If the consumer is unable to utilize all the generated power, the excess power is supplied to the grid usually via distribution lines.

The efficiency of most combined heat and power installations are composed of two part; electric power efficiency and heat recovery efficiency. The total efficiency of most installed CHP is 67%; the efficiency and heat recovery efficiency are 23% and 44% respectively. When compared to single cycle power plants and heat boilers, the main energy used for power generation will be minimized by 35% which is a cost saving and efficiency related advantage. The environment is also a beneficiary because carbon dioxide emissions are reduced by 30% and 10% when compared to coil power plants and combined gas power plants respectively (Office., 2009). Examples of CHP power plant based technologies installed in U.S.A are shown in Table 3.2.

Table 3.2: Installed CHP in the USA (Agency & Partnership, 2015)

PRIME MOVER	CAPACITY MW
Reciprocating Engine	2288
Gas Turbine	53320
Steam Turbine	26741
Microturbine	78
Fuel Cell	84

Source: ICF CHP Installation Database, April 2014

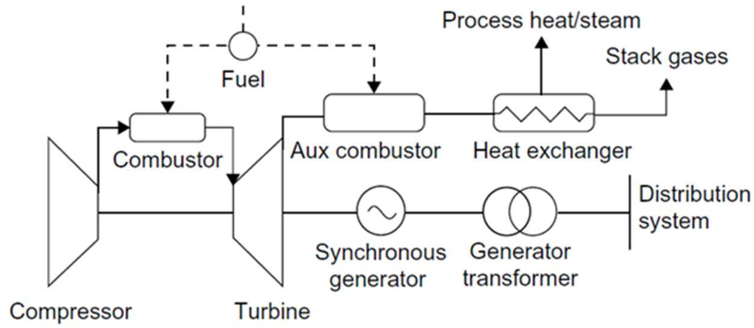


Figure 3.2: Gas turbine based CHP with heat recovery system (Office., 2009)

3.3. Fuel Cells

Fuel cells (FC) are devices which are able to generate electricity by the principle of electrochemical reactions. Unlike most fossil fuel based plants, fuel cells do not burn or combust fuels but are still able to produce heat from the electrochemical reactions. Hydrogen and water are fused together by the electrochemical device which produces heat and water as the byproducts. Fuel cells have generation capacity from small, medium to high voltage ranges. The small FCs have capacity of 1kW, the medium FCs have capacity of 100kW and finally the high voltage FCs have capacity of 1MW (Ett, Janólio, & Ett, 2002). The fuel cell technology was first unearthed by Christian Friedrich Shoenbein; a German scientist but the technology was first expanded and made meaningful in 1839 by William Robert Grove.

Fuel cell devices transform chemical energy into electricity or electric power, they do not produce harmful substance which will have adverse effects on the environment. One major advantage of fuel cell technology is that the levels of CO2 and SO2 emitted are much lower when compared to conventional fossil fuel plants and other power plants; also its efficiency is much higher (Soo, Loh, Mohamad, Daud, & Wong, 2015) – (Peksen, 2015). The output (0.5V – 0.9V) voltage generated by fuel cells have low values hence to achieve much higher voltages several fuel cells are combined to achieve this aim. This does not mean that megawatts capacity fuels are not available on the market but on the contrary they are available. The efficiency of fuel cells ranges between 40% to 60%; the possibility of increasing this efficiency to 85% is possible when applied as CHP (Hatti, 2007; Rajasekar et al., 2015). Figure 3.3 shows the fuel cell technology.

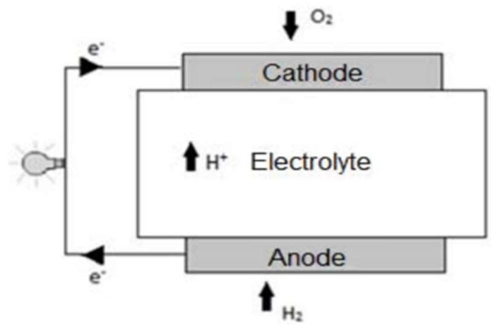


Figure 3.3: Fuel cell technology (Hatti, 2007)

3.4. Microturbine

Microturbines as family of distributed energy resources is receiving much focus because of its numerous advantages such quick responds to variations or changes in load profiles, minimum noise and vibrations when in operation, multi fuel device requires no maintenance or at least needs minimum (Farret & Simoes, 2006). Microturbines can be utilized in several ways such as: standalone power unit providing power for a facility or as standby generator when utility power fails and finally used to provide power during peak hours (Gaonkar, Patel, & Pillai, 2006) (Noroozian, Abedi, Gharehpetian, & Hosseini, 2009). Basically microturbines are small power plants where liquefied or gaseous fuels are combusted in a combustion chamber and the produced heat is used to power a generator. An example of a microturbine with a cutaway section is shown in Figure 3.4.

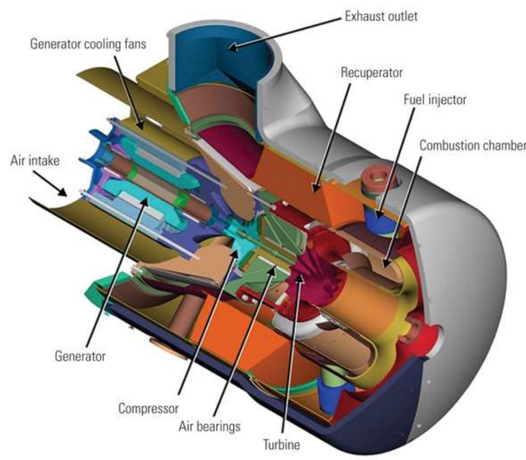


Figure. 3.4: Microturbine (Gaonkar et al., 2006)

3.5. Microgrid

The introduction of renewable energy sources and distributed energy resources has shifted the focus of electric power generation from a centralized system to a local or decentralized system. Hence generation, transmission and operation of power system is no longer dependent on centralized generation units. Microgrid (MG) is an example of localized generation unit and it's mostly composed of a variety of energy sources such as photovoltaic system, wind energy, mini hydroelectric plants. Microgrid is a decentralized power generation system composed of transmission system, power condition unit (converters, inverter), energy storage systems, DGs and communications system (Guerrero, Loh, Lee, & Chandorkar, 2013; Lasseter, 2002). Better still, microgrid can be defined as a collection of interlinked DGs and loads within a specified area which is controlled as a single unity. Microgrids sometimes referred to as mini-grid can either be a standalone system or grid connected; also min-grid can have energy storage systems or may not. Hybrid mini-grid is a combination of direct current (dc) busbar and ac busbar systems. The following headings briefly best explain the microgrid;

Standalone mini-grid: standalone microgrid is an isolated grid which is not connected to utility or main power provider (grid). Standalone microgrids are also known as islanded mode and it's a self-sustaining system, energy storage systems are crucial parts of standalone microgrid.

Grid connected mini-grid: the grid tied mini-grids are microgrids which have interconnections with main utility provider, energy storage systems are not necessary since excess power on both sides can be transferred to each other.

Hybrid minigrid: Hybrid mini-grid is a combination of direct current (dc) busbar and ac busbar systems. Several control methods are applicable in effective and efficient control of microgrid, some examples are:

- REACTIVE POWER CONTROL
- MG ISLANDED CONTROL OPERATION
- HIERARCHICAL CONTROL OF DROOP CONTROLLED MICROGRIDS
- CONVENTIONAL AND FUZZY-PI BASED
- FREQUENCY CONTROL HYBRID MG CONTROL UNDER ISLANDING MODE

CHAPTER 4

MATRIX CONVERTER

4.0 Introduction

Matrix converter has been seen as a substitute for bidirectional current flow based converters and also very efficient when direct power conversion is required especially in the case of ac – ac power conversion. This section of my thesis reviews selected papers on matrix converter thoroughly based on the various common literature headings such as: type of topology whether it's direct matrix converter or indirect matrix converter, its applications in flexible ac transmissions, the type of control technique that is utilized. It's very important to state that most of literature on matrix converter is based on the control technique because the converter topology can hardly be changed unless newer topologies are to be developed.

4.1 Matrix Converter

Matrix converter topology is made up of a nine switch converter having bidirectional current flow capabilities and also four quadrants functionality. The matrix converter performs a wide variety of power conditioning such as conversions and inversions i.e. dc-ac, dc-dc, ac-dc and ac-ac. When the matrix converter performs power conditioning as dc-ac task, it's known as inverter (D. G. Holmes, 1990), if the task is dc-dc it's known as chopper, for ac-dc power conditioning it's known as a rectifier (D. Holmes & Lipo, 1989) and lastly, cycloconverter task is transfer ac-ac power condition (Venturini, 1980; Venturini & Alesina, 1980) (Neft & Schauder, 1988). Also the matrix converter is single stage conversion topology. Basically the output voltage type is independent of the input voltage type. Also in the case of the input phase and output phase, they are independent of each other; 3 phases at the input side can be reduced to either 1 or 2 phases or maintained at three phases as required by the system. Matrix converter was first introduced by (Gyugyi & Pelly, 1976). But it was later in 1981 that additional research was carried out by Venturini (Venturini, 1980). As in the case of all newly developed topologies, several drawbacks were presented hence this limited the application of the matrix inverter but suitable improvements were made to make the matrix converter have industrial applications (Alesina & Venturini, 1988; Beasant, Beattie, & Refsum, 1990). The circuit diagram of the nine bidirectional based switch is shown in Figure 4.1.

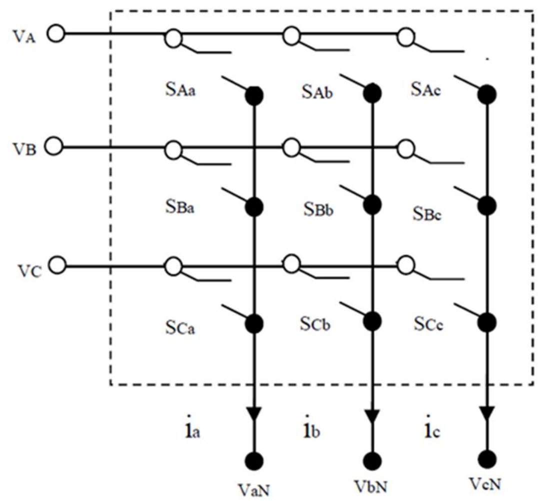


Figure 4.1: Matrix Converter (Beasant et al., 1990)

Figure 4.1 is the conventional circuit representation of a matrix converter but other publications have shown that number of maximum input and output phases is not limited to three but rather its matrix representation is ***m x n*** where ***m*** and ***n*** represent the number of output phases and input phases respectively. Hence a new circuit representation is shown in Figure 4.2.

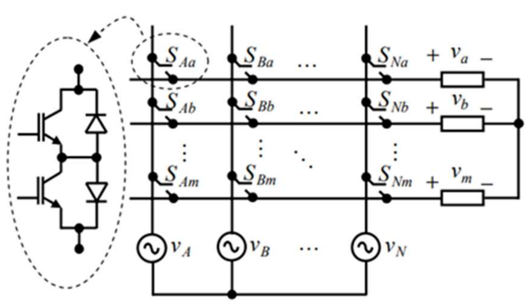


Figure 4.2: ***m x n*** matrix converter (Babaei, Hosseini, Gharehpetian, & Sabahi, 2006)

The input current and output voltage of a matrix converter as in the case of Figure 4.1 is shown by (4.1) and (4.2) respectively.

$$I_I = T^T \text{ x } I_0 = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \tag{4.1}$$

$$V_0 = T \text{ x } V_I \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{4.2}$$

4.1.1 Bidirectional Switch

The bidirectional switches used in matrix converters is not readily available or already developed but has to be designed by the engineer depending on the power ratings of the proposed converter. This is achieved by utilizing any of the four methods of producing bidirectional switches; a) diode bridge configuration, b) common emitter arrangement, c) common collector configuration, d) anti parallel configuration, f) reverse blocking configuration) and g) the hybrid structure as shown in Figure 4.3.

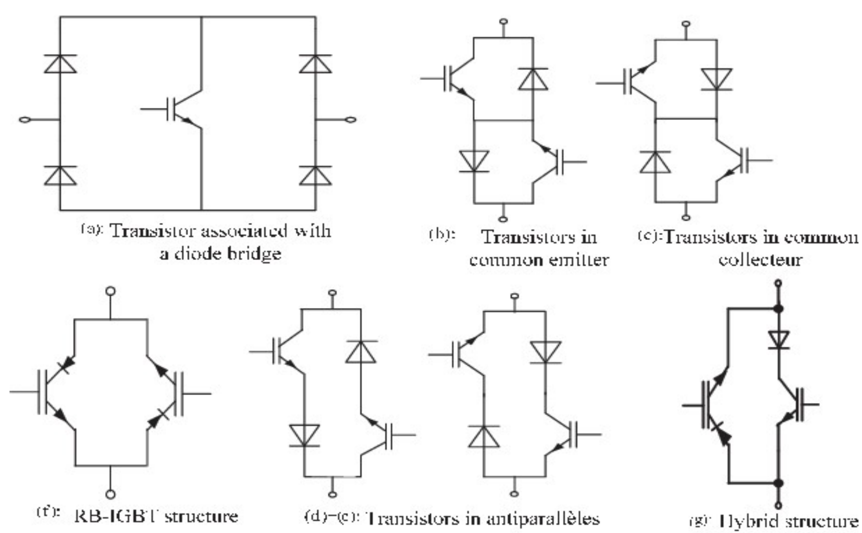


Figure 4.3: Bidirectional switches (Rmili, Rahmani, Vahedi, & Al-Haddad, 2014)

Matrix converter poses several advantages such as: output frequency changing capabilities, single stage conversion/converter, displacement factor boosting capabilities (Gyugyi &

Pelly, 1976; Venturini & Alesina, 1980), unity displacement factor, bidirectional power circulation, apex power density (Pan, Chen, & Shieh, 1993), input and output voltages have sinusoidal waveforms, the sinusoidal output voltage and frequency are variable, unity power factor current at the input and high efficiency (Huber & Borojevic, 1995). Minimum number of reactive elements (Zuckerberger, Weinstock, & Alexandrovitz, 1996), reduced size because large storage elements are omitted hence the input filter size and cost are minimized (P Wheeler & Grant, 1997), the layout will be compact because of the lack storage unit (Nielsen, Blaabjerg, & Pedersen, 1997). Also the matrix converter poses a few drawbacks such as limitation of the voltage transfer to 87%, the control scheme is much complicated when compared to other converters especially the voltage source inverter, lack of readymade bidirectional switches is a huge limitation (Nielsen et al., 1997). Voltage and current spikes occur during commutation of switches but safe commutation methods are possible but come with complicated control method (Burany, 1989; Huber, Burány, & Borojević, 1992). Due to lack of energy storage unit in the converter, the input power is directly transferred to the output hence any characteristics of the input will be present at the output (Nielsen et al., 1997). The component count is much higher 18 diodes and switches (Sunter & Altun, 1998).

4.2 Converter Losses

One major factor which reduces the efficiency of converters is the losses occurring in the used switches and the converter as whole. Reducing the converter losses will greatly boost the efficiency of the converter as such research into converter losses have been study by a couple of papers. In (PW Wheeler & Grant, 1992), the losses of the matrix converter were grouped into ***switching losses*** and ***conduction losses***. However there are other losses caused by leakage currents; ***off-state*** and ***gate*** losses, these losses are not considered because they are negligible. Conduction losses and switching losses are at maximum when switching frequency is low and high respectively (Sunter & Altun, 1998). The switching losses can be explained as the finite duration of the switch say IGBT to change state. In other words, switching losses depand on heavy junction temperature. Also switching frequencies affects switching losses; higher switching frequencies increase the switching losses whiles lower switching frequencies reduces the switching losses. Also snubber circuits affect switching losses. On the other hand, conduction losses are due to the forward voltage and current of the switch and duration of operation (PW Wheeler & Grant, 1992). Basically conduction loss occurs when the switch and diode are on on-state (Sunter & Altun, 1998). The conduction loss of a switch is given by (4.3) which is the product of the following parameters: a) duty cycle, b) forward voltage c) average current. Two components are used in the calculations; diode and IBGT. Saturation voltage and collector current of IGBT are represented by V_{ce} and I_c respectively whiles the forward voltage and forward current of the diodes are V_f and I_f respectively. The switching loss is the product of energy loss per pulse and switching frequency and the result given by (4.4).

$$P_{cond,phase} = \sum_{n=1}^{n=3}\left[(V_{cen} I_{cn} d_n) + (V_{fn} I_{fn} d_n)\right] = I_f(V_{ce} + V_f) \qquad (4.3)$$

$$P_{switch,phase} = 3f_s \text{ x } E_{loss} \qquad (4.4)$$

The sum of the conduction loss and switching loss determines the total losses in a matrix converter and it's expressed in (4.5).

$$P_{total\ loss} = 3(P_{cond,phase} + P_{switch,phase}) \qquad (4.5)$$

Fig. 4.4 show the losses diagram of matrix converter having 5kW capacity and using the following IBGT and diode ratings; IRGBCZO 600Volt, 13Amp IGBTs and MUR860 600Volt, 8Amp diodes.

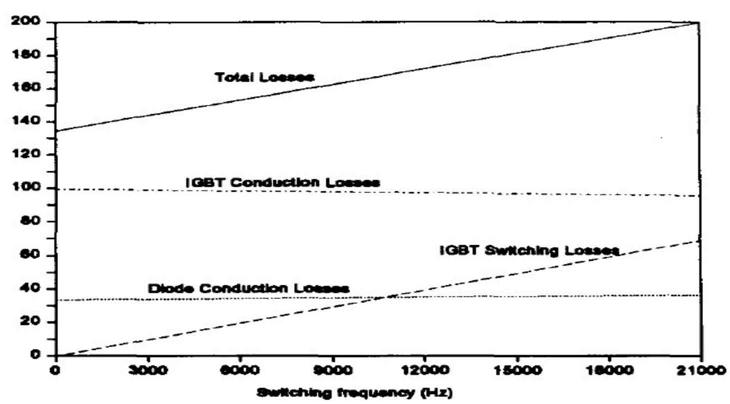


Figure 4.4: Loss diagram of a matrix converter (PW Wheeler & Grant, 1992)

Conduction losses are due to the forward voltage and current of the switch and duration of operation but in the case of switching losses of a matrix converter can be minimized by utilizing switches having limited switching durations, also another method for reducing the switching losses is applying suitable commutating method. Applying partially symmetrical pulsewidth modulation control method will also reduce switching losses.

Furthermore, by providing an overlap between each half of the bidirectional switches during switching periods will lead to reduction in switching losses; this process describes current commutation method which leads to zero current switching provided by turning on of the next switch which renders the outgoing switch to be reverse biased. Also with PWM method and appropriate switch selection method as describe in (PW Wheeler & Grant, 1992), switching losses can be reduced. The comparison of losses between matrix converter and an inverter shows that higher switching frequencies, matrix converter has less switching losses than the inverter and at lower switching frequencies, the losses of the matrix converter is slightly higher than a regular inverter (PW Wheeler & Grant, 1992).

In (Pan et al., 1993), a new bidirectional switch with zero switching loss capabilities is introduced. This switch is able to turn-on and turn-off at zero current and zero voltage respectively hence soft switching and zero losses can be obtained. The proposed switch is composed of active and passive components. The active components are diodes and two switches which have unidirectional power flow. The designs makes it possible for the switches to turn-on and turn-off at zero current and zero voltage respectively hence voltage and current spikes are eliminated and also zero switching loss is achieved. High switching frequency produces waveforms with very good qualities but has the disadvantage of increasing the losses due to switching, reducing the switching lose will significantly reduce the converter losses. Soft switching techniques are proposed in (Cho & Cho, 1991; Klaassens, Van Wesenbeeck, Lauw, & Tan, 1992) to help mitigate these problems.

The proposed bidirectional switch having zero switching loss is shown in Fig. 4. Two types of the bidirectional switch is represented a) the basic topology and b) the voltage clamped topology. Analysis of the basic topology shows that, four diodes D_1, D_2, D_3 and D_4 constitutes a bridge rectifier whiles the switches with simultaneous turn on and turn off capabilities are Q_1 and Q_2. The two passive components are inductor L and capacitor C, it should however be noted that the passive components voltage and current flow are unidirectional. Detailed explanation of converter losses is illustrated in (Sunter & Altun, 1998).

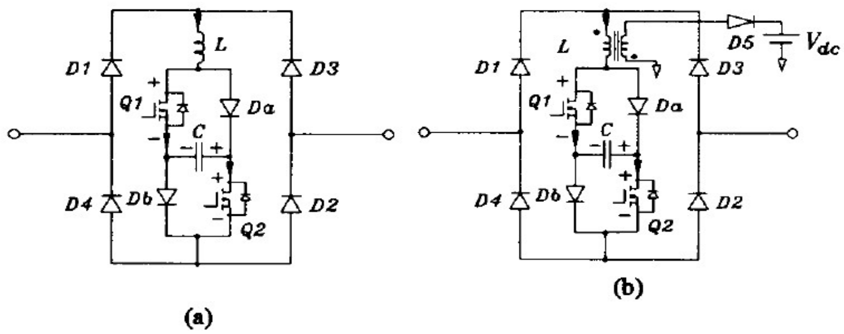


Figure 4.5: Bidirectional switch with zero switching loss (Pan et al., 1993)

Brief explanation of the mode of operation of the bidirectional switch is given below with adequate references shown in Fig. 4.6. When the two switches Q_1 and Q_2 are gated on, their respective currents (i_{Q1} and i_{Q2}) will start flowing from zero hence zero current switching is obtained; the direction of current flow or path of conduction is shown in Fig. 4.6a. This path of conduction will be represented Fig. 4.6b when the capacitor full discharges or its voltage V_c decays to zero. The full load current is carried by the inductor hence the turn-on process is accomplished but the capacitor voltage is still at zero waiting for the beginning of the turn-off process. In the turn-off process, switches Q_1 and Q_2 are gated off and the their respective switch voltages (V_{Q1} and V_{Q2}) will start the process from zero due to the turn-on conditions,

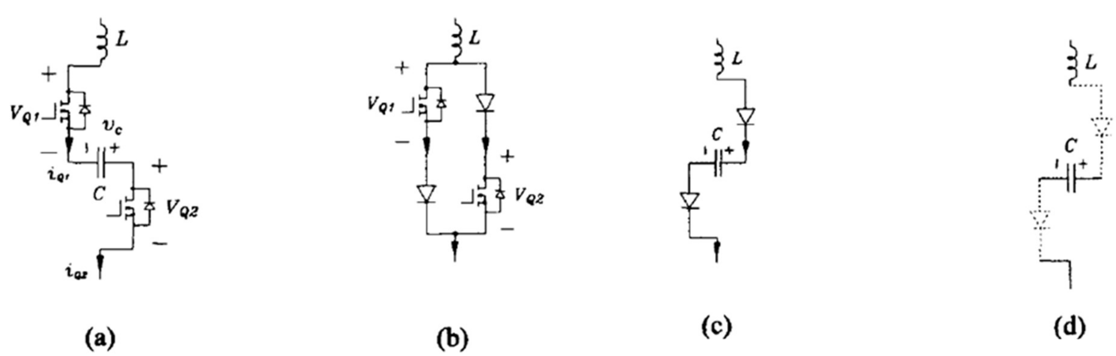


Figure 4.6: Mode of operation (Pan et al., 1993)

this process is shown in Fig. 5c. Finally Fig. 4.6d shows the states where the inductor voltage is fully dissipated to zero. The voltage and current waveforms of the proposed bidirectional switch under the different modes of operation is shown in Figure 4.7.

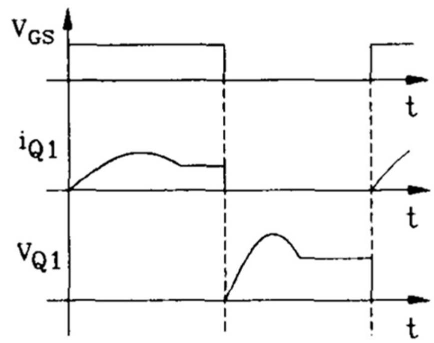


Figure 4.7: Current and voltage waveforms (Pan et al., 1993)

4.3 Direct Matrix Converter

Direct matrix converter is a single stage converter which utilizes nine bidirectional switches to change the amplitude, phase and frequency of an AC input voltage to a desired AC voltage with a desired amplitude, phase and frequency. Basically direct matrix converter is used in ac-ac power conversion. The number bidirectional switches is not limited to nine because new proposed topologies have varied number of bidirectional switches. Also the direct matrix converter can be used as chopper but its use as cycloconverter is most common because the buck-boost dc-dc converter has maximum efficiency due to limited number of active and passive components.

In (Kazerani & Ooi, 1993), a new switched based direct ac-ac matrix converter is proposed. The proposed topology is derived from the conventional voltage source inverter. The number of switches used in the proposed topology equals the number in the conventional matrix converter. The proposed topology offers better mode of operations which results in reduced error between simulation results and theoretical results. The structure of the proposed topology is shown in Figure 4.8 and it’s made up of three voltage source inverters operating together to form one converter. The output of this VSI type matrix converter is used to power a three phase load.

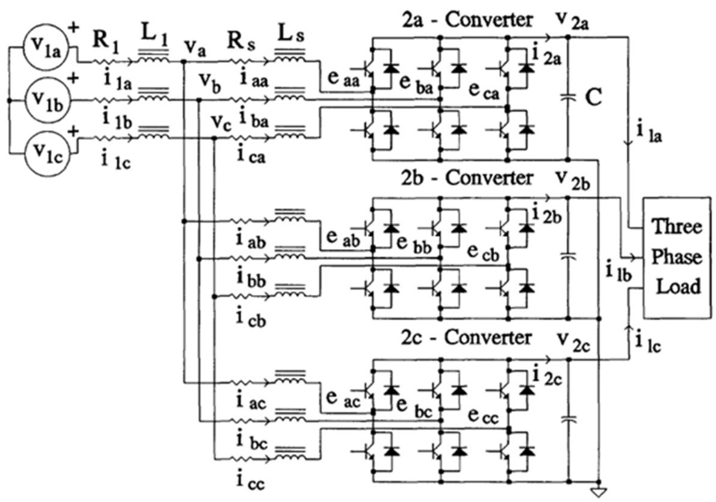


Figure 4.8: VSI type matrix converter (Kazerani & Ooi, 1993)

The above VSI based matrix converter has the advantages of; a) utilizing existing VSI technology, b) eliminating the complicated control technique and switching associated with the conventional matrix converter, c) reduced converter losses, d) unity power factor and field vector control at the input and output side of the converter respectively. However distorted waveforms and undesired components are present at the output side due to two factors; a) presence of dc components and b) transformation matrix topology (Kazerani & Ooi, 1993; Ooi & Kazerani, 1995). Detailed explanation of the elimination of the unwanted components is done in (Ooi & Kazerani, 1995) but basically, it involves the introduction of a transformer connected in a delta method as shown in Figure 4.9.

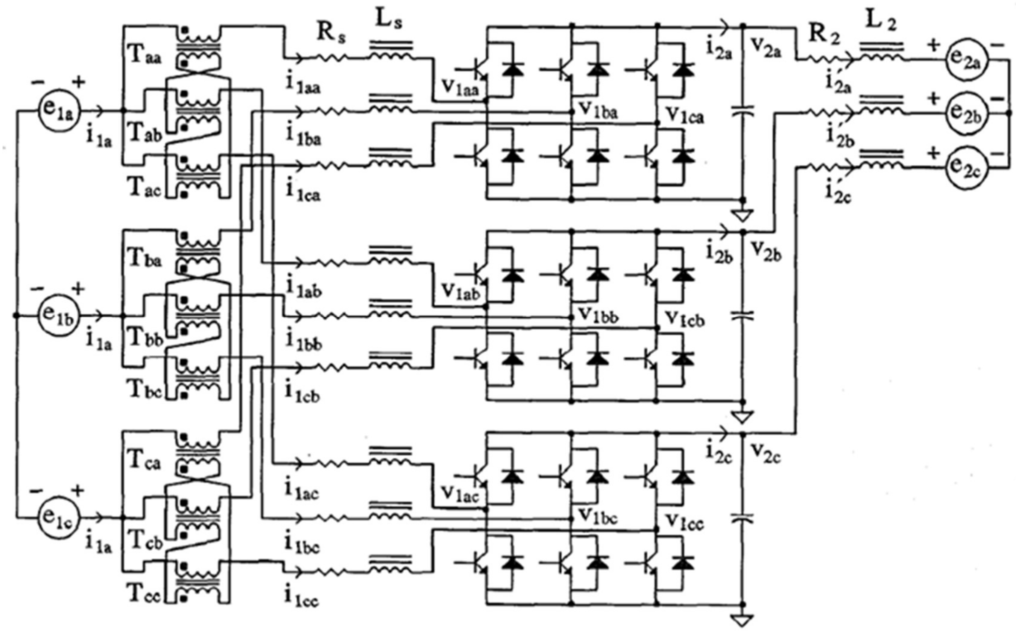


Figure 4.9: VSI based matrix converter with transformers (Ooi & Kazerani, 1995)

A similar topology of ac-ac matrix converter as in (Kazerani & Ooi, 1993) is presented in (Neacsu, 1999) but with different source and switch configurations. The input source is a current source and the semiconductor switch structure is unidirectional. A new control method is also presented which minimizes the switching loss and application of this converter in OWIM (open winding induction motor) is attempted. The structure of the proposed current source ac-ac matrix converter is shown in Figure 4.10.

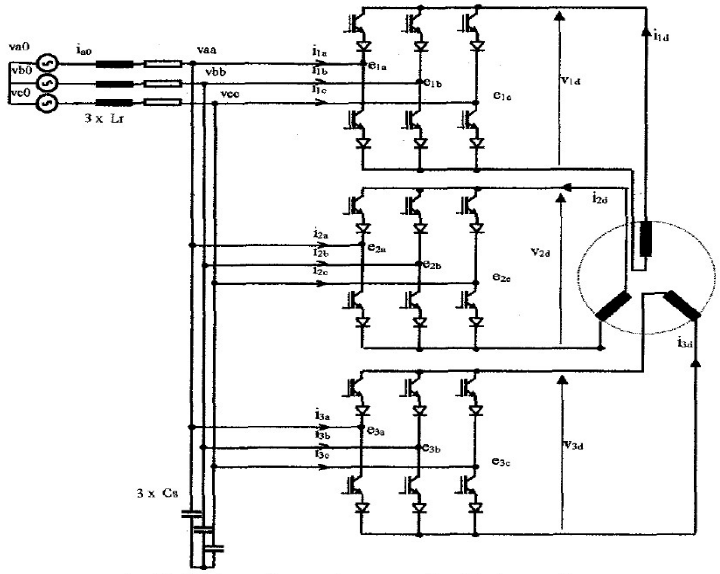


Figure 4.10: Current source ac-ac matrix converter (Neacsu, 1999)

A single phase ac-ac matrix converter is presented in (Idris & Hamzah, 2006). The aim of this topology is to study the behavior of single phase matrix converter topology when used with passive component based load, also SPWM control method produce by Xilinx FPGA is applied for the switch control and finally low-risk commutation is utilized to eliminate voltage and current spikes. The first single phase matrix converter was first published by (Zuckerberger, Weinstock, & Alexandrovitz, 1997). After this several other single phase matrix converter topologies have been investigated (Hosseini & Babaei, 2001; Idris & Hamzah, 2006; Khoei & Yuvarajan, 1988). These investigations studied the converter structure, the type of semiconductor switch and sinusoidal pulsewidth modulation control scheme.

The structure of the single phase matrix converter is shown in Fig. 4.11. The structure is composed of four common emitter based bidirectional. The common emitter switch is composed of two paths of current flow, i.e. switch S1 has two paths of current; S1a and S1b, this is the condition for all four switches; S2 = S2a and S2b, S3 = S3a and S3b, and S4 = S4a and S4b. The waveform of sinusoidal pulsewidth control method is shown in Figure 4.12, two reference amplitudes v_r and carrier amplitude v_c are compared to produce the SPWM output waveform.

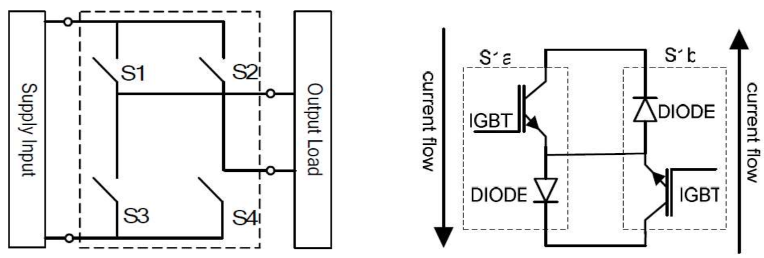


Figure 4.11: Single phase matrix converter(Idris & Hamzah, 2006)

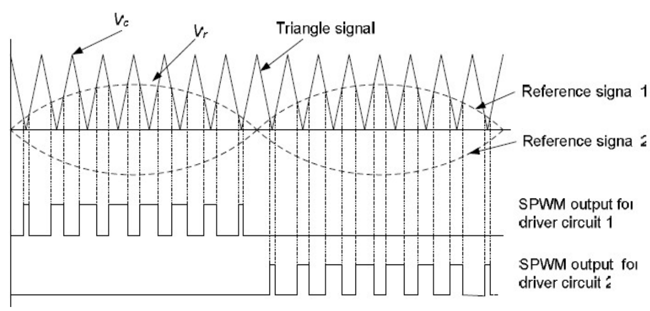


Figure 4.12: SPWM (Idris & Hamzah, 2006)

The switching states implemented in (Idris & Hamzah, 2006) shows four states of operation, two positive and two negative cycle state operation. Its operation is similar to the single phase matrix inverter but the negative cycle in the input source differentiates between the single phase ac-ac matrix converter and the single phase inverter. The required switch to be gated on during commutation is also given. The switch circuit and the commutation procedure diagram are shown in Figure 4.13a and 4.13b respectively. Table 4.1 shows the case scenario for 50Hz frequency input and variable output frequency, switching states and the required switch for commutation are given in the table.

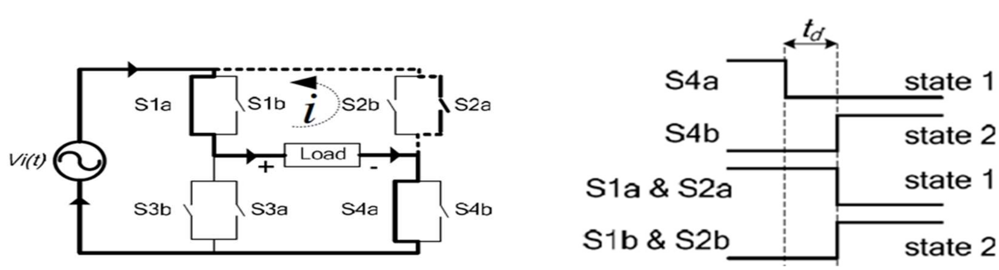


Figure 4.13: a) switch circuit b) commutation procedure (Idris & Hamzah, 2006)

Table 4.1: Switching pattern (Idris & Hamzah, 2006)

Input Frequency	Target Output Frequency	Time Interval	State	Switch "Modulated"
50 HZ	25 HZ	1	1	SI a and S4a
		2	4	S2a and S3a
		3	3	S2b and S3b
		4	2	S1b and S4b
	12.5HZ	1	1	Si a and S4a
		2	4	S2a and S3a
		3	1	Si a and S4a
		4	4	S2a and S3a
		5	3	S2b and S3b
		6	2	S i b and S4b
		7	3	S2b and S3b
		8	2	Si b and S4b

Impedance network based single phase matrix converter is presented in (Fang, Cao, & Li, 2010). Three phase version of this topology is already presented in (Fang & Chen, 2009). This topology combines the advantages of Z source networks with the advantages of matrix converter topology. The impedance network or Z source structure applied in this topology is the conventional Z source structure which is made up of symmetrical passive components; two inductors (L_1 , L_2) and two capacitors (C_1 and C_2). The impedance network offers the following merits; buck-boost functionality, increasing the voltage transfer ratio of the matrix converter, shoot through capabilities, and immunity to noises generated by EMIs. The Z source structure was proposed by (F. Peng, 2002).

The purpose of Z source based single phase matrix converter in (Fang et al., 2010)is to be applied as ac-ac frequency regulator. There are several methods to produce variable ac-ac frequency, the thyristor based switch is a classic example but has the drawback of low order harmonic content in the output power and buck frequency changer. The matrix converter on the other hand offers several advantages when utilized as ac-ac frequency changer, some examples are; bidirectional power flow, sinusoidal power input, sinusoidal power output, lower order harmonics are eliminated or minimized and displacement factor control. Some drawbacks of the matrix converter are; weak voltage transfer ratio, complex control method and lack of shoot through capabilities. The structure of the ZS single phase matrix converter is presented in Figure 4.14.

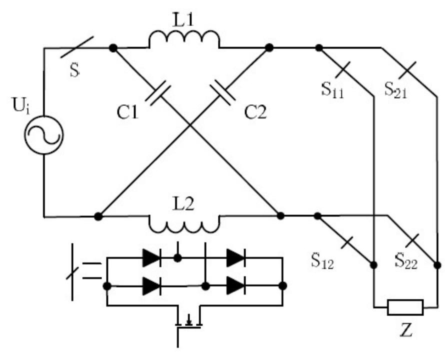


Figure 4.14: ZS matrix converter (Fang et al., 2010)

The circuit is made of impedance structure and matrix converter structure. The impedance network has one active switch which can be a bidirectional switch for bidirectional power flow purpose or a diode to prevent bidirectional power flow as in the case of PV based ZSI. There two symmetrical components each, L_1 and L_2, C_1 and C_2. The matrix converter structure has four bidirectional switches S_{11}, S_{21}, S_{12} and S_{22}. The type of bidirectional switch used is the diode bridge topology which is made-up of four diodes and a switch.

The mode of operation of ZS single phase matrix converter is not much different from single phase matrix converter. The shoot through state is added to the control of single phase matrix converter which is similar to the control method of single phase ZSI. The single phase matrix converter has four states of operation; two active states when switches S_{11} and S_{22} are on for the first active state and when switches S_{21} and S_{12} are for the second active state. For zero states; switches S_{11} and S_{21} are gated on to produce zero or switches S_{12} and S_{22} are gated to produce zero. The equivalent circuit for the shoot through and non-shoot through modes are shown in Fig. 4.15 and Fig. 4.16 respectively. The shoot through mode is achieved by turning on all switches on one leg of the converter or turning on all switches to short circuit the converter side of the structure hence switch S will be turned off. In the none-shoot through mode, switch S conducts just as the switches in matrix topology.

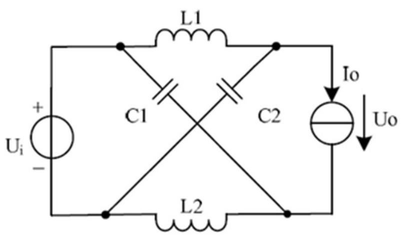


Figure 4.15: None-shoot through mode

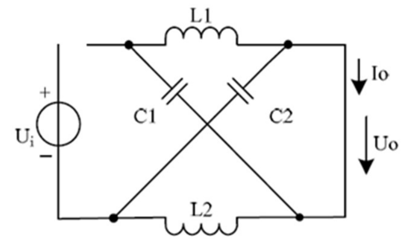


Figure 4.16: Shoot through mode (Fang et al., 2010)

The following mathematical explanations are valid for the shoot through mode and non-shoot through mode.

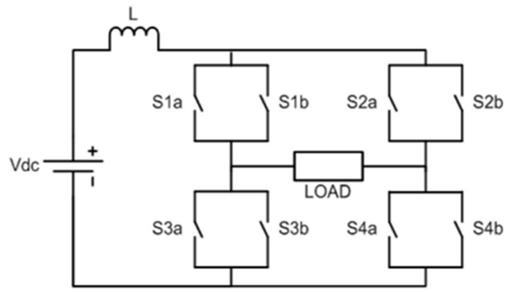
Shoot through mode:

$$\begin{cases} V_L = V_C \\ V_S = 2V_C \\ V_i = 0 \end{cases} \tag{4.6}$$

None-shoot through mode:

$$\begin{cases} V_L = V_O - V_C \\ V_S = V_O \\ V_i = V_c - V_L = 2V_C - V_O \end{cases} \tag{4.7}$$

Another direct matrix converter is illustrated in (Noor, Rahman, & Hamzah, 2010) where a single phase matrix converter is applied as a ***chopper*** i.e. dc-dc converter. This topology functions a boost converter because the output voltage is greater than input voltage. Instead of the conventional dc-dc boost converter which is made up of passive components (inductor and capacitor) and active components (switch and diode), the single phase matrix converter is rather utilized as the boost converter. The single phase matrix converter is applied because the dc source is variable and also at very low level but a much higher level of dc voltage is expected at the output, this topology allows for bidirectional power flow which is absent in the conventional dc-dc boost converter. The structure of single phase matrix converter applied as dc-dc boost converter and the conventional dc-dc converter are shown in Fig. 4.17 and Fig. 4.18 respectively.



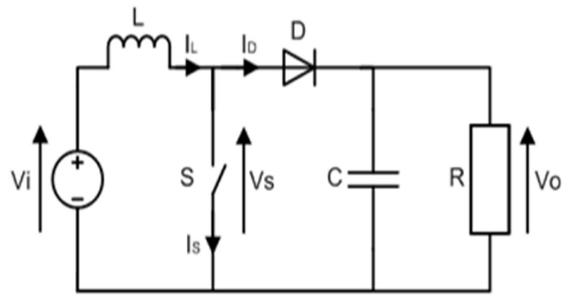


Figure 4.17: Matrix converter **Figure 4.18:** Conventional dc-dc boost converter (Noor et al., 2010)

Four bidirectional switches with common emitter topology are used in the single phase matrix converter. Each bidirectional switch has the ability to conduct current in both forward and reverse directions as shown in Fig. 4.19, also it can block voltages forward and reverse directions. The matrix converter has the advantage of four quadrant functionality and this is applied in dc-dc boost conversion.

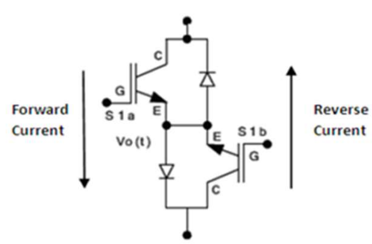


Figure 4.19: Bidirectional switch (Noor et al., 2010)

The conventional four quadrant chopper produces variable dc voltage at the output from a static dc voltage at the source or input. It functions as buck-boost chopper and it's widely used in variable dc drives due to the following advantages; bidirectional power flow, higher efficiency, fast response, versatility (Mohammad Noor, Abdul Rahman, & Hamzah, 2011;

Samosir & Yatim, 2008). The switching patter for the four quadrant operation is shown in Table 4.2 and its corresponding waveform is shown in Fig. 4.20.

Table 4.2: Switching Pattern (Noor et al., 2010)

Switches	**1st Quadrant**	**2nd Quadrant**	**3rd Quadrant**	**4th Quadrant**
S1a	ON	OFF	OFF	OFF
S1b	OFF	ON	OFF	OFF
S2a	OFF	OFF	PWM	OFF
S2b	OFF	OFF	OFF	ON
S3a	PWM	PWM	ON	OFF
S3b	OFF	OFF	OFF	ON
S4a	ON	OFF	OFF	PWM
S4b	OFF	ON	ON	OFF

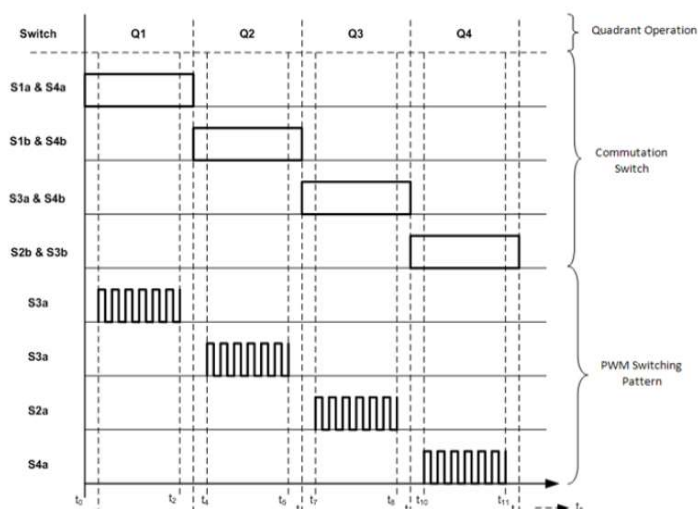


Figure 4.20: Four quadrant output waveform (Noor et al., 2010)

An advanced rectifier using single phase matrix converter topology is proposed in (Baharom & Hamzah, 2010), the design has the addition of power filters to eliminate unwanted components. The design maintains all the merits of matrix converters such as bidirectional power flow, sinusoidal input waveform etc. different loads require different forms of power (ac or dc), but most utility providers produce ac power hence requisite devices are required to condition the power as required by the load, a typical example is the rectifier; which is the act of converting ac power to dc power (Singh et al., 2003). The conventional rectifier circuit is the diode bridge circuit which is good but has drawbacks such as unidirectional power flow and lacks control functionality. The matrix converter on the other hand can overcome all these drawbacks when applied as rectifier (Hua, Leu, Jiang, & Lee, 1994). The proposed matrix converter rectifier circuit is shown in Fig. 4.21. The circuit is a boost rectifier which means the output voltage is increased very high than the input voltage, also the function of the inductor is to eliminate EMIs.

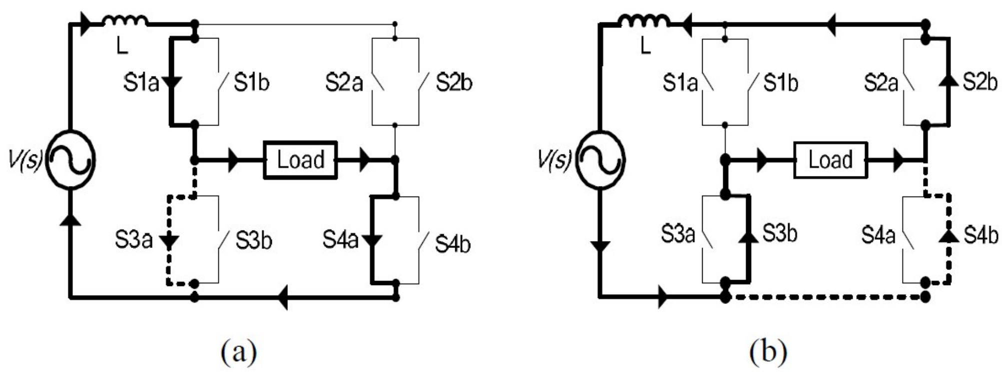


Figure 4.21: a) Boost rectifier positive cycle b) Boost rectifier negative cycle (Baharom & Hamzah, 2010)

One major disadvantage of matrix converters which has greatly reduced its penetration into industry is the commutation difficulties coupled with its complex control methods. Commutation difficulties arise when the load of the matrix converter is an inductive load, the load energy or inductive energy cause voltage and current spikes when ***turn-off*** of paired switches is done. To avoid commutation problems, switching is supposed to be done immediately and concurrently but this is only achievable in theoretically but not experimentally due to difference in the response of the semiconductor switches (turn-on and turn-off features) (Baharom & Hamzah, 2010). Secured commutation method was designed to overcome the commutation challenges.

4.3.1 Other Direct Matrix Converter Topologies

Several topologies of direct matrix converter with different functionality have been published over the years. These topologies have different structural design and control methods. This section will focus on the structure or topology. Topologies which seek to reduce the number of switches but achieve the same functions as the conventional topology will be analyzed.

The first topology to be investigated is the new 3 phase cycloconverter proposed in (Heris, Sadeghi, & Babaei, 2011). This topology has master switches and slave switches just as in case of load; master load and slave load. The conventional cycloconverter has the main limitation of reduced voltage transfer ratio, in other to resolve this problem, researchers focus more on control methodologies (Alesina & Venturini, 1981) rather than structural design of the conventional. The Alsesina-Venturini and the dc algorithm (Ziogas, Khan, & Rashid, 1986) control methods increased the voltage transfer ratio by 0.5 and 1.053 respectively. The proposed cycloconverter has the attributes to increase the voltage transfer ratio to 1.5 with low order harmonics eliminated. The load of proposed topology is independent of the topology. In the case of the traditional 3-phase to 3-phase cycloconverters (Fig. 4.22) the output voltage is limited to V_{im} which is the phase voltage amplitude but the proposed cycloconverter (Fig. 4.23) the output voltage is $\sqrt{3}V_{im}$ which is the line voltage amplitude.

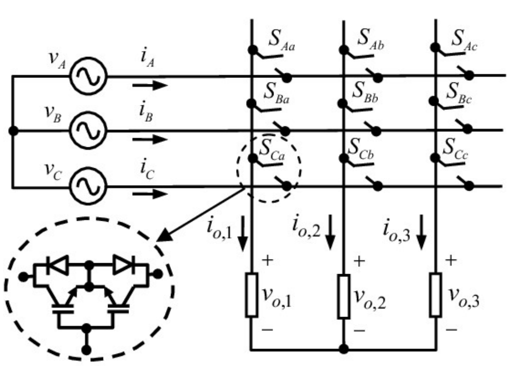


Figure 4.22: Traditional cycloconverter

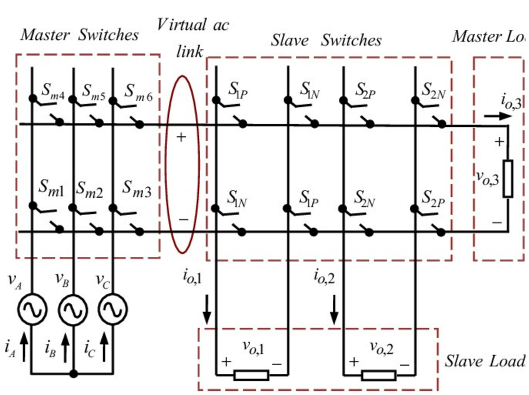


Figure 4.23: Proposed *3x3* phase cycloconverter (Heris et al., 2011)

The input and output voltages of the proposed cycloconverter are given by (4.8) and (4.9). The amplitude and angular frequency of the input factors are V_{im} and ω_i and the amplitude and angular frequency of the output factors are V_{0m} and ω_0.

$$\begin{cases} v_A(t) = V_{im}\sin(\omega_i t) \\ v_B(t) = V_{im}\sin(\omega_i t - 120^0) \\ v_C(t) = V_{im}\sin(\omega_i t + 120^0) \end{cases} \tag{4.8}$$

$$\begin{cases} v_{0,1}(t) = V_{0m}\sin(\omega_0 t) \\ v_{0,2}(t) = V_{0m}\sin(\omega_o t - 120^0) \\ v_{0,3}(t) = V_{0m}\sin(\omega_o t + 120^0) \end{cases} \tag{4.9}$$

The switching pattern for the proposed 3-phase to 3-phase cycloconverter (master switches and slave switches) and its corresponding output voltages are shown in Table 4.3.

Table 4.3: Switching pattern and Output Voltage

	Mode	**Switches**	**Output Voltage V_0**
	1	S_{m1} and S_{m5}	$v_A - v_B$
	2	S_{m1} and S_{m6}	$v_A - v_C$
Master	3	S_{m2} and S_{m6}	$v_B - v_C$
	4	S_{m2} and S_{m4}	$v_B - v_A$
	5	S_{m3} and S_{m4}	$v_C - v_A$
	6	S_{m3} and S_{m5}	$v_C - v_B$
	I	S_{1P} and S_{1P}	$V_{ac\ link}$
	II	S_{1N} and S_{1N}	$-V_{ac\ link}$
Slave	III	S_{2P} and S_{2P}	$V_{ac\ link}$
	IV	S_{2N} and S_{2N}	$-V_{ac\ link}$

A three phase to 2 phase cycloconverter with a new switching technique is proposed in (Babaei et al., 2006). The circuit of the 2 x 3 matrix converter is shown in Fig. 4.24. Analyses of the matrix converter with the new switching technique are investigated under two conditions: balanced and unbalanced load conditions. The input voltage of the 2 x 3 matrix converter is given by (4.10) and its corresponding output voltage after implementation of the proposed switching technique is given by (4.11). The fundamental component of the output current is given by equation (4.12).

$$\begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} = \text{Vim} \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t - \frac{2\pi}{3} \\ \cos(\omega_i t + \frac{2\pi}{3} \end{bmatrix} \tag{4.10}$$

$$\begin{cases} v_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} \\ v_b(t) = R_b i_b(t) + L_b \frac{di_b(t)}{dt} \end{cases} \tag{4.11}$$

$$\begin{cases} i_a(t) = \frac{V_{am}}{\sqrt{(L_a\omega_0)^2 + R_a^2}} \cos(\omega_0 t - \tan^1\left(\frac{L_a\omega_0}{R_a}\right)) \\ i_b(t) = \frac{V_{bm}}{\sqrt{(L_b\omega_0)^2 + R_b^2}} \sin(\omega_0 t - \tan^{-1}(\frac{L_b\omega_0}{R_b})) \end{cases} \tag{4.12}$$

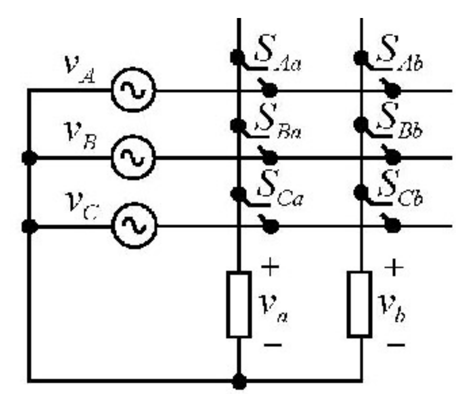


Figure 4.24: *2 x 3* Matrix converter (Babaei et al., 2006)

Comparison of two types of three phases to one phase matrix converters is done in (Babaei & Heris, 2009), the first converter uses three bidirectional switches to achieve the same results as the second converter which uses six bidirectional switches. The circuits of the two matrix converters are shown in Fig. 4.25a and 4.25b.

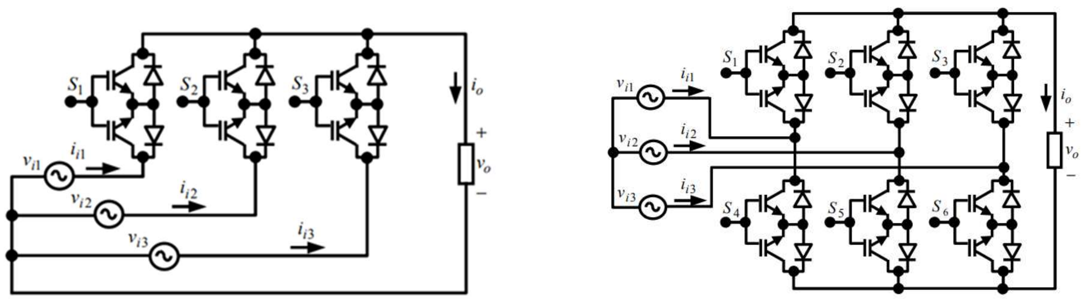


Figure 4.25: a) 3 switched 1 x 3 matrix converter b) 6 switched 1 x 3 matrix converter (Babaei & Heris, 2009)

Table 4.4: Switching Pattern (Babaei & Heris, 2009)

Mode	Switch	Output Voltage v_0	Output current i_0
	3 switches based *1x3* matrix converter		
1	S1	v_{i1}	i_{i1}
2	S2	v_{i2}	i_{i2}
3	S3	v_{i3}	i_{i3}
	6 switches based *1x3* matrix converter		
1	S_1 and S_5	$v_{i1} - v_{i2}$	$i_{i1} = -i_{i2}$
2	S_1 and S_6	$v_{i1} - v_{i3}$	$i_{i1} = -i_{i3}$
3	S_2 and S_6	$v_{i2} - v_{i3}$	$i_{i2} = -i_{i3}$
4	S_2 and S_6	$v_{i2} - v_{i1}$	$i_{i2} = -i_{i1}$
5	S_3 and S_4	$v_{i3} - v_{i1}$	$i_{i3} = -i_{i1}$
6	S_3 and S_5	$v_{i3} - v_{i2}$	$i_{i3} = -i_{i2}$
7	(S_1 , S_4) or (S_2 , S_5) or (S_3 , S_6)	0	i_0

A boost matrix converter known as the ***one-step*** boost type matrix converter is proposed in (Huang, Wan, Hu, & Chen, 2017) to solve the major deficiency of the matrix converter which limited voltage transfer ratio currently at 0.866 (Alesina & Venturini, 1989). Most suggested improvement of the voltage transfer ratio focus on modulation techniques (Zhou, 2013) but ***one-step*** method is a topological improvement of the conventional matrix converter topology. Results from the one-step analysis shows that the voltage transfer ratio is improved from 0.866 to 1, also the converter control or switching mechanism is less complicated in this proposed topology. The structure of the proposed one-step boost matrix converter is shown in Fig. 4.26. Two stages of switching operation exist in the proposed matrix converter based on the on/off states of the switches (S_{jk}). This is done for the sole purpose of explanations hence experimentally there are no division of the switching patterns from each other. It should however be noted that the proposed converter is a 3 phase to 3 phase structure.

The boost mechanism applied to the one-step matrix converter is similar to the boost mechanism of the impedance structure or Z source networks. There are two groups of switches; the matrix converter main switches S_{jk} made up of nine bidirectional switches and a fly-wheel switch which is made up of six unidirectional switches. Inductors and capacitors serve as the boost or storage devices. Two periods conductions are present in the one-step converter analysis; t_1 and t_2. During t1, the main switches are controlled according to the type of modulation scheme but three switches in the fly-wheel group disconnects the source power but during t2, the main switches and the three switches from the fly-wheel group are all disconnected. This method helps to store energy in the capacitor and inductors hence the voltage transfer ratio is increased to 1 from 0.866.

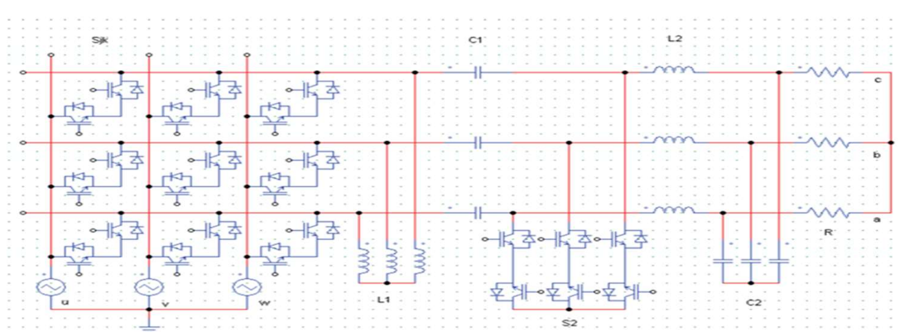


Figure 4.26: One-step Boost matrix converter (Huang et al., 2017)

The output voltage of the proposed one-step matrix with boosting factor attributes is given by (4.13)

$$U_0 = \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = U_{0m} \begin{cases} \cos(\omega_0 t + \emptyset_0) \\ \cos(\omega_0 t + \frac{2\pi}{3} + \emptyset_0) \\ \cos(\omega_0 t + \frac{4\pi}{3} + \emptyset_0) \end{cases} \tag{4.13}$$

4.4 Indirect Matrix Converter

Conversion of ac power to ac power with different amplitude and frequency is mostly required in industry where variable drive systems are used. Before the introduction of matrix converters, ac-ac power conversion was achieved in two stage conversion system; rectifier and an inverter cascaded tropology. The conventional ac-ac converter was grouped into PWM boost converter and PWM inverter which was fed by a dc link being the output of the boost converter. Two energy storage systems are required in the conventional ac-ac converter; an inductor at the source and large capacitor in the dc link (S. Kim, Sul, & Lipo, 2000). The capacitor used in the dc-link is a major source of drawbacks for the converter because; it's expensive, its size means the size and weight of the converter is increased and the lifespan of the capacitor is limited especially in high power applications. The inductor size is also a major problem due to its occupied area; 20% to 40% of the converter area. Solutions to these problems were addressed in the following publications (Holtz & Boelkens, 1989; J. S. Kim & Sul, 1993). Bidirectional power flow, unlimited range of output voltage and unity power factor operation at the source is some advantages of the conventional ac-ac converter.

With the introduction of matrix converters, some of the limitations of the conventional ac-ac converter were resolved but the matrix converter itself introduced a number of drawbacks; limited voltage transfer ratio, complicated control mechanism and etc. these limitation gave birth to the introduction of the indirect matrix converter which is a double stage conversion structure; rectifier and an inverter combined. A hybrid converter; matrix converter and conventional ac-ac converter is proposed in (S. Kim et al., 2000). This hybrid converter is an indirect converter because it has two stages of power conversion ac-dc-ac. The structure is made up of unidirectional switches in the rectifier and inverter stages. The huge inductor and capacitor are omitted in the hybrid topology; the structure is shown in Fig. 4.27.

The principle of operation of the hybrid topology is in two stages; rectifier operation and inverter operation. The rectifier stage is ac to dc power conversion and the unidirectional switch used in the bridge is known as IGBT (insulated gate bipolar transistor). The switching pattern of the IGBT switches in the rectifier stage is shown in Fig. 4.28 . In each cycle, they switched on for 120^0 using the source frequency as the switching frequency. The rectifier stage output voltage is a dc voltage with ripples and the inverter ac output voltage is dependent on the rectifier voltage and its generated using space vector modulation technique (J.-S. Kim & Sul, 1995; Van Der Broeck, Skudelny, & Stanke, 1988).

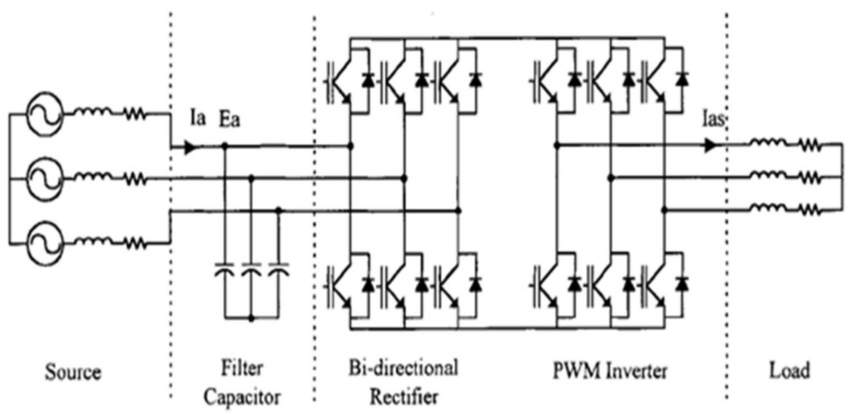


Figure 4.27: Hybrid ac-ac converter (S. Kim et al., 2000)

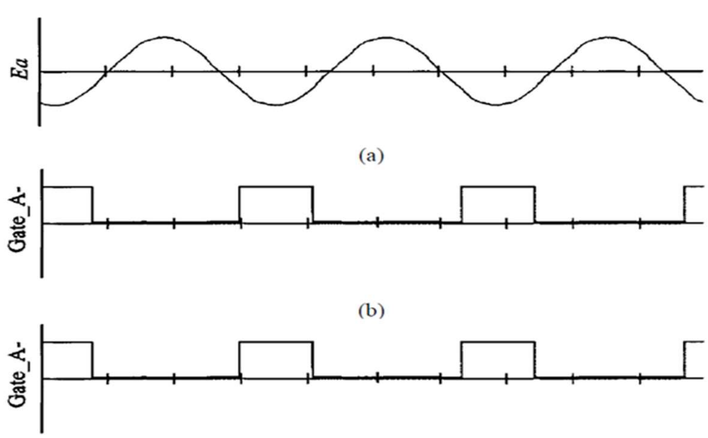


Figure 4.28: Rectifier bridge switching pattern (S. Kim et al., 2000)

Analysis of indirect matrix converter's behavior under open circuit is investigated in (Shi & Zhou, 2017). The indirect matrix is an improvement of the direct matrix converter hence all the advantages of the direct matrix converter are retained by indirect matrix converter such as; high power density bidirectional power flow and no need for bulky storage elements. The indirect matrix converter has some advantages of its own; basic clamping circuit, basic commutation technique and simple control methods. Lack of storage elements makes the matrix converter suitable for harsh high pressure working territories (Thomas Friedli, Kolar, Rodriguez, & Wheeler, 2012; Kolar, Friedli, Rodriguez, & Wheeler, 2011).

Timely fault detection or diagnosis is very crucial in power electronics especially in military and aerospace industry. Major analysis of faults in power electronic based industries shows that capacitors breakdown by a percentage of 30% whiles semiconductor switches follow by 21% (Wolfgang, 2007). The use of indirect matrix converter improves the efficiency and reliability of the converter due to the elimination of capacitor. The figure of indirect matrix converter under open circuit investigation is shown in Fig. 4.29. The circuit is made up of the load, camp circuit, source power supply, rectifier and inverter circuits, filter to remove unwanted components. The rectifier circuit is made up of common emitter bidirectional switches and the inverter circuit is made up of unidirectional switches. Open circuit fault in the rectifier circuit simple means that the IGBT is faulty but since each bidirectional switch is composed of two IGBTs then three possible cause of open circuit is possible as illustrated in Fig. 4.30a. Either the first IGBT in the bidirectional switch is faulty, or the second IGBT or both IGBTs are faulty at the period (Cruz, Ferreira, Mendes, & Cardoso, 2011). However, in the inverter circuit open fault conditions, only one IGBT can be faulty since unidirectional switches are utilized. Analysis of open circuit faults under indirect matrix converter is done under three topics; kind of open-circuit fault, current flow direction during faulty periods, analysis of dc link during faulty periods.

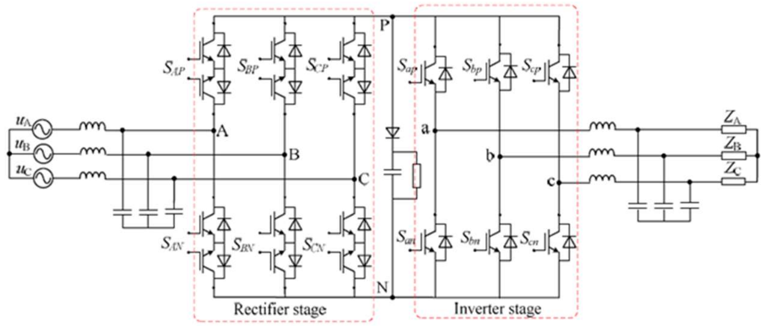


Figure 4.29: Indirect matrix converter (Shi & Zhou, 2017)

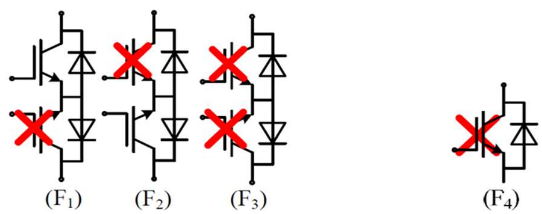


Figure 4.30: Switch failure in indirect matrix converter (Shi & Zhou, 2017)

In (Guo, Liu, Ge, & Abu-Rub, 2018), the quasi Z source network is combined with the indirect matrix converter to produce a new converter known as qZSIMC which combines the advantages of the two structures hence better suitable for wide industrial applications. The quasi Z source network is an improvement on the conventional Z source structure. It has the advantage of achieving all the merits ZS topology plus its own merits. Two types of quasi Z source topologies exist; qZS with continuous current input and qZS with discontinuous current input. The advantages of two qZS topologies are: no inrush current, common ground, high boosting factor, immunity to noise generated by EMI, reduced voltage stress on components, continuous or discontinuous current input.

Three factors determine the level of voltage in the qZSIMC and these factors are: a) modulation ratio of the inverter, b) modulation ratio of the rectifier and duty cycle ratio of the shoot through mode. The low voltage transfer ratio of the indirect matrix converter limits its applications in industrial variable ac drives (Lee Empringham, Kolar, Rodriguez, Wheeler, & Clare, 2013). To increase the voltage gain of indirect matrix converter, two ways are most common; control technique and structural improvements are done. The control techniques such as combined modulation and over modulation increase the voltage gain but not significantly. Moreover the modified modulation control technique is complex. In the case of structural improvements, the addition of ZS or qZS topologies to the indirect matrix converter will enable it have high buck-boost capabilities (Chiang & Itoh, 2013; F. Z. Peng, 2003). Combination of impedance networks with the various types of matrix converters can be found in the following literatures (Ge, Lei, Qian, & Peng, 2012; You et al., 2016). The circuit of qZSIMC is shown in Fig. 4.31 and its operation is the combination of shoot through mode and the control strategy for any indirect matrix converter.

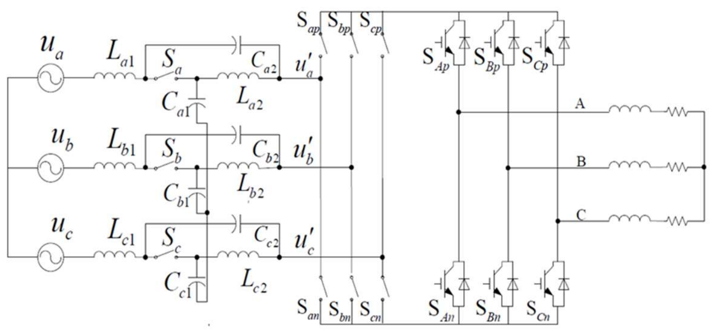


Figure 4.31: qZSIMC (Guo et al., 2018)

A different methodology is proposed in (Zhang et al., 2017) for quick diagnosis of fault based on open circuit in indirect matrix converter. The proposed technique is the model predictive control (MPC) type i.e. finite control set technique. Failure of power electronic converter is unavoidable occurrences which will happen in the lifespan of a converter no matter the preventive measures put in place hence its necessary to put in effective detection mechanism which will promptly detect faults in the converter; this will reduce the impact of damage on the overall system. Principal causes of faults in power converters are the failure of the major components such as diode, controller, switches and gate drives (L Empringham et al., 2011). Several publications have been carried out on open circuit fault detection in direct matrix converters (Ferreira, Cruz, & Cardoso, 2008; T. Peng et al., 2016). Unlike direct matrix converters, only few publications have been made on open circuit fault detection in indirect matrix converters (Andrade-Romero, Herrera, & Romero, 2012; E. Lee & Lee, 2012). Using the proposed fault detection method; finite control set-MPC, fault analysis of the indirect matrix converter is done under four modes, two states of fault operations; a) inverter state, b) rectifier state and two states of fault detection; rectifier state and inverter state.

A highly efficient indirect matrix converter is presented in (T Friedli, Heldwein, Giezendanner, & Kolar, 2006) which use a different topology of bidirectional switches. Reverse blocking insulated gate bipolar transistor RB-IGBT switch or bidirectional switch is used. The RB-IG BT bidirectional switch is derived from the antiparallel connection of two IGBT. When RB-IGBT are used in matrix converter circuits; the dissipated power is exponentially reduced because of the conduction losses during on-mode (Adamek, Hofmann, & Lindemann, 2003; Itoh et al., 2004). Also the number of switches and diodes are reduced to 18 from 36, this leads to a more reliable and compact matrix converter. Conduction losses in conventional matrix converter and RB-IGBT based matrix converters are different, the conduction losses in the latter are much minimized because reduced component count. Reduced conduction loss implies that higher efficiency in RB-IGBT based matrix converter (Itoh et al., 2004) (Sun, Zhou, Mei, Huang, & Matsuse, 2006). Using high switching reduces the efficiency of RB-IGBT based matrix converters but when low switching frequency is employed; the efficiency increases significantly. The circuit of reverse blocking insulated gate bipolar transistor based indirect matrix converter is shown in Figure 4.32.

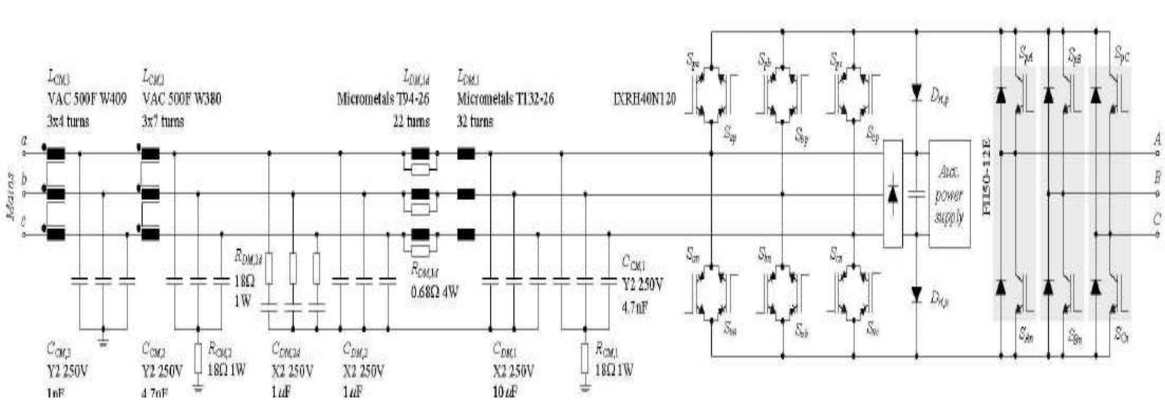


Figure 4.32: RB-IGBT based indirect matrix converter(T Friedli et al., 2006)

4.5 Control Techniques

Several publications have been made on control techniques for direct matrix converter and indirect matrix converters. This section will review selected papers on modulation strategies applied in the control of matrix converters and their effects on the converter as a whole.

High switching frequency based matrix converters are most times controlled by PWM; pulse width modulation. PWM is control method involves the comparison of two signals; the carrier signal and reference signal (Dallago & Sassone, 1997). PWM technique has the disadvantage of huge peak noise in the carrier frequency, minimum pulse width are sometimes produced by PWM which is a huge issue because it's difficult for semiconductor switches to track these small width of pulses produced by PWM and this causes distortion in the output waveform. The use of delta-sigma modulation method for control of converters is published in (Hirota, Nagai, & Nakaoka, 1999; Sun et al., 2006). In (Hirota & Nakaoka, 2006), the delta-sigma control method is applied to a matrix converter; this method produces quality sine wave at the output of the matrix converter. The quality sine wave is produced by a noise shaping feature in the delta-sigma modulator by quashing the noise peaks (Candy & Temes, 1992). It's evident that delta-sigma modulator is able remove the noise components in output voltage than the PWM technique (Hirota & Nakaoka, 2006).

Indirect space vector modulation (ISVM) technique for the control of matrix converter is published in (K.-B. Lee & Blaabjerg, 2006; SenthilKumaran & Siddharth, 2010). The modulation of matrix converter by ISVM technique is a combination of two processes; rectification stage and the inverter stage. The rectification stage produces the voltage for dc link which feeds the inverter for the generation of the output voltages. Reference vector is produced in the indirect space vector modulation by the integrations of two vectors; zero vector and 2 adjoining vectors. The direction of the reference vector is determined by the duty cycle ratio of the 2 adjoining vectors. The duty cycles d_γ d_α of the rectification and inverter active switching is determined by (4.14) and (4.15) respectively. The reference voltage in the rectification and inverter stages are shown by Fig. 4.33a 4.33b.

$$d_\gamma = m_I \sin\left(\frac{\pi}{3} - \theta_{in}^*\right),\ d_\delta = m_I \sin\theta_{in}^* \quad (4.14)$$

$$d_\alpha \, m_U \sin\left(\frac{\pi}{3} - \theta_{out}^{*}\right), \; d_\beta = m_U \sin \theta_{out}^{*} \tag{4.15}$$

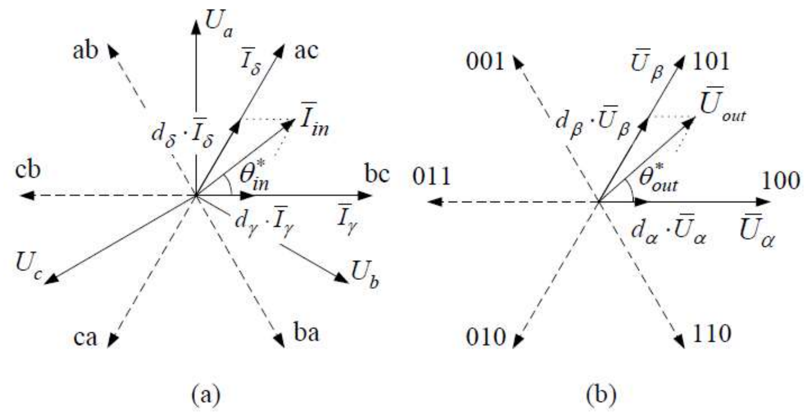


Figure 4.33: Reference voltage in (a) rectification stage, (b) inversion stage (K.-B. Lee & Blaabjerg, 2006)

With the indirect space vector modulation, two reference vectors or are voltages will have to be unified; the rectification stage vector or the current input vector I_i and the inverter stage vector which is the same as output vector V_0. The combination of the two vectors; input vector and output vector as done in (Xiao & Rahman, 2006) yields (4.16).

$$\left\{\begin{array}{c} D_{\alpha\gamma} = d_\alpha * d_\gamma, \; d_{\alpha\delta} = d_\alpha * d_\delta, \; d_{\beta\delta} = d_\beta * d_\delta, \\ d_{\beta\delta} = d_\beta * d_\delta, \; d_{\beta\gamma} = d_\beta * d_\gamma \\ d_0 = \frac{T_0}{T_s} = 1 - d_{\alpha\gamma} - d_{\alpha\delta} - d_{\beta\delta} - d_{\beta\gamma} \end{array}\right\} \tag{4.16}$$

The space vector modulation SVM technique is one of the common control methods of matrix converter and other converters to achieve the frequency conversion with sinusoidal power output waveforms at the required frequency (Fukuda, Iwaji, & Hasegawa, 1990; Watler, 1998). The levels of output voltage available to the matrix converter are 16 as depicted in (Watler, 1998)and its diagram is shown in Fig. 4.34. It should however be noted that this 16 level output corresponds to a phase output in the three phase system of the matrix converter. These levels of output voltage are shown as vectors revolving with source input are angular displacement $\omega_1 t$. The various output phases have a corresponding reference voltage also revolving with angular displacement $\omega_2 t$. The value of the vectors for the first 3 vectors is shown in Table 5. Basically let's assume we are dealing with phase A of the 3 phase matrix converter hence the input source amplitude is given by A.

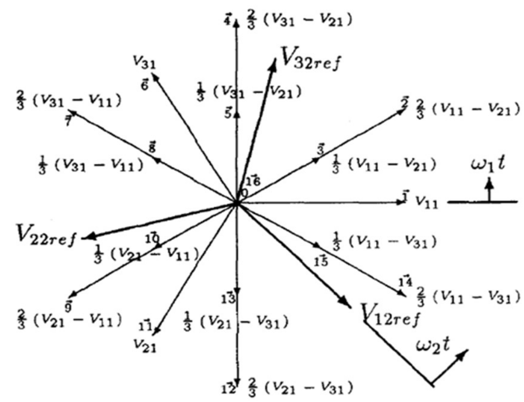


Figure 4.34: Matrix converter vectors (Watler, 1998)

Table 4.5: Vector values (Watler, 1998)

Vector	Value V
$\overline{1}$	V11 = $Ae^{j\omega_1 t}$
$\overline{2}$	$\frac{2}{3}(V11 - V21) = \frac{2}{\sqrt{3}} Ae^{j(\omega_1 t + \frac{\pi}{6})}$
$\overline{3}$	$\frac{1}{3}(V11 - V21) = \frac{1}{\sqrt{3}} Ae^{j(\omega_1 t + \frac{\pi}{6})}$

In (Huber & Borojevic, 1995), the space vector modulation technique is applied in the correction of input power factor in a 3x3 matrix converter. The application of SVM technique is possible in both direct and indirect transfer function as shown in (Huber & Borojevic, 1995).in the indirect transfer approach, the matrix converter is treated as a rectifier in the first stage and in the second stage as an inverter. Table 4.6 shows the 3 phase to 3 phase algorithm for both direct and indirect matrix converter transfer technique.

Table 4.6: Control technique for 3x3 matrix converter (Huber & Borojevic, 1995)

INDIRECT TRANSFER FUNCTION APPROACH			
Diode-Bridge-Rectifier / PWM-Inverter (IDF = 1)		PWM-Rectifier / Square-Wave-Inv.	PWM-Rectifier / PWM-Inverter ($A_{vmax} = \sqrt{3}/2$)
Without compensation of full-wave-rectified input-line-voltages ripple	With compensation of full-wave-rectified input-line-voltages (V_{FWR}) ripple ($A_{vmax} = \sqrt{3}/2$)	• VSR with modified Sine-PWM [2], [3]	• Adjustable IDF - Simultaneous output-voltage and input-current space-vector-modulation [10] • IDF = 1 - Modified Sine-PWM in both VSR and VSI [2], [3] - Hysteresis current controller in both VSR and VSI [11] - VSR with six-step PWM and VSI with ramp-comparison current controller [12]
• Sine-PWM with triangular carrier in VSI [4] • Modified Sine-PWM with triangular carrier in VSI [2], [3]	• Sine-PWM with amplitude-modulated triangular carrier in VSI [5] • VSI with Sine-PWM (or PWM with harmonic elimination) with duty cycle proportional to $1/V_{FWR}$ [6] (includes also adjustable IDF) • VSI with space-vector-modulation with duty cycle proportional to $1/V_{FWR}$ [7] • VSI with hysteresis current controller [8] • VSI with predictive current controller [9]		

DIRECT TRANSFER FUNCTION APPROACH		
Synthesis of output phase-voltages		Synthesis of output line-voltages
Output neutral connected to input neutral ($A_{vmax} = 0.5$)	Output neutral modulated with respect to input neutral ($A_{vmax} = \sqrt{3}/2$)	• Six-step PWM using two input line-voltages ($A_{vmax} = \sqrt{3}/2$, IDF = 1) [19] • Six-step PWM using three input line-voltages ($A_{vmax} = 3/4$, IDF = 1) [19]] • Unrestricted frequency changers (UFC [20]) with PWM ($A_{vmax} < \sqrt{3}/2$, IDF = ± ODF, LF harmonics) - Uniform PWM with triangular carrier [2], [3] - Sine-PWM with triangular carrier [21] - Clipped-Sine-PWM with triangular carrier [21] - PWM with selective harmonic elimination [22]
• Restricted IDF (IDF ≤ ODF) [1]	• Adjustable IDF - Injection of input and output 3rd harmonics [13], [14], [15], [16] - Six-step PWM with extension to unity duty-cycle [18] • IDF = 1 (Injection of input and output 3rd harmonics) [17]	

Comparison of the space vector modulation technique and Venturini control method is explained in (Watthanasam, Zhang, & Liang, 1996). From the analysis it was proved that both Venturini and SVM have the following merits:

a. Equal voltage transfer ratio; 86.6%
b. Concurrent control of displacement angle of input current and output waveforms
c. Space vector modulation is less complicated
d. 20% less switch commutation for each switching period.

Detailed explanation of the Venturini control technique is done (Watthanasam et al., 1996) and basically states that the required output voltage of a 3 phase matrix converter is derived from its corresponding 3 phase input matrix converter which is synthesized by successive piecewise sampling of input undulation. In order for the desired output waveform and the reference waveform to be in phase, mathematical calculation of the sample period is done to certify that the output waveform's average value follow the desired output waveform. The Venturini method, the input and output currents are related by (4.17) and the input and output voltage are related by (4.18). In other to control the input current and output voltage concurrently, two parameters are considered; the input frequency and voltage (ω_i, V_i) and the output frequency and current (ω_0, I_0). The input voltage equation is given by (4.19) and the output current equation is given by (4.20).

$$[I_i] = [M(t)]^T [I_0] \tag{4.17}$$

$$[V_0] = [M(t)][V_i] \tag{4.18}$$

$$[V_i] = \begin{bmatrix} \cos(\omega_i t) \\ \cos\left(\omega_i t - \frac{2\pi}{3}\right) \\ \cos\left(\omega_i t - \frac{4\pi}{3}\right) \end{bmatrix} \tag{4.19}$$

$$[I_0] = \begin{bmatrix} \cos(\omega_i t - \emptyset_0) \\ \cos\left(\omega_i t - \emptyset_0 - \frac{2\pi}{3}\right) \\ \cos\left(\omega_i t - \emptyset_0 - \frac{4\pi}{3}\right) \end{bmatrix} \tag{4.20}$$

In (Yan, Zhao, Xia, & Shi, 2014)space vector modulation technique is applied in the control of matrix converter fed permanent magnet motor (synchronous). The SVM technique used is already explained in (Huber & Borojevic, 1995) so detailed explanation was curtailed. The effect of common mode voltage is the production of bearing currents which is a serious drawback in the operation of ac-ac variable speed drives (Chen, Lipo, & Fitzgerald, 1996; Halkosaari & Tuusa, 1999). Space vector modulated matrix converter (direct and indirect) and VSI are compared based on the common mode voltage to determine the converter with the least amount of common mode voltage (Jussila, Alahuhtala, & Tuusa, 2006).

In (Wang & Venkataramanan, 2006b) a PWM control method is applied in the control of direct matrix converters, the aim of the control technique applied is to increase the voltage transfer ratio from 0.866% to 1pu. The control method is known as six step frequency modulation technique. Fourier series method is used in analyzing the voltage transfer ratio. The proposed control method is applied to matrix converter with the following type of switches single pole double throw and single pole triple throw switches. According to (Luo & Pan, 2006), the following control techniques used in the implementation of matrix converters produces high harmonic content in the output current; Venturini technique, Maximum envelope modulation technique, SVM. When these techniques are applied to direct matrix converters, the high total harmonic content damages other electrical devices connected to the system. Hence sub envelope modulation technique is proposed in (Luo & Pan, 2006) to minimize the harmonic content in the output current. Basically the sub envelope method is achieved by modulation of output phase and two adjoining input/source phase, the output voltage's pulse magnitude is low hence the output voltage high frequency parts can be minimized and so the dv/dt and total THD are minimized. A carrier pulsed width modulation technique is applied in (Wang & Venkataramanan, 2006a) for the realization of indirect matrix converters, also a pulse width modulation strategy is implemented in (Hasegawa & Takeshita, 2010)which seeks to reduce the harmonics content in the output current. Field oriented control technique is applied in (Djahbar, Mazari, & Mansour, 2005) to control a high performance motor based matrix converter, this method was first published in (Blaschke, 1972). A similar field oriented topology but adaptive neural fuzzy inference system technology is used in the implementation of the matrix converter (Venugopal, 2010a). Fuzzy logic controller for direct torque control of matrix converter based motor system is realized in (Venugopal, 2010b). The control of torque an indirect matrix converter based motor is presented in (Aghasi, Faraji, Khaburi, & Kalantar, 2010). A simple modulation technique for direct matrix converter control is realized in (Rao, Chatterjee, Subramanian, & Rajasekhar, 2010) and its goal is to achieve the following; minimize the losses due to switching and produce a converter with maximum efficiency (Huber & Borojevic, 1995). Some other control methods are indirect model predictive control method (Marco Rivera et al., 2017), predictive control (M Rivera et al., 2017), torque control (Kozakevich, 2017), adaptive sliding mode control (Alalei, Kermadi, Nesba, & Hazzab, 2017), multimodular matrix converter controlled by multi-carrier PWM (Patel & Mulla, 2017).

A new control method for controling forced commutated matrix converters also known as cycloconverter is presented in (Babaei & Heris, 2009); this control new method is based on pulsewidth modulation principle. A three phase to two phase matrix converter is presented in (Mirazimi, Sharifian, & Babaei, 2012) and the applied control method is hysteresis control technique. In (Hajbani, Babaei, Hosseini, & Nouri, 2012), a new control technique based on the principle of the improved sinusoidal PWM is utilized in the control of a matrix converter. Two signals are utilized in the ISPWM technique; reference signal and carrier signal, the reference signal is sinusoidal amplitude and the carrier signal is triangular amplitude; comparison of the reference and carrier signals is used to generate the output pulses. A review of control techniques applicable to matrix converters; both direct and indirect matrix converters is presented in (Rodriguez, Rivera, Kolar, & Wheeler, 2012), a summary of the presented control techniques is shown in Fig. 4.35. A new switching technique is proposed in (Babaei et al., 2006) and it's used to realize a *2x3* matrix converter under balanced and unbalanced load conditions.

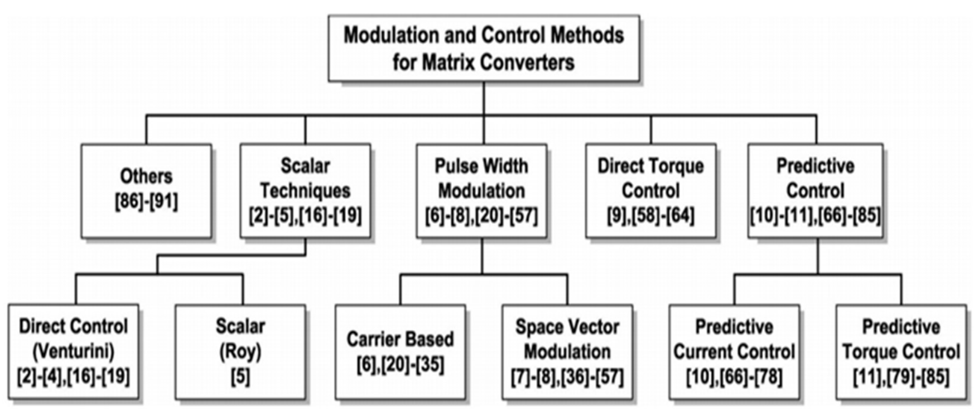


Figure 4.35: Control and modulation techniques for matrix converters (Rodriguez et al., 2012)

CHAPTER 5

SIMULATION RESULTS

5.0 Introduction

Matrix converter has been seen as a substitute for bidirectional current flow based converters and also very efficient when direct power conversion is required especially in the case of ac – ac power conversion. Conventional matrix converters are made up nine switches which are classified as bidirectional switches. The power conversion or conditioning status of matrix converters is of wide variety i.e. ac to ac power conversion, ac to dc power conversion, dc to dc power conversion and dc to ac power conversion. Matrix converters have the capability to change the output power phase irrespective of the input power phase. Matrix converter poses several advantages such as: output frequency changing capabilities, single stage conversion/converter, displacement factor boosting capabilities (Gyugyi & Pelly, 1976; Venturini & Alesina, 1980), unity displacement factor, bidirectional power circulation, apex power density (Pan et al., 1993), input and output voltages have sinusoidal waveforms, the sinusoidal output voltage and frequency are variable, unity power factor current at the input and high efficiency (Huber & Borojevic, 1995). Minimum number of reactive elements (Zuckerberger et al., 1996), reduced size because large storage elements are omitted hence the input filter size

In this thesis, a single phase ac to ac and dc to ac power conversion matrix converter will be simulated in PSCAD and results produced for validation purposes. The control technique to be used in controlling the single phase matrix converter is the general method proposed in (Babaei et al., 2006). This method has two components; positive control method and negative control method. Several control techniques are proposed for the simulation of matrix converters, some examples are: Alesina-Venturini method, Basic method, PWM, SPWM. The latter method is utilized. Fig. 5.1 shows the generalized circuit diagram of an ***m x n*** cycloconverter or matrix converter. The circuit diagram for the single phase input to single phase output ac to ac cycloconverter is shown in Fig. 5.2. The used switches are of bidirectional nature and made by the connection of two IGBTs and diodes in a structure popularly referred to as common emitter connection. To increase efficiency of matrix converters or cycloconverters appropriate control method should be utilized to reduce the switching and conduction losses though conduction losses are mostly caused by switches.

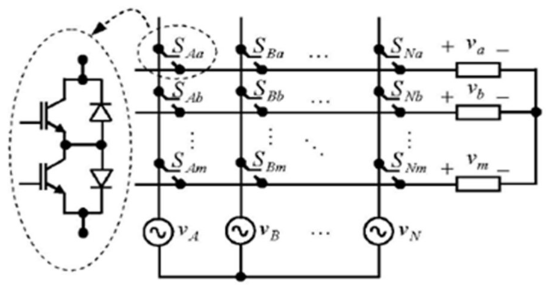


Figure 5.1: generalized ***m x n*** cycloconverter (Babaei et al., 2006)

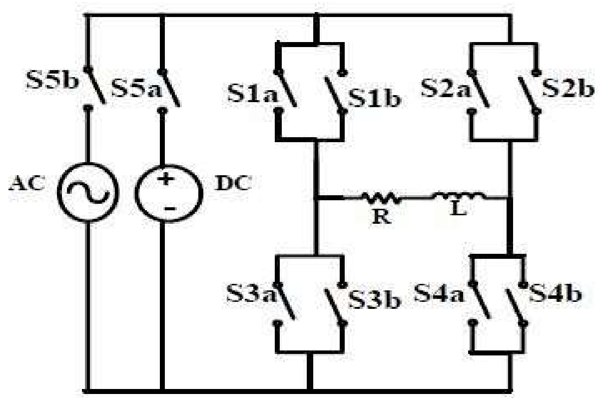


Figure 5.2: Single phase matrix converter

The input and output voltages of the single phase matrix converter is given by equations (5.1) and (5.2) respectively.

$$v_i = V_{im} sin\omega_i t \tag{5.1}$$

$$v_o = V_{om} sin\omega_o t \tag{5.2}$$

From Fig. 5.2 the switching period of the matrix converter is divided into two parts; t1 and t2 which imply that the total switching period T_s is given by:

$$T_s = t_1 + t_2 \quad (5.3)$$

$$T_s = \frac{1}{f_s} \quad (5.4)$$

Producing a matrix representation of the switching pattern of the matrix converter will yield the matrix below:

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \quad (5.5)$$

In other to produce and even distribution of switches for each half of Ts switching, the new matrix below is produced.

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{matrix} S_{11} \\ S_{21} \end{matrix} \quad (5.6)$$

The output voltage is segmented into two parts; positive input voltage ($+v_i$) and negative input voltage ($-v_i$). In the duration of t_1, positive input voltage ($+v_i$) flows and in the duration of t_2, negative input voltage ($-v_i$) flows hence the flowing equations can be written:

$$v_o = +v_i \text{ during } t_1 \quad (5.7)$$

$$v_o = -v_i \text{ during } t_2 \quad (5.8)$$

where $P_1 = \frac{t_{1,P}}{T_s}$; $P_2 = \frac{t_{2,P}}{T_s}$ (5.11)

$$P_1 = \frac{1+\frac{V_{om}\sin(\omega ot)}{V_{im}\sin(\omega it)}}{2} \quad ; \; P_2 = \frac{1-\frac{V_{om}\sin(\omega ot)}{V_{im}\sin(\omega it)}}{2} \tag{5.12}$$

$$t_{1,P} = T_s\left(\frac{1+\frac{V_{om}\sin(\omega ot)}{V_{im}\sin(\omega it)}}{2}\right) \; ; \; t_{2,P} = T_s\left(\frac{1-\frac{V_{om}\sin(\omega ot)}{V_{im}\sin(\omega it)}}{2}\right) \tag{5.13}$$

The input and output currents of Fig.5.2 are given by equations blow:-

$$v_o = v_R + v_L \longrightarrow v_o = Ri_o + L\frac{di_o}{dt} \tag{5.14}$$

$$v_o = V_{om}sin\omega_o t \longrightarrow i_o = \frac{V_{om}}{\sqrt{R^2+(L\omega_o)^2}}sin\left[\omega_o t + tan^{-1}\left(\frac{L\omega_o}{R}\right)\right] \tag{5.15}$$

by defining : $I_{om} = \frac{V_{om}}{\sqrt{R^2+(L\omega_o)^2}}$ and $\emptyset_o = tan^{-1}\left(\frac{L\omega_o}{R}\right)$ (5.16)

Output Current:

$$i_o = [I_{om}\sin(\omega_o t + \emptyset_o)] \tag{5.17}$$

Input Current:

$$i_i = (P_1 - P_2)i_o \tag{5.18}$$

The input parameters used for the simulation and the desired output parameters are given in (5.19) and (5.20):

$$v_i = 100sin100\pi t \tag{5.19}$$

$$v_o = 30sin200\pi t \tag{5.20}$$

From the above equations, the input components are; peak input voltage (V_{im}) is 100V and the input frequency (f_i) is 50Hz. The output components of the output voltage are; peak output voltage (V_{om}) is 30V and output frequency (f_o) is 100Hz, the switching frequency (f_s) is 5 kHz and the load is an RL load where the resistor (R) is 20ohms and the inductor (L) is 40mH. It should be noted that by applying ***positive control*** method for the simulation of the single phase matrix converter, the matrix converter becomes a booster for output frequency whiles in the case of the case of the output voltage, the matrix converter becomes a buck converter.

(A boost (step-up) converter for frequency)

(A buck (step-down) converter for voltage).

5.1 Simulation Results

5.1.1 AC Voltage input

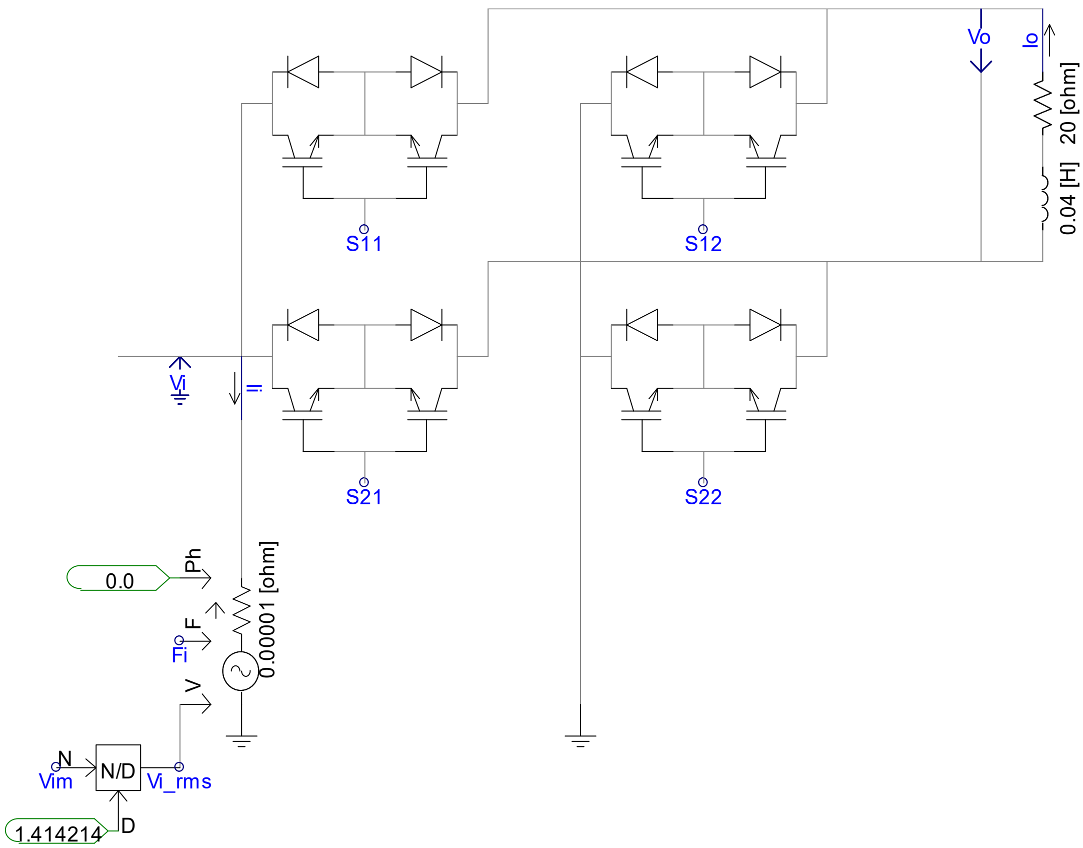


Figure 5.3: Circuit Diagram **of** single phase cycloconverter

5.1.2 Simulation Results of AC Voltage input

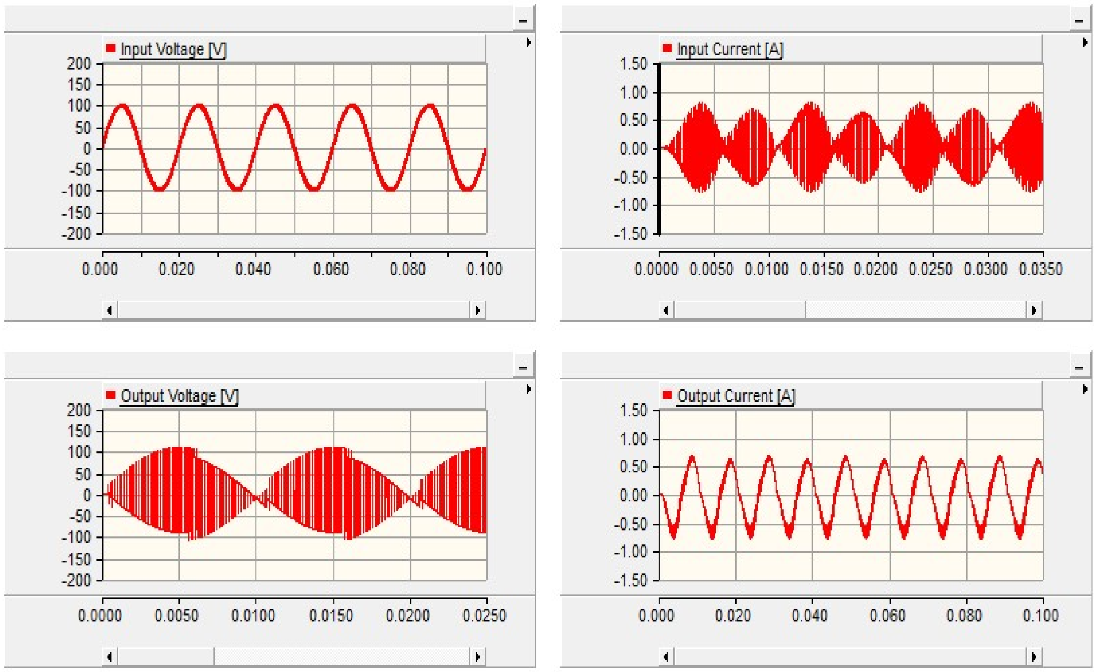


Figure 5.4: Single phase cycloconverter simulation results

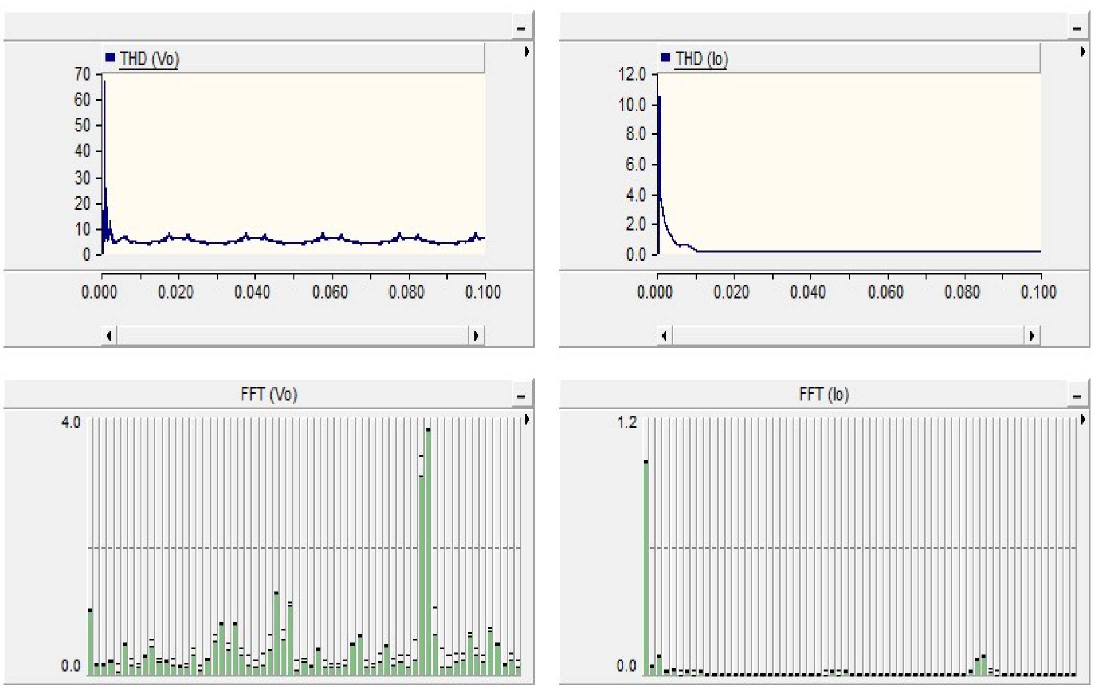


Figure 5.5: THD , FFT Single phase cycloconverter simulation results

5.1.3 DC Voltage input

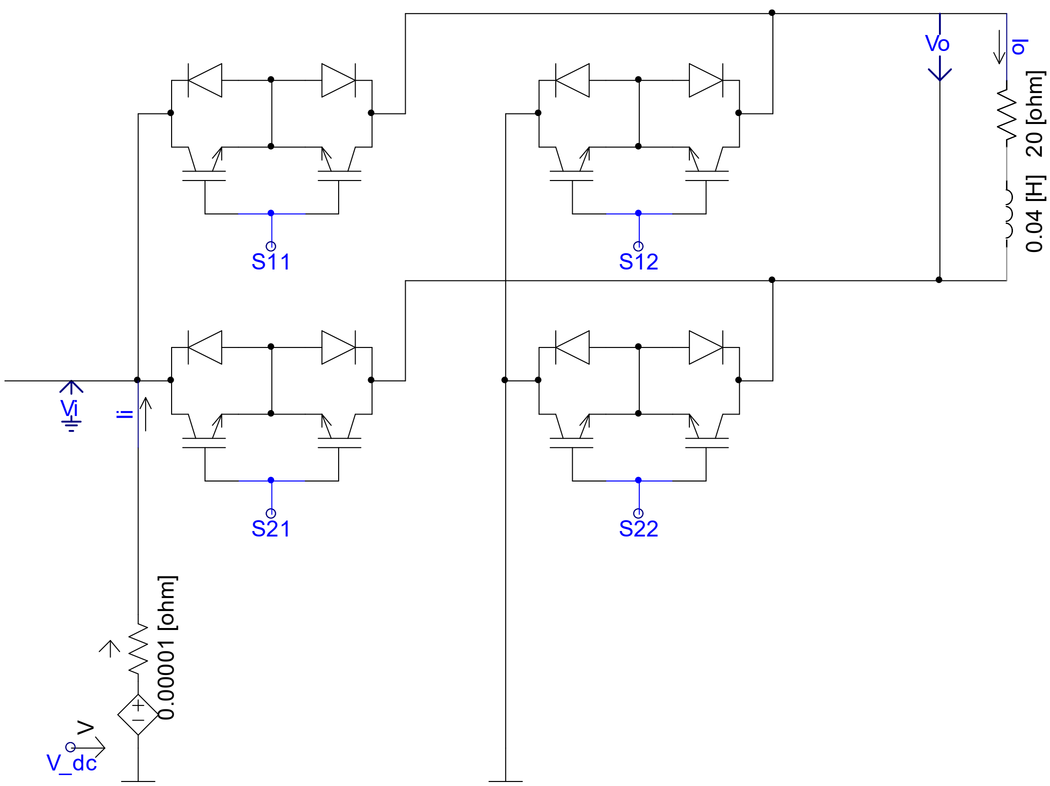


Figure 5.6: Circuit Diagram **of** single phase Inverter

5.1.4 Simulation Results of DC Voltage input

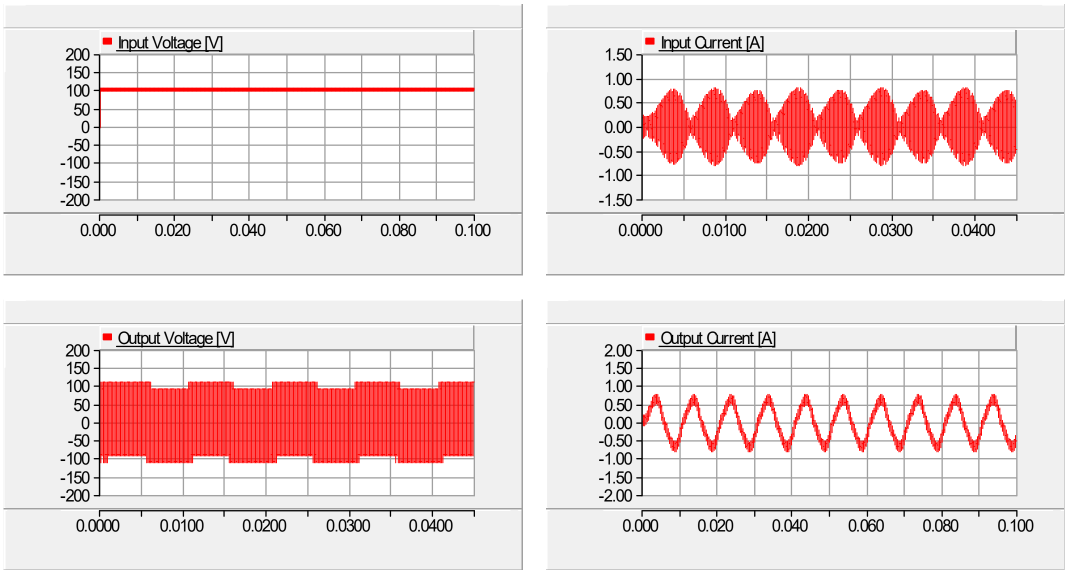


Figure 5.7: single phase Inverter simulation results

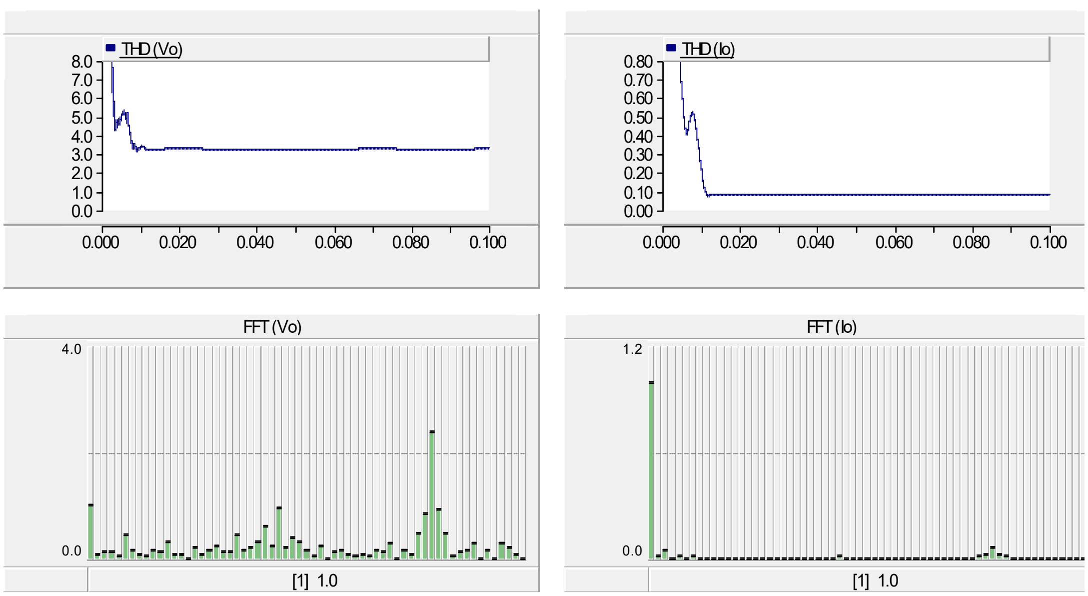


Figure 5.8: THD, FFT Single phase Inverter simulation results

The results produced above for the single phase matrix is for ac to ac conversion and dc to ac i.e. the matrix converter is applied as a cycloconverter and as an inverter. The matrix converter can be applied as a rectifier and a chopper or dc to dc converter. When the matrix converter is applied as a rectifier, the current flow and switches in operation are shown in Fig. 5.9a and 5.9b. The positive and negative current flow from the source and its direction and corresponding switches in operation are given by Fig. 5.9a and 5.9b respectively.

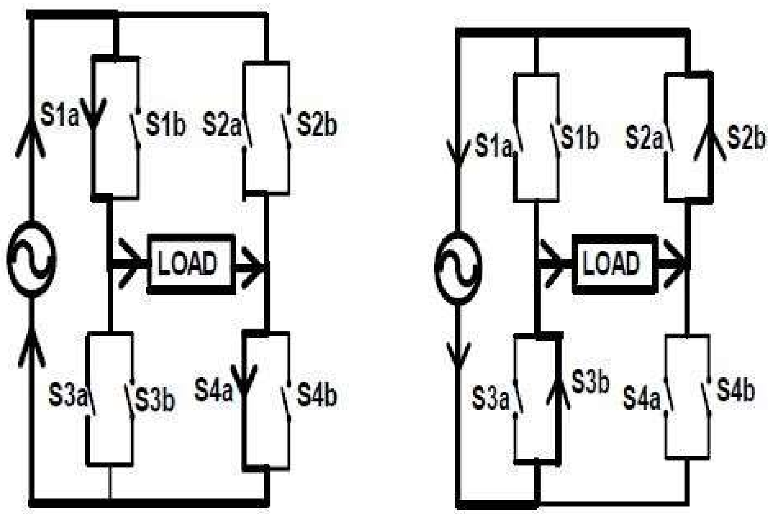


Figure 5.9: Matrix converter based rectifier

In the case of dc-dc converter or chopper application, the matrix converter converts a dc voltage at source to a required level of dc voltage ate the output. Since the matrix converter is functions as a buck converter; the output voltage of the matrix converter is always less than the input voltage but in case of frequency, the matrix converter functions as a boost frequency converter. The above analysis is derived when the positive control method is applied. The current flow and switches in operation when the matrix converter is utilized as chopper is shown in Fig. .510. Only switches S1a, S4a are in operation because of the nature of the source voltage.

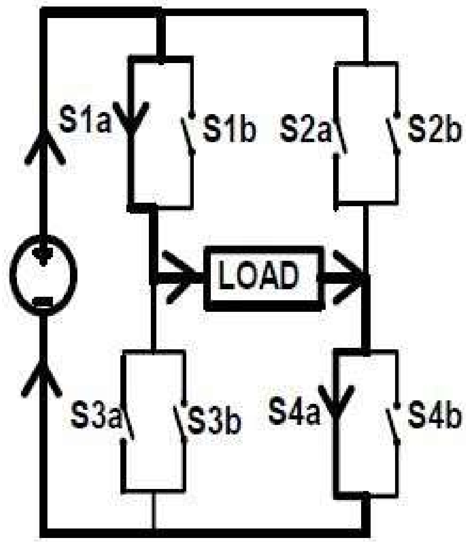


Figure 5.10: Chopper based matrix converter

In situation where matrix converter is applied as an inverter, the circuit for current flow is shown in Fig. .511. Two figures are used because both positive and negative voltages are required at the output of the inverter.

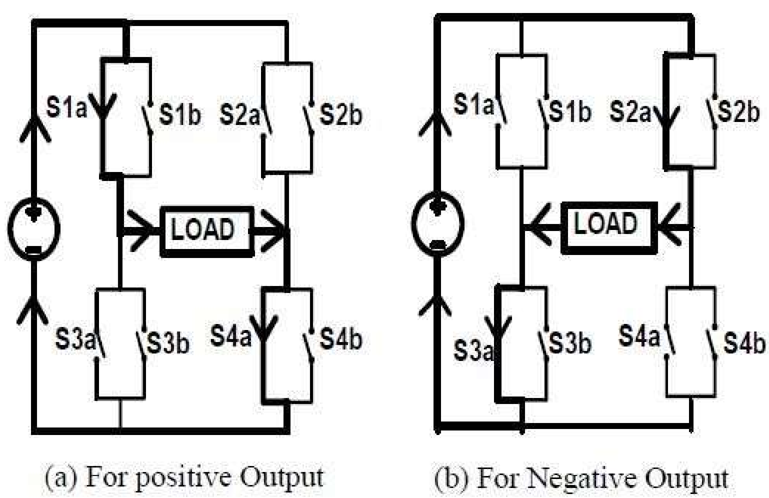
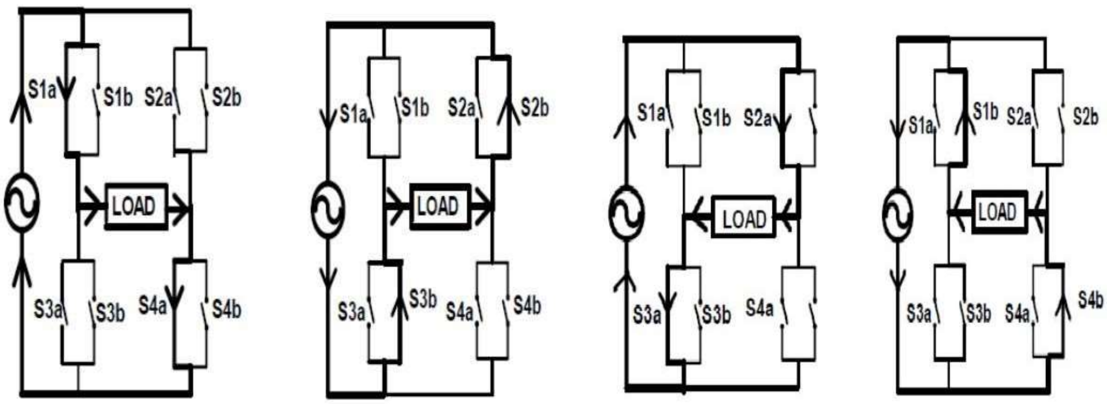


Figure 5.11: Inverter based matrix converter

If the matrix converter is applied as a cycloconverter just as in the case of single phase cycloconverter under investigation, four circuits are produced for the switching, two circuits for the positive cycle and two circuits for the negative circuits. Cycloconverters which are sometimes called static frequency changers are types of ac–ac converters which produce variable voltage and variable frequency at their output using constant ac power source have constant frequency and voltage, the setup is always devoid of a dc link. There are varied application areas for which cycloconverters can be put to maximum application; powers system motor control especially in low speed, power industries where variable frequency and voltage are required, heavy industrial applications (Azam, 2014; LeMone, Ehara, & Nehl, 1986).



(a) positive output switching (b) negative output switching

Figure 5.12: Cycloconverters

5.2 3- Phase to 2- Phase matrix converter

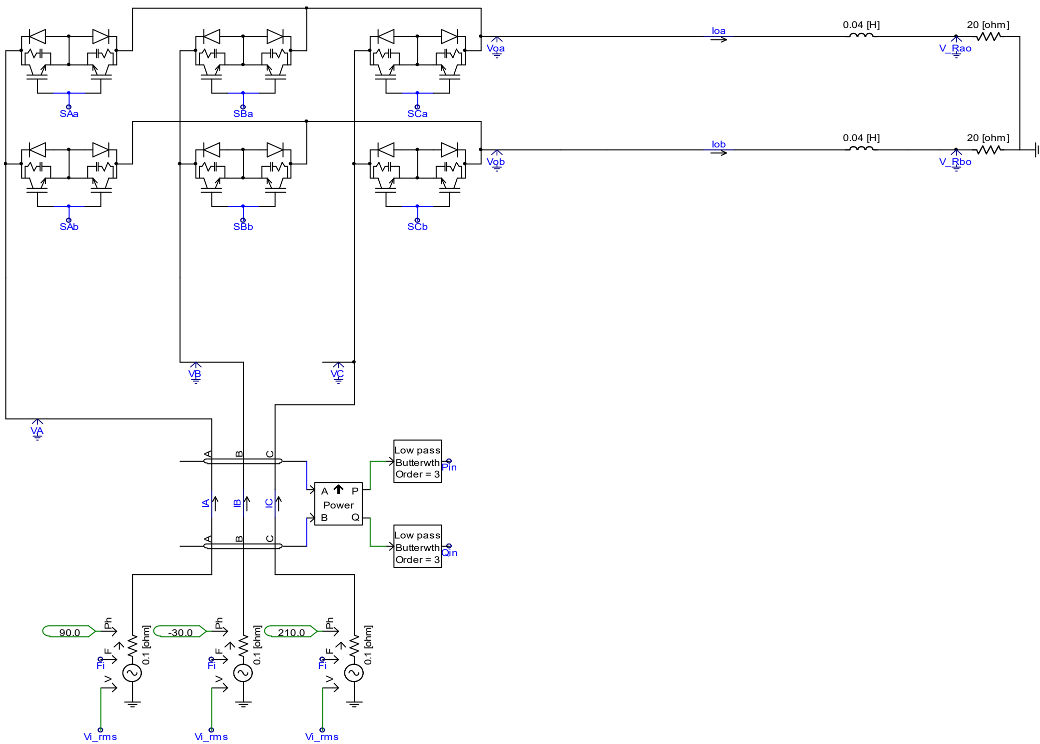


Figure 5.13: 3-phase to 2- phase matrix converter

The input and output voltages of the 3- phase to 2- phase matrix converter is given by equations (5.21) and (5.22) respectively.

$$\begin{bmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{bmatrix} = V_{im} \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t - \frac{2\pi}{3}) \\ \cos(\omega_i t + \frac{2\pi}{3} \end{bmatrix} \tag{5.21}$$

$$\begin{bmatrix} V_a(t) \\ V_b(t) \end{bmatrix} = V_{om} \begin{bmatrix} \cos(\omega_o t) \\ \cos(\omega_o t - \frac{\pi}{2}) \end{bmatrix} = V_{om} \begin{bmatrix} \cos(\omega_o t) \\ \sin(\omega_o t) \end{bmatrix} \tag{5.22}$$

From Fig. 5.13 the switching period of the matrix converter is divided into three parts; t_1, t_2 and t_3 which imply that the total switching period T_s is given by:

$$T_s = t_1 + t_2 + t_3 \tag{5.23}$$

$$T_s = \frac{1}{f_s} \tag{5.24}$$

Producing a matrix representation of the switching pattern of the matrix converter will yield the matrix below:

$$S = \begin{bmatrix} S_{Aa} & S_{Ab} \\ S_{Ba} & S_{Bb} \\ S_{Ca} & S_{Cb} \end{bmatrix} \tag{5.25}$$

In other to produce and even distribution of switches for each half of Ts switching, the new matrix below is produced.

$$S = \begin{bmatrix} S_{Aa} & S_{Ab} \\ S_{Ba} & S_{Bb} \\ S_{Ca} & S_{Cb} \end{bmatrix} \tag{5.26}$$
$$\quad S_{Aa} \quad S_{Ab}$$

ON switches During t_{1P}

ON switches During t_{2P}

ON switches During t_{3P}

Where:

$$P_1 = \frac{t_{1,P}}{T_s}\ ;\ P_2 = \frac{t_{2,P}}{T_s} \quad P_3 = \frac{t_{3,P}}{T_s} \tag{5.27}$$

The average output voltage given by equations blow:-

$$v_a = P_1 \,.\, v_A + P_2 \,.\, V_B + P_3 \,.\, v_C \qquad (5.28)$$

$$v_b = P_1 \,.\, v_B + P_2 \,.\, V_C + P_3 \,.\, v_A \qquad (5.29)$$

$$P_1 = \frac{1}{3} + \frac{2\sqrt{3}}{9}\frac{V_{om}}{V_{im}}\{cos[(\ \omega_i + \omega_o)t - 30^o] + cos[(\ \omega_i + \omega_o)t + 30^o] - cos(\ \omega_i + \omega_o)t + cos(\ \omega_i - \omega_o)t + sin(\ \omega_i + \omega_o)t\ \} \qquad (5.30)$$

$$P_2 = \frac{1}{3} + \frac{2\sqrt{3}}{9}\frac{V_{om}}{V_{im}}\{cos[(\ \omega_i + \omega_o)t + 60^o] - cos[(\ \omega_i - \omega_o)t + 60^o] - cos[(\ \omega_i + \omega_o)t + 30^o] - cos[(\ \omega_i - \omega_o)t + 30^o]\} \qquad (5.31)$$

$$\boldsymbol{P_3 = \frac{1}{3} + \frac{2\sqrt{3}}{9}\frac{V_{om}}{V_{im}}\{cos[(\ \omega_i + \omega_o)t - 60^o] - cos[(\ \omega_i - \omega_o)t - 60^o] - sin(\ \omega_i + \omega_o)t - sin(\ \omega_i - \omega_o)t\}} \qquad (5.32)$$

The output voltages and currents for the two phase R-L load given by equations blow:

$$\boldsymbol{v_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt}} \qquad (5.33)$$

$$\boldsymbol{v_b(t) = R_b i_b(t) + L_a \frac{di_a(t)}{dt}} \qquad (5.34)$$

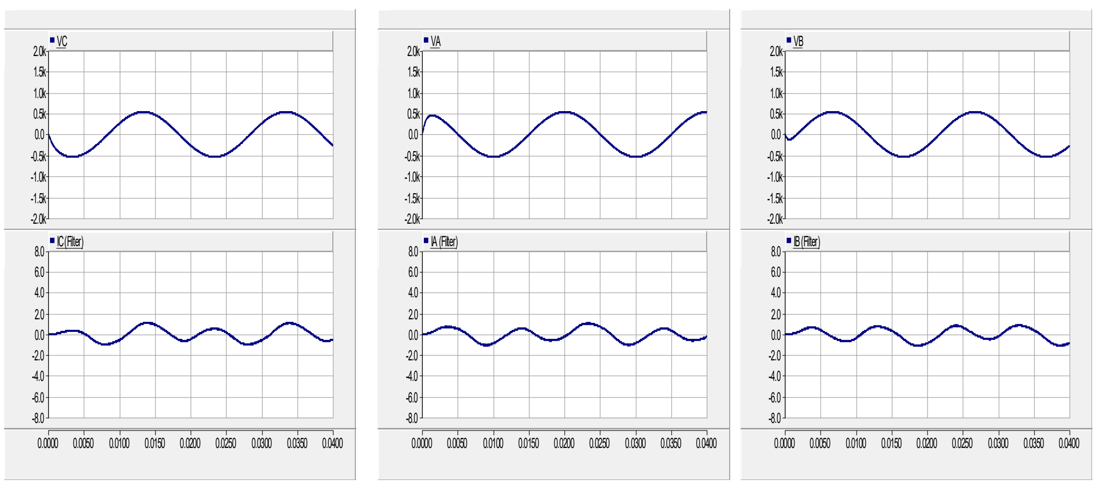
$$\boldsymbol{i_a(t) = \frac{V_{am}}{\sqrt{(L_a\omega_o)^2 + {R_a}^2}} cos(\omega_o t - tan^{-1}\left(\frac{L_a\omega_o}{R_a}\right))} \qquad (5.35)$$

$$\boldsymbol{i_b(t) = \frac{V_{bm}}{\sqrt{(L_b\omega_o)^2 + {R_b}^2}} sin(\omega_o t - tan^{-1}\left(\frac{L_a\omega_o}{R_b}\right))} \qquad (5.36)$$

The input parameters used for the simulation and the desired output parameters are given blow :

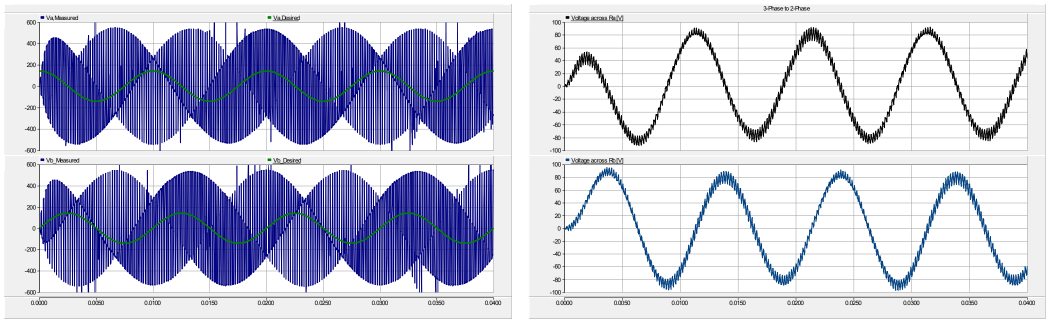
V_{im}=380$\sqrt{2}$V = 537.4V
$f_i = 50Hz$
$f_s = 5000Hz$
$V_{am} = 100\sqrt{2}V = 141.4V$
$V_{bm} = 100\sqrt{2}V = 141.4V$
$f_o = 100Hz$
R = 20 Ohms
L=40mH

5.2.1 Simulation Results for 3- Phase to 2- Phase



(a) VC and IC (b) VA and IA (c) VB and IB

Figure 5.14: Input voltage and current for each phase



(a) Va, Vb Measured and Va,Vb Desired (b) Voltage across Ra,Rb

Figure 5.15: Measured and Desired Output Voltage

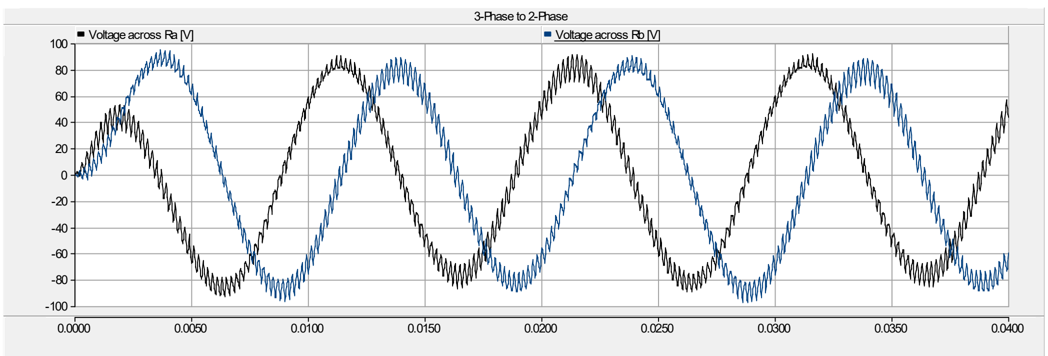
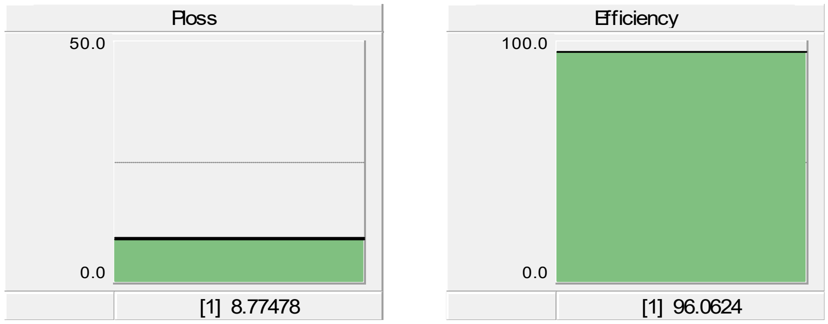


Figure 5.16: Voltage across Ra,Rb

(a) P input (b) P output

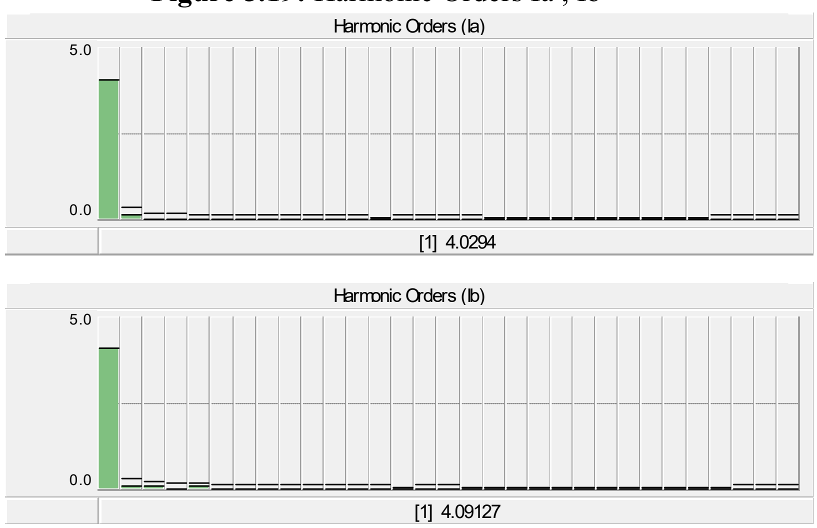
Figure 5.17: Input and Output Power



(a) P loss (b) Efficiency

Figure 5.18: Power losses and Efficiency

Figure 5.19: Harmonic Orders Ia , Ib



5.3 Losses Calculations

Practical applications of converters require that the losses produced should be reduced to barest level in other to make to produce converters with high efficiency which is a tradeoff between cost and return of investments. Several methods have been proposed to determine losses in converters; the calculations are mostly on switching and conduction losses which are the principal contributors to converter losses. Detailed semiconductor losses calculations have been explained in (Sunter & Altun, 1998). Due to the lack of experimental investigation of the proposed thesis, the determination of losses in this section will be based on theoretical analysis since component data provided by the manufacturer is not available.

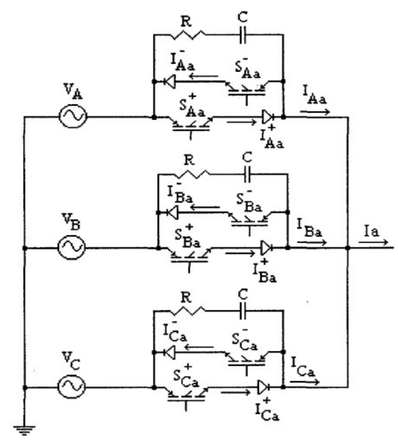


Figure 5.20: 3- Phase Matrix Converter (Sunter & Altun, 1998)

According to [24], the semiconductor loss calculations are determined by the equations provided below. First is to determine V_f; forward voltage drop for both components diode and semiconductor since each bidirectional switch is composed of two IGBTs and two diodes. In the conduction phase, V_f is the function result of collector current and junction temperature. The V_f of each switch in Fig. 5.20 is determined by (5.37) where the variable in the expression are provided by the datasheet provided by the manufacturer.

$$V_f = \left(V_T + R_T.I^{\beta}\right) + \left(V_d + R_d.I\right) \quad (5.37)$$

In each conducting period one IGBT and one diode from each bidirectional switch of Fig. 5.20 will conductor hence the total number of components gated on for each conduction period are three IGBTs and three diodes. Energy loss (Sunter & Altun, 1998)for the three switches conducting at that period is given by:

$$E = \int_{t_1}^{t_2}\Big[(V_d + V_T)(I_{Aa} + I_{Ba} + I_{Ca}) + R_d(I_{Aa}^2 + I_{Ba}^2 + I_{Ca}^2) +$$
$$R_T(I_{Aa}^{\beta+1} + I_{Ba+}^{\beta+1} + I_{Ca+}^{\beta+1})\Big]dt \quad (5.38)$$

The positive half cycle energy dissipation is given by (5.39) where I_{om} is maximum output current:

$$E = \int_{0}^{\pi/\omega_o}\Big[(V_d + V_T)I_{om}\sin(\omega_o t) + R_d I_{om}^2 \sin_2(\omega_o t) +$$
$$R_T I_{om}^{\beta+1}\sin^{\beta+1}(\omega_o t)\Big]dt \quad (5.39)$$

The average power loss is given by (5.40):

$$P_c = \frac{E}{(\frac{2\pi}{\omega_o})} = \frac{I_{om}}{\pi}(V_d + V_T) + \frac{I_{om}^2}{4}R_d + \frac{I_{om}^{\beta+1}R_T}{(\frac{2\pi}{\omega_o})}\int_0^{\pi/\omega_o}\sin^{\beta+1}(\omega_o t)\,dt \quad (5.40)$$

Another method for calculating the losses of switches in a matrix converter is the sum of the loss for the following; switching, conduction and blocking. Basically the average total losses of a switch are given by:

$$P_{switch,av} = P_{switching,av} + P_{conduction,av} + P_{blocking,av} \quad (5.41)$$

The switching losses are calculated by:

$$P_{switching,av} = P_{ON,av} + P_{OFF,av} \quad (5.42)$$

$$P_{ON,av} = \frac{1}{T_s} \int_0^{t_{on}} V_s i_s dt \tag{5.43}$$

$$P_{OFF,av} = \frac{1}{T_s} \int_0^{t_{off}} V_s i_s dt \tag{5.44}$$

The conduction and blocking losses are given (5.45) and (5.46) respectively.

$$P_{ON,av} = \frac{1}{T_s} \int_0^{T_{ON}} V_s i_s dt = V_{ON} I_{ON} \frac{T_{ON}}{T_S} \tag{5.45}$$

$$P_{blockin,av} = \frac{1}{T_s} \int_0^{T_{OFF}} V_s i_s dt = V_{OFF} I_{OFF} \frac{T_{OFF}}{T_S} \tag{5.46}$$

CHAPTER 6

CONCLUSION

The importance of energy in today's world cannot be underestimated; gradually energy in all forms (petrochemical energy, renewable; solar, wind, hydro, wave etc.) have become very important commodities that help in the smooth running of affairs in our day to day activities such transportation; aviation, railways, automobile and ships, construction, health delivery, education, communication etc. The absence of energy will have crippling effect on the socio-economic development of any society. Electric power or energy applications is changed conventional utilization to new application areas such as electric vehicle. The negative effects such as environmental pollution, emission of CO_2 gases, depletion of ozone layer, conflicts etc. of conventional method of using fossil fuel for electric power generation has paved the way for rapid utilization of raw materials derived from RES for electric power generation. The application of RES are the principal components in the development of microgrid and distributed generations.

As the world energy utilization is shifting from fossil fuels to renewable energy source, efficiency has become an integral part in power generation, transmission and distribution. Efficiency is a very critical component required in renewable energy conversion to reduce losses and hence produce power at affordable cost to the consumer and also wisely apply the source energy. Due to the above concerns, power generation systems are now shifting from centralized systems to a more localized system such as distributed generation and microgrid systems; these systems offers reduced transmission losses which translates to reduced cost and better and energy management.

Power conversion or condition requires the use of power converters and these converters should be suitable for the specific application, minimize losses and most important boost or increase the voltage as much as possible. Energy conversion processes (such inversion capabilities, the process of rectification, cycloconverter applications and dc chopper applications.) are very important task in today's energy generation systems because of the various methods of electric power generation and the different types of loads. Some applications of energy conversion in electrical systems are inversion capabilities, the process of rectification, cycloconverter applications and dc chopper applications.

In the case of my thesis, matrix converters are selected to effectively and efficiently condition multiple energy sources from distributed generation to the desired output condition.

Matrix converter has been seen as a substitute for bidirectional current flow based converters and also very efficient when direct power conversion is required especially in the case of ac – ac power conversion. Matrix converter topology is made up of a nine switch converter having bidirectional current flow capabilities and also four quadrants functionality. The matrix converter performs a wide variety of power conditioning such as conversions and inversions.

In the simulation aspect of my thesis, a single phase cycloconverter and the inverter was simulated in PSCAD software and simulation results produced. Also explanation for various switch control during different power conditioning such as rectification; changing ac power to dc power, inversion; changing dc power to ac power, chopper application; changing one level of dc power to another level of dc. These explanations go to show that matrix converter application is not limited to only cycloconverters. The simulation results produce show good voltage transfer ratio which is mostly limited to 86.6% of the input voltage. For improving disadvantage of the limited voltage transfer the impedance or Z source topology is applied. Several impedance network based topologies exist which can perform a variety of function but with goal of increasing the voltage gain.

One major concern of matrix converters is the losses due to conduction and switching. But fortunately these concerns have been addressed in various publications where appropriate switching mechanism significantly reduces the conduction losses even though higher number of semiconductor switches are utilized, similarly, most PWM based control methods reduces losses caused by switching. Actually switching losses are concerns for all converters where higher switching frequencies are applied. There’s always a tradeoff between quality output waveform and reduced switching frequency.

Although Matrix converters have several advantages; variable output voltage and frequency, single stage power conversion, bidirectional power flow etc. they are yet to be fully commercialized when compared to other converters. Utilizing matrix converter as power conditioning device is an appropriate choice due its several merits.

REFERENCES

Adamek, J., Hofmann, W., & Lindemann, A. (2003). *Switching performance and demands of bidirectional IGBT-configurations in matrix converters.* Paper presented at the Record of the 9 European Conference on Power Electronics and Applications (EPE).

Admin. (2016). Off the Grid Guide – Hybrid Solar System.

Agency, U. S. E. P., & Partnership, C. H. a. P. (2015). catalog of CHP Technologies Retrieved from https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies_section_1._introduction.pdf

Aghasi, M., Faraji, V., Khaburi, D., & Kalantar, M. (2010). *A novel direct torque control for doubly fed induction machine based on indirect matrix converter.* Paper presented at the National Conference on Electrical, Electronics and Computer Engineering.

Alalei, A., Kermadi, M., Nesba, A., & Hazzab, A. (2017). *Adaptive sliding mode control of DFIG fed by matrix converter during grid faults.* Paper presented at the 2017 IEEE Conference on Energy Conversion (CENCON).

Alesina, A., & Venturini, M. (1981). Solid-state power conversion: A Fourier analysis approach to generalized transformer synthesis. *IEEE transactions on circuits and systems, 28*(4), 319-330.

Alesina, A., & Venturini, M. (1988). *Intrinsic amplitude limits and optimum design of 9-switches direct PWM AC-AC converters.* Paper presented at the PESC'88 Record., 19th Annual IEEE Power Electronics Specialists Conference.

Alesina, A., & Venturini, M. G. (1989). Analysis and design of optimum-amplitude nine-switch direct AC-AC converters. *IEEE Transactions on Power Electronics, 4*(1), 101-112.

Andrade-Romero, J. A., Herrera, V., & Romero, J. F. A. (2012). *Open-Circuit fault detection analysis for indirect matrix converter in Microturbine generation systems.* Paper presented at the IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society.

Azam, A. (2014). Three to single-phase high-power quality switch-mode cycloconverter. *IET Power Electronics, 7*(6), 1603-1617.

Babaei, E., & Heris, A. A. (2009). *PWM-based control strategy for forced commutated cycloconverters.* Paper presented at the 2009 IEEE Symposium on Industrial Electronics & Applications.

Babaei, E., Hosseini, S. H., Gharehpetian, G. B., & Sabahi, M. (2006). *A new switching strategy for 3-phase to 2-phase matrix converters.* Paper presented at the 2006 SICE-ICASE International Joint Conference.

Baharom, R., & Hamzah, M. (2010). *Advanced single-phase ac-dc converter using single-phase matrix converter topology incorporating with active power filter function.* Paper presented at the 2010 IEEE International Energy Conference.

Barker, P. P., & De Mello, R. W. (2000). *Determining the impact of distributed generation on power systems. I. Radial distribution systems.* Paper presented at the 2000 Power Engineering Society Summer Meeting (Cat. No. 00CH37134).

Beasant, R., Beattie, W., & Refsum, A. (1990). *An approach to the realization of a high-power Venturini converter.* Paper presented at the 21st Annual IEEE Conference on Power Electronics Specialists.

Blaschke, F. (1972). The principle of field orientation as applied to the new transvector closed-loop system for rotating-field machines. *Siemens review, 34*(3), 217-220.

Burany, N. (1989). *Safe control of four-quadrant switches.* Paper presented at the Conference Record of the IEEE Industry Applications Society Annual Meeting.

Candy, J. C., & Temes, G. C. (1992). *Oversampling delta-sigma data converters: theory, design and simulation*: IEEE Press.

Chen, S., Lipo, T. A., & Fitzgerald, D. (1996). Source of induction motor bearing currents caused by PWM inverters. *IEEE Transactions on Energy conversion, 11*(1), 25-32.

Chiang, G. T., & Itoh, J.-i. (2013). Comparison of two overmodulation strategies in an indirect matrix converter. *IEEE Transactions on Industrial Electronics, 60*(1), 43-53.

Cho, J., & Cho, G. (1991). Soft switched matrix converter for high frequency direct AC-to-AC power conversion, EPE Conf. *Rec., Firenze*, 4.

Consumption, U. S. E. (2008). Solar at glance

Cruz, S. M., Ferreira, M., Mendes, A. M., & Cardoso, A. J. M. (2011). Analysis and diagnosis of open-circuit faults in matrix converters. *IEEE Transactions on Industrial Electronics, 58*(5), 1648-1661.

Dallago, E., & Sassone, G. (1997). Advances in high-frequency power conversion by delta-sigma modulation. *IEEE transactions on circuits and systems I: Fundamental theory and applications, 44*(8), 712-721.

DiPippo, R. (2016). *Geothermal Power Generation: Developments and Innovation*: Elsevier Science.

Djahbar, A., Mazari, B., & Mansour, N. (2005). *High performance motor drive using three-phase matrix converter.* Paper presented at the International Conference on Computational Intelligence for Modelling, Control and Automation and International Conference on Intelligent Agents, Web Technologies and Internet Commerce (CIMCA-IAWTIC'06).

Duran, S. (2005). Computer aided design of horizontal axis wind turbine blades. *Master's thesis, Middle East Technical University, Ankara, Turkey*.

Empringham, L., De Lillo, L., Khwan-On, S., Brunson, C., Wheeler, P., & Clare, J. (2011). *Enabling technologies for matrix converters in aerospace applications.* Paper presented at the 2011 7th International Conference-Workshop Compatibility and Power Electronics (CPE).

Empringham, L., Kolar, J. W., Rodriguez, J., Wheeler, P. W., & Clare, J. C. (2013). Technological issues and industrial application of matrix converters: A review. *IEEE Transactions on Industrial Electronics, 60*(10), 4260-4271.

Environmental and Energy Study Institute (EESI). (2009). Concentrated Solar Power.

Ett, G., Janólio, G., & Ett, V. (2002). Geração de energia elétrica distribuida a partir de célula a combustível. *Procedings of the 4th Encontro de Energia no Meio Rural*.

Fang, X., Cao, M., & Li, C. (2010). *Single-phase Z-source matrix converter.* Paper presented at the 2010 International Conference on Electrical Machines and Systems.

Fang, X., & Chen, Z. (2009). *Current-fed Z-source matrix converter.* Paper presented at the 2009 International Conference on Applied Superconductivity and Electromagnetic Devices.

Farret, F. A., & Simoes, M. G. (2006). *Integration of alternative sources of energy*: John Wiley & Sons.

Ferreira, M., Cruz, S., & Cardoso, A. (2008). *Modeling and simulation of matrix converter drives for diagnostic purposes.* Paper presented at the 2008 18th International Conference on Electrical Machines.

Friedli, T., Heldwein, M., Giezendanner, F., & Kolar, J. W. (2006). *A high efficiency indirect matrix converter utifizing RB-IGBTs.* Paper presented at the 2006 37th IEEE Power Electronics Specialists Conference.

Friedli, T., Kolar, J. W., Rodriguez, J., & Wheeler, P. W. (2012). Comparative evaluation of three-phase AC–AC matrix converter and voltage DC-link back-to-back converter systems. *IEEE Transactions on Industrial Electronics, 59*(12), 4487-4510.

Friedman, N. R. (2002). *Distributed energy resources interconnection systems: Technology review and research needs*. Retrieved from

Fukuda, S., Iwaji, Y., & Hasegawa, H. (1990). PWM technique for inverter with sinusoidal output current. *IEEE Transactions on Power Electronics, 5*(1), 54-61.

Gaiddon, B., Kaan, H., & Munro, D. (2009). *Photovoltaics in the Urban Environment: Lessons Learnt from Large-scale Projects*: Earthscan.

Gaonkar, D., Patel, R., & Pillai, G. (2006). *Dynamic model of microturbine generation system for grid connected/islanding operation.* Paper presented at the 2006 IEEE International Conference on Industrial Technology.

Ge, B., Lei, Q., Qian, W., & Peng, F. Z. (2012). A family of Z-source matrix converters. *IEEE Transactions on Industrial Electronics, 59*(1), 35-46.

González-Longatt, F. (2008). Impacto de la Generación Distribuida en el Comportamiento de los Sistemas de Potencia. *Universidad Central de Venezuela*.

Gorlov, A. (2001). Tidal energy. *Elements of Physical Oceanography*, 103-108.

Guerrero, J. M., Loh, P. C., Lee, T.-L., & Chandorkar, M. (2013). Advanced control architectures for intelligent microgrids—Part II: Power quality, energy storage, and AC/DC microgrids. *IEEE Transactions on Industrial Electronics, 60*(4), 1263-1270.

Guo, M., Liu, Y., Ge, B., & Abu-Rub, H. (2018). Optimum Boost Control of Quasi-Z Source Indirect Matrix Converter. *IEEE Transactions on Industrial Electronics, 65*(10), 8393-8404.

Gyugyi, L., & Pelly, B. R. (1976). *Static power frequency changers: theory, performance, and application*: John Wiley & Sons.

Hajbani, F., Babaei, E., Hosseini, S. H., & Nouri, T. (2012). *A new control method for single-phase to three-phase matrix converter based on SPWM technique.* Paper presented at the 20th Iranian Conference on Electrical Engineering (ICEE2012).

Halkosaari, T., & Tuusa, H. (1999). *Reduction of conducted emissions and motor bearing currents in current source PWM inverter drives.* Paper presented at the 30th Annual IEEE Power Electronics Specialists Conference. Record.(Cat. No. 99CH36321).

Hasegawa, T., & Takeshita, T. (2010). *PWM strategy of voltage harmonics minimization for matrix converters.* Paper presented at the IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society.

Hatti, M. (2007). *Neural Network Power Controller for PEM Fuel Cells Systems.* Paper presented at the 2007 IEEE International Conference on Mechatronics.

Heris, A. A., Sadeghi, M., & Babaei, E. (2011). *A new topology for the three-phase to three-phase cycloconverters.* Paper presented at the 2011 2nd Power Electronics, Drive Systems and Technologies Conference.

Hirota, A., Nagai, S., & Nakaoka, M. (1999). *Performance evaluations of delta-sigma modulated voltage source inverter.* Paper presented at the Proceedings of the IEEE 1999 International Conference on Power Electronics and Drive Systems. PEDS'99 (Cat. No. 99TH8475).

Hirota, A., & Nakaoka, M. (2006). *A low noise three-phase matrix converter introducing delta-sigma modulation scheme.* Paper presented at the 2006 37th IEEE Power Electronics Specialists Conference.

Holmes, D., & Lipo, T. (1989). *Implementation of a controlled rectifier using AC-AC matrix converter theory.* Paper presented at the 20th Annual IEEE Power Electronics Specialists Conference.

Holmes, D. G. (1990). *A new modulation algorithm for voltage and current source inverters, based on AC-AC matrix converter theory.* Paper presented at the Conference Record of the 1990 IEEE Industry Applications Society Annual Meeting.

Holtz, J., & Boelkens, U. (1989). Direct frequency convertor with sinusoidal line currents for speed-variable AC motors. *IEEE Transactions on Industrial Electronics, 36*(4), 475-479.

Horlock, J. H. (1987). Combined heat and power.

Hosseini, S., & Babaei, E. (2001). *A new generalized direct matrix converter.* Paper presented at the ISIE 2001. 2001 IEEE International Symposium on Industrial Electronics Proceedings (Cat. No. 01TH8570).

Hua, G., Leu, C.-S., Jiang, Y., & Lee, F. (1994). Novel zero-voltage-transition PWM converters. *IEEE Transactions on Power Electronics, 9*, 213-219.

Huang, J., Wan, H., Hu, K., & Chen, Q. (2017). *A new three-phase "one-step" boost type matrix converter.* Paper presented at the 2017 Chinese Automation Congress (CAC).

Huber, L., & Borojevic, D. (1995). Space vector modulated three-phase to three-phase matrix converter with input power factor correction. *IEEE transactions on industry applications, 31*(6), 1234-1246.

Huber, L., Burány, N., & Borojević, D. (1992). *Analysis, design and implementation of the space-vector modulator for forced-commutated cycloconvertors.* Paper presented at the IEE Proceedings B (Electric Power Applications).

Idris, Z., & Hamzah, M. K. (2006). *Implementation of a new single-phase cycloconverter based on single-phase matrix converter topology using sinusoidal pulse width modulation with passive load condit.* Paper presented at the 2006 1ST IEEE Conference on Industrial Electronics and Applications.

Infobook, T. N. P. I. E. (2018). solar. Retrieved from https://www.need.org/files/curriculum/infobook/solari.pdf

Itoh, J., Sato, I., Odaka, A., Ohguchi, H., Kodatchi, H., & Eguchi, N. (2004). *A novel approach to practical matrix converter motor drive system with reverse blocking IGBT.* Paper presented at the 2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No. 04CH37551).

Jorgensen, P., Sorensen, A. G., Chistensen, J., & Herager, P. (1997). *Dispersed CHP Units in the Danish Power System.* Paper presented at the CIGRE Symposium on Impact of demand side management, integrated resource planning and distributed generation Neptun, Romania.

Jussila, M., Alahuhtala, J., & Tuusa, H. (2006). *Common-mode voltages of space-vector modulated matrix converters compared to three-level voltage source inverter.* Paper presented at the 2006 37th IEEE Power Electronics Specialists Conference.

Kazerani, M., & Ooi, B. (1993). *Direct AC-AC matrix converter based on three-phase voltage-source converter modules.* Paper presented at the Proceedings of IECON'93-19th Annual Conference of IEEE Industrial Electronics.

Khoei, A., & Yuvarajan, S. (1988). Single-phase AC-AC converters using power MOSFETs. *IEEE Transactions on Industrial Electronics, 35*(3), 442-443.

Kim, J.-S., & Sul, S.-K. (1995). A novel voltage modulation technique of the space vector PWM. *Transactions-Korean Institute of Electrical Engineers, 44*, 865-874.

Kim, J. S., & Sul, S. K. (1993). *New control scheme for AC-DC-AC converter without DC link electrolytic capacitor.* Paper presented at the Proceedings of IEEE Power Electronics Specialist Conference-PESC'93.

Kim, S., Sul, S.-K., & Lipo, T. A. (2000). AC/AC power conversion based on matrix converter topology with unidirectional switches. *IEEE transactions on industry applications, 36*(1), 139-145.

Klaassens, J., Van Wesenbeeck, M., Lauw, H., & Tan, M. (1992). *AC-AC converter with Soft-switching.* Paper presented at the EUROPEAN CONFERENCE ON POWER ELECTRONICS AND APPLICATIONS.

Kolar, J. W., Friedli, T., Rodriguez, J., & Wheeler, P. W. (2011). Review of three-phase PWM AC–AC converter topologies. *IEEE Transactions on Industrial Electronics, 58*(11), 4988-5006.

Kozakevich, I. (2017). *Investigation of the direct torque control system of an electromechanical system with a matrix converter.* Paper presented at the 2017 International Conference on Modern Electrical and Energy Systems (MEES).

Lasseter, R. H. (2002). *Microgrids.* Paper presented at the 2002 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 02CH37309).

Lee, E., & Lee, K.-B. (2012). *Fault diagnosis for a sparse matrix converter using current patters.* Paper presented at the 2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC).

Lee, K.-B., & Blaabjerg, F. (2006). *Sensorless scheme for induction motor drives fed by a matrix converter using power theory.* Paper presented at the 2006 37th IEEE Power Electronics Specialists Conference.

LeMone, C., Ehara, M., & Nehl, L. (1986). *AC adjustable speed application for the cement industry.* Paper presented at the Proceedings of IEEE Cement Industry Technical Conference, Salt Lake City, UT.

Liebreich, M. (2017). Evolution of wind turbine

heights and output. Retrieved from https://data.bloomberglp.com/bnef/sites/14/2017/09/BNEF-Summit-London-2017-Michael-Liebreich-State-of-the-Industry.pdf

Luo, F. L., & Pan, Z. Y. (2006). Sub-envelope modulation method to reduce total harmonic distortion of AC/AC matrix converters. *IEE Proceedings-Electric Power Applications, 153*(6), 856-863.

Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2010). *Wind energy explained: theory, design and application*: John Wiley & Sons.

Masters, G. M. (2004). Renewable and Efficient Electric Power Systems; A John Wiley & Sons. *Inc., Hoboken, New Jersey*, 468-473.

Mirazimi, M., Sharifian, M., & Babaei, E. (2012). *Hysteresis control of a three-phase to two-phase matrix converter.* Paper presented at the 2012 IEEE 5th India International Conference on Power Electronics (IICPE).

Mohammad Noor, S., Abdul Rahman, N., & Hamzah, M. (2011). Single phase matrix converter operating as a four quadrant dc chopper controlled using xilinx FPGA. *Int J Electr Electron Syst Res, 4*.

Neacsu, D. O. (1999). *Current-controlled AC/AC voltage source matrix converter for open-winding induction machine drives.* Paper presented at the IECON'99. Conference Proceedings. 25th Annual Conference of the IEEE Industrial Electronics Society (Cat. No. 99CH37029).

Neft, C. L., & Schauder, C. D. (1988). *Theory and design of a 30-hp matrix converter.* Paper presented at the Conference Record of the 1988 IEEE Industry Applications Society Annual Meeting.

Nielsen, P., Blaabjerg, F., & Pedersen, J. K. (1997). *Novel solutions for protection of matrix converter to three phase induction machine.* Paper presented at the IAS'97. Conference Record of the 1997 IEEE Industry Applications Conference Thirty-Second IAS Annual Meeting.

Noor, S. Z. M., Rahman, N. F. A., & Hamzah, M. K. (2010). *Simulation of DC to DC converter using single phase matrix converter topology.* Paper presented at the 2010 IEEE Symposium on Industrial Electronics and Applications (ISIEA).

Noroozian, R., Abedi, M., Gharehpetian, G., & Hosseini, S. (2009). *Modelling and Simulation of Microturbine Generation System for on-grid and off-grid Operation Modes.* Paper presented at the Int. l Conf. on Renewable Energies and Power Quality (ICREPQ'09).

Office, U. S. D. o. t. i. B. o. R. P. R. (2005). Managing Water Resources in the West

Office., U. G. S. (2009). Digest of UK Energy Statistics Retrieved from http://www.decc.gov.uk/en/content/cms/statistics /publications/dukes/dukes.aspx

Ooi, B.-T., & Kazerani, M. (1995). *Elimination of the waveform distortions in the voltage-source-converter type matrix converter.* Paper presented at the IAS'95. Conference

Record of the 1995 IEEE Industry Applications Conference Thirtieth IAS Annual Meeting.

Outlook, W. E. (2017). Global average annual net capapcity additions by type. Retrieved from https://www.iea.org/weo2017/

Pan, C.-T., Chen, T.-C., & Shieh, J.-J. (1993). *A zero switching loss matrix converter.* Paper presented at the Proceedings of IEEE Power Electronics Specialist Conference-PESC'93.

Patel, P., & Mulla, M. A. (2017). *Multi-carrier pulse width modulation for multimodular matrix converter.* Paper presented at the 2017 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC).

Peksen, M. (2015). Numerical thermomechanical modelling of solid oxide fuel cells. *Progress in energy and combustion science, 48*, 1-20.

Peng, F. (2002). *Z-source inverter.* Paper presented at the Conference Record of the 2002 IEEE Industry Applications Conference. 37th IAS Annual Meeting (Cat. No. 02CH37344).

Peng, F. Z. (2003). Z-source inverter. *IEEE transactions on industry applications, 39*(2), 504-510.

Peng, T., Dan, H., Yang, J., Deng, H., Zhu, Q., Wang, C., . . . Guerrero, J. M. (2016). Open-switch fault diagnosis and fault tolerant for matrix converter with finite control set-model predictive control. *IEEE Transactions on Industrial Electronics, 63*(9), 5953-5963.

Poole, L. (2001). *Concentrating solar power: Energy from mirrors*. Retrieved from

Power, C. S. (2009). Global Outlook 09. *ESTELA, IEA SolarPACES, Greenpeace International*.

Rajasekar, N., Jacob, B., Balasubramanian, K., Priya, K., Sangeetha, K., & Babu, T. S. (2015). Comparative study of PEM fuel cell parameter extraction using Genetic Algorithm. *Ain Shams Engineering Journal, 6*(4), 1187-1194.

Rao, A. K., Chatterjee, J., Subramanian, S., & Rajasekhar, V. (2010). *Improved operation of a three phase matrix converter using simple modulation strategy.* Paper presented at the 2010 Joint International Conference on Power Electronics, Drives and Energy Systems & 2010 Power India.

Rivera, M., Nasir, U., Tarisciotti, L., Wheeler, P., Dragicevic, T., & Blaabjerg, F. (2017). *Predictive control strategies for an indirect matrix converter operating at fixed switching frequency.* Paper presented at the 2017 CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON).

Rivera, M., Toledo, S., Baier, C., Tarisciotti, L., Wheeler, P., & Verne, S. (2017). *Indirect predictive control techniques for a matrix converter operating at fixed switching frequency.* Paper presented at the 2017 IEEE International Symposium on Predictive Control of Electrical Drives and Power Electronics (PRECEDE).

Rmili, L., Rahmani, S., Vahedi, H., & Al-Haddad, K. (2014, 1-4 June 2014). *A comprehensive analysis of Matrix Converters: Bidirectional switch, direct topology, modeling and control.* Paper presented at the 2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE).

Rodriguez, J., Rivera, M., Kolar, J. W., & Wheeler, P. W. (2012). A review of control and modulation methods for matrix converters. *IEEE Transactions on Industrial Electronics, 59*(1), 58-70.

Samosir, A., & Yatim, A. (2008). *Implementation of new control method based on dynamic evolution control with linear evolution path for boost dc-dc converter.* Paper presented at the 2008 IEEE 2nd International Power and Energy Conference.

Sawyer, S. (2017). Global wind power: 2017 market and outlook to 2022. Retrieved from http://cdn.pes.eu.com/v/20160826/wp-content/uploads/2018/06/PES-W-2-18-GWEC-PES-Essential-1.pdf

SenthilKumaran, M., & Siddharth, R. (2010). *Real-Time Controller Design for Matrix Converter for Load and Input Variations.* Paper presented at the 2010 3rd International Conference on Emerging Trends in Engineering and Technology.

Shi, B., & Zhou, B. (2017). *Open-circuit behavior analysis for indirect matrix converter.* Paper presented at the IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society.

Sieminski, A. (2014). International energy outlook. *Energy Information Administration (EIA), 18*.

Singh, B., Singh, B. N., Chandra, A., Al-Haddad, K., Pandey, A., & Kothari, D. P. (2003). A review of single-phase improved power quality AC-DC converters.

Soo, L. T., Loh, K. S., Mohamad, A. B., Daud, W. R. W., & Wong, W. Y. (2015). An overview of the electrochemical performance of modified graphene used as an electrocatalyst and as a catalyst support in fuel cells. *Applied Catalysis A: General, 497*, 198-210.

Spera, D. A. (1994). Wind turbine technology.

Sriram, N., & Shahidehpour, M. (2005). *Renewable biomass energy.* Paper presented at the IEEE Power Engineering Society General Meeting, 2005.

Sun, K., Zhou, D., Mei, Y., Huang, L., & Matsuse, K. (2006). *Performance improvements for matrix converter based on reverse blocking IGBT.* Paper presented at the 2006 37th IEEE Power Electronics Specialists Conference.

Sunter, S., & Altun, H. (1998). *A method for calculating semiconductor losses in the matrix converter.* Paper presented at the MELECON'98. 9th Mediterranean Electrotechnical Conference. Proceedings (Cat. No. 98CH36056).

Tiwari, G. N., & Dubey, S. (2009). *Fundamentals of photovoltaic modules and their applications*: Royal Society of Chemistry.

Van Der Broeck, H. W., Skudelny, H.-C., & Stanke, G. V. (1988). Analysis and realization of a pulsewidth modulator based on voltage space vectors. *IEEE transactions on industry applications, 24*(1), 142-150.

Venturini, M. (1980). A new sine wave in sine wave out, conversion technique which eliminates reactive elements. *Proc. Powercon 7*.

Venturini, M., & Alesina, A. (1980). *The generalised transformer: A new bidirectional, sinusoidal waveform frequency converter with continuously adjustable input power factor.* Paper presented at the 1980 IEEE Power Electronics Specialists Conference.

Venugopal, C. (2010a). *ANFIS based field oriented control for matrix converter fed induction motor.* Paper presented at the 2010 IEEE International Conference on Power and Energy.

Venugopal, C. (2010b). *Fuzzy logic based DTC for speed control of Matrix Converter fed Induction Motor.* Paper presented at the 2010 IEEE International Conference on Power and Energy.

Vu Van, T., Driesen, J., & Belmans, R. (2004). Interconnection of distributed generators and their influences on power system. *Proceedings of Electric supply industry in transition: issues and prospects for Asia, 6*(13), 51-66.

Wang, B., & Venkataramanan, G. (2006a). *A carrier based PWM algorithm for indirect matrix converters.* Paper presented at the 2006 37th IEEE Power Electronics Specialists Conference.

Wang, B., & Venkataramanan, G. (2006b). *Six step modulation of matrix converter with increased voltage transfer ratio.* Paper presented at the 2006 37th IEEE Power Electronics Specialists Conference.

Watler, M. (1998). *Space vector and two dimensional PWM control algorithms for the matrix converter with sinusoidal output currents.* Paper presented at the 1998 Seventh International Conference on Power Electronics and Variable Speed Drives (IEE Conf. Publ. No. 456).

Watthanasam, C., Zhang, L., & Liang, D. (1996). *Analysis and DSP-based implementation of modulation algorithms for AC-AC matrix converters.* Paper presented at the PESC Record. 27th Annual IEEE Power Electronics Specialists Conference.

Wheeler, P., & Grant, D. (1992). *Reducing the semiconductor losses in a matrix converter.* Paper presented at the IEE colloquium on variable speed drives and motion control.

Wheeler, P., & Grant, D. (1997). Optimised input filter design and low-loss switching techniques for a practical matrix converter. *IEE Proceedings-Electric Power Applications, 144*(1), 53-60.

Wolfgang, E. (2007). Examples for failures in power electronics systems. *ECPE tutorial on reliability of power electronic systems, Nuremberg, Germany*, 19-20.

Xiao, D., & Rahman, M. (2006). *A modified direct torque control for a matrix converter-fed interior permanent magnet synchronous machine drive.* Paper presented at the 2006 37th IEEE Power Electronics Specialists Conference.

Yan, Y., Zhao, J., Xia, C., & Shi, T. (2014). Direct torque control of matrix converter-fed permanent magnet synchronous motor drives based on master and slave vectors. *IET Power Electronics, 8*(2), 288-296.

You, X., Ge, B., Liu, S., Nie, N., Jiang, X., & Abu-Rub, H. (2016). Common mode voltage reduction of quasi-Z source indirect matrix converter. *International Journal of Circuit Theory and Applications, 44*(1), 162-184.

Zhang, J., Wheeler, P., Empringham, L., De Lillo, L., Dan, H., & Rivera, M. (2017). *Indirect matrix converter open circuit fault detection and diagnosis with model predictive control strategy.* Paper presented at the 2017 IEEE Southern Power Electronics Conference (SPEC).

Zhou, Y. (2013, 16-17 Jan. 2013). *A Study of the Method of Increasing Matrix Converter Voltage Transfer Ratio.* Paper presented at the 2013 Fifth International Conference on Measuring Technology and Mechatronics Automation.

Ziogas, P. D., Khan, S. I., & Rashid, M. H. (1986). Analysis and design of forced commutated cycloconverter structures with improved transfer characteristics. *IEEE Transactions on Industrial Electronics*(3), 271-280.

Zuckerberger, A., Weinstock, D., & Alexandrovitz, A. (1996). Simulation of three-phase loaded matrix converter. *IEE Proceedings-Electric Power Applications, 143*(4), 294-300.

Zuckerberger, A., Weinstock, D., & Alexandrovitz, A. (1997). Single-phase matrix converter. *IEE Proceedings-Electric Power Applications, 144*(4), 235-240.

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