



School of Information Technology and  
Engineering at the ADA University



School of Engineering and Applied Science  
at the George Washington University

ENHANSING GRID STABILITY AND POWER QUALITY IN RENEWABLE  
ENERGY INTEGRATION USING STATCOM

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## THESIS ACCEPTANCE

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## ABSTRACT

Wind and solar energy gain popularity among renewable sources due to their cost-effectiveness, widespread availability, scalability. Nonetheless, integration of Green Energy Sources can lead to a reduction of power quality at the point of common coupling (PCC), introducing harmonic components into electrical networks. It is crucial for these harmonics to stay within predefined limits to avoid potential adverse effects [24].

The acceptable level for power quality has dependency from the sensitivity of the installed load [25]. Various factors, including network strength, load characteristics, utilization of electronic equipment, geographical location, network length, climate conditions, operational practices of utility operators, affect the frequency and occurrence of power quality issues. Principal components of Renewable Energy Sources (RES) - Power Electronics (PE) converters in Photovoltaic (PV) and wind generation systems introduce high-level harmonics that have the potential to harm connected devices, diminishing their efficiency and lifetime. Additionally, these converters heavily depend on the quality of the voltage signal. Therefore, it is crucial to enhance power quality by implementing diverse measures to establish the smooth operation of the system [2]. Power quality problems arise when there are abnormalities in voltage or current waves, and their regularity is influenced by the strength of the system, presenting challenges particularly in the context of renewable sources.

To enhance the power quality of Renewable Energy Sources (RESs), various measures are implemented, including the implementation of improved control strategies and the use of different auxiliary devices. These measures encompass sub-categorizations such as filters, flexible AC transmission systems (FACTS) devices, energy storages, and converter control, all aimed at improving power quality.

Addressing power quality issues in PV/wind systems involves the application of advanced filtering technologies like active and passive filters [33]. However, the drawback of Passive Filters (PFs) lies in their cost, size, and weight dependence on the power rating of converters. Such devices as inductors and capacitors behave as reactive power receivers or delivers provide fixed level of compensation, consequently, PFs may not be the optimal solution [34,33]. On the contrary, a highly attractive solution is the utilization of flexible AC transmission systems (FACTS) to enhance various aspects of power quality, including harmonics, power factor, oscillations in electrical quantities, and voltage dips, especially in systems with high renewable penetration. An example of a FACTS device, the Static Synchronous Compensator (STATCOM), is introduced in the paper to address power quality problems in renewable energy systems.

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## LIST OF ABBREVIATIONS

| Abbreviation | Explanation                        |
|--------------|------------------------------------|
| RES          | Renewable Energy Sources           |
| PE           | Power Electronics                  |
| RMS          | Root Mean Squared                  |
| PCC          | Point of Common Coupling           |
| FACTS        | Flexible AC Transmission Systems   |
| PF           | Passive filters                    |
| VSC          | Voltage Source Converters          |
| EMS          | Energy Management System           |
| SCR/SCL      | Short Circuit Ratio/Level          |
| THD          | Total Harmonic Distortion          |
| ROCOF        | Rate Of Change Of Frequency        |
| PID          | Proportional Integral Derivative   |
| GTO          | Gate Turn Off                      |
| IGBT         | Insulated-Gate Bipolar Transistor  |
| CREZ         | Competitive Renewable Energy Zones |
| WES          | Wind electric station              |
| SES          | Solar Electric station             |
| VCO          | Voltage Controlled Oscillator      |
| PLL          | Phase Lock Loop                    |
| TCR          | Thyristor Controlled Reactor       |
| TSC          | Thyristor-Switched Capacitor       |
| WOA          | Whale Optimization Algorithm       |
| KVL          | Kirkoff Voltage Law                |

# CHAPTER ONE

## Introduction

### 1.1 Introduction

The way how the energy is generated depends on myriad of factors including environmental protection, economic impacts, development of new infrastructure and many others. For so many years before Green energy transitions, “Brown Energy” especially fossil fuel and oil in Azerbaijan were the most reliable energy sources because of their role in industrialization and economic growth. However with their positive affects they brought some environmental issues as well. This led the process of green energy shift to speed up. This in turn leads to impacts such as shifting seasons, rising sea-level, disappearing Arctic sea-ice and more intense heat waves. Renewable energy brings some advantages and disadvantages. Nevertheless, even in 2023 there is huge dependence on traditional energy generation all over the world because of unpredictable nature of Green energy. The technologies that can serve as problem solvers encompass several control strategies, optimization techniques, fault current limiters and energy storage devices [2]. According to Paris agreement which set up in 2016 the main aim of which is to limit the temperature increase below 2 °C (approximately 1.5 °C), the plan of mitigation of global warming and regularly reports have to be determined by each country and the targets should grow every 5 years [53]. Also in the period of adaptation, well developed countries had to support developing ones financially until 2020. Despite The initial target in the emission reduction was 45% by 2030 and net 100% by 2050, the problems with global warming just speed up the process and now the 100% reduction is planned by 2036. The established target for the United States by 2035 is to attain a power sector entirely free of carbon pollution, and achieve a net-zero emissions economy by no later than 2050

[52]. So basically, to mitigate global warming on the Earth the transition to the energies such as PV energy, wind, hydro and thermal is essential.

### **1.1.1 Advantages and Disadvantages of the Renewable energy transition**

As mentioned before transition to renewable energy takes time and has both advantages and disadvantages. Some facts that can be included among privileges of green energy are:

1. The fact that it is clean and no pollution released into air, which reduces CO<sub>2</sub> level.
2. Lower price.
3. Sustainability – this energy type will never be up-to-date, will be always accessible.
4. Maintenance in devices are done rarer in comparison with traditional energy resources [32].

Despite the fact that modern society tends to decrease CO<sub>2</sub> emissions in order to hinder global warming, it brings some challenges too:

1. The fact that renewable generation doesn't depend on the demand it directly depends on weather conditions.
2. There some gaps may occur between demand and supply. It is caused by variability and uncertainty of renewable sources.
3. Some specific areas are needed in order to obtain sufficient amount of energy. As a rule, considerable land is used to fulfill energy demand using renewables and since RES has to be installed in specific areas the transmission cost can vary depending on how far the generation is located.
4. The Storage problems in energy sector are still actual. Energy density and efficiency features are the most problematic points. With higher penetration of renewables, the demand is growing which causes the batteries hold huge amount of energy for later usage. But these limitations in battery capacity don't let them provide long term solutions to

unpredictable nature of Renewable Energy. In terms of efficiency, the batteries don't release 100 % of the energy they accumulate while discharging which causes loss. Another issue is lifetime and durability of batteries which is usually 5-6 years. It decreases over time and after disposal causes another environmental problem.

5. Inertia problems:

Inertia is - the ability of the system to withstand changes in speed. The stored kinetic energy is released through masses in synchronous generators which slowing down them giving time to bear demand -Supply imbalance. When the inertia decreases it affects critical time clearing time declines which deteriorates the robustness of the system. Renewable generation sources work with minimum- case of wind or 0 inertia (solar PV energy) because these systems use asynchronous generators and usually converter based electromechanical devices. In case of wind turbines, there is small inertia because there is rotational mass but it is decoupled from the grid by converters. Low inertia also causes fast decreases and fluctuations of frequency.

6. Energy prediction challenges:

Another challenge in energy prediction is the plenty of methods that let controllers that to make accurate predictions based on historical data and weather for renewable energy systems, particularly PV generation. One such method is the Energy Management System (EMS), which combines historical data and weather with modern machine learning algorithms like Artificial Neural Networks (ANNs) and Support Vector Machines (SVMs) as well as mathematical techniques like regression, fuzzy logic models, time series models, and so on.

At this point after the usage of modern methods as machine learning algorithms the number of other challenges spring up such as inaccuracy of data when the ML model should preprocess and clean the impurities in the input signal.

Otherwise problems with data can hamper the speed of process making the output model inaccurate and therefore unreliable. This problem is also called data overfitting [4] In addition to that, ML Models require up-to-date information to adapt to changes and proceed.

7. Frequency abnormalities appeared by unbalance between supply and demand may affect power factor as well. When the load increases suddenly, the angle between voltage and current may change as well immediately increasing or decreasing reactive power.

In energy systems mostly reliant on renewable sources, especially wind and solar, there is a significantly greater level of operational variability and uncertainty. This variability and uncertainty extend across various time scales, ranging from seconds and minutes, affecting regulation and load-following reserves, to hours, which may necessitate the introduction of new types of flexibility and ramping reserves [3].

These challenges and problems make the grid weaker. Inverters require strong systems and ability of grid synchronization to work reliably. On the other hand electronic sources usage instead of usual synchronous generators decreases the short circuit ratio which affects the system equilibrium changing voltage levels and other measures. This can lead to outages [1].

Voltage quality problems are categorized to steady state distortions and events.

Voltage sag (also called voltage dip), harmonic distortions, voltage imbalance, voltage flickers, and voltage swells are examples of power quality components in a power system [5].

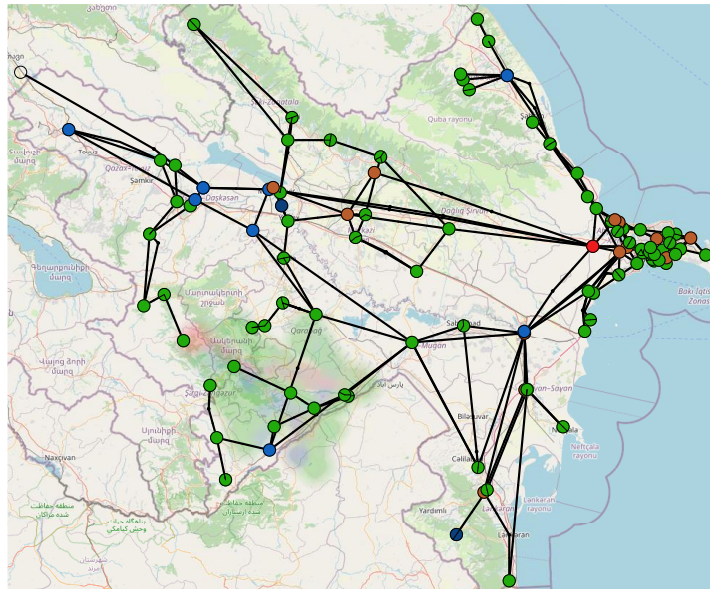
## **1.2 Motivation**

The electrical power system of Azerbaijan, like in many other countries, consists of various components and infrastructure that work together to generate, transmit, distribute,

and supply electricity to consumers. Azerbaijan generates electricity from a mix of sources, including natural gas, oil, hydroelectric, and very small amount of renewable energy sources. Currently, the total installed power of Azerbaijan's energy system is 7226.24 MW. The standard voltage levels of Azerbaijan transmission system are 110 kV, 220 kV, 330 kV, 500kV.

From the renewables energy perspective, in recent years, Azerbaijan has shown an increasing interest in developing its renewable energy sector, particularly solar and wind energy. The country's favorable geographical location allows for the potential exploitation of solar energy resources. Wind energy projects have also been initiated to diversify the energy mix and reduce reliance on fossil fuels. In the current situation, the total of 50 MW wind generation is installed. Currently, 38 MW solar generation (24 MW Nakhchivan SES, 2.8 MW Sahil SES, 2.8 MW Surakhani SES, 2.8 MW Samukh SES, 2.8 MW Sumgait SES, 2.8 MW Pirallahi SES), 55.3 MW wind generation (50 MW Yeni Yashma SES, 3.6 MW Yashma gardens WES, 1.7 MW Shurabad WES), 6.4 MW Gobustan Hybrid ES and solid domestic waste incineration plant (37 MW BMTYZ) were installed. Like many other countries, Azerbaijan power system faces challenges related to energy security, sustainability, and modernization of its power infrastructure. To address these challenges, the country has been working on initiatives to enhance energy efficiency, increase the share of renewable energy in the energy mix, and improve the overall reliability and stability of its power system.

The System topology in terms of substations, generation units, transmission lines, transformers, static VAR compensators, and loads are modelled based on what the system dispatcher and planner observe from the SCADA system. AzerEnerji system topology is depicted in Fig.1.1 In addition, the geographical location of AzerEnerji system elements is modelled in DigSilent PF to ease tracking of the system particularly from renewables integration perspective.



*Fig1.1 Geographical representation of AzerEnergy system*

This thesis studies the impacts of the transmission to renewable energy. There are several pros and cons, however the main subject of master thesis is to present possible power quality issues appearing and the most effective mitigation method. The Objective is to select the most effective method for power quality improvement which is STATCOM make comparison with other technique which is popular nowadays such as SVC and prove the advantages of chosen method over it. In the basis of Azerbaijan system, the difference in voltage at no STATCOM and STATCOM installed versions of system will be presented via DigSilent PF and corresponding voltage change. Also the STATCOM model is created in MATLAB SIMULINK will be visually presented in order to show its merits in Power factor correction and harmonics mitigation.

### **1.3 Structure of the thesis**

An introduction to the topic is given in Chapter 1, which also includes the goals of the work, the description of the problem, and the reasons for conducting the research.

Chapter 2 presents an overview of problems and possible solutions also the pros and cons of the used methods in comparison with other. Chapter 3 talks about the methodology proposed for STATCOM used for “Simulation and Results” chapter. In Chapter 4 DigSilent PF and Simulink programs are utilized in order to show overall effect of installed device into the system. Also there is STATCOM model simulation is given based on predefined parameters of the system. Chapter 5 summarizes the key findings of the thesis and presents ideas for the future research work.

# CHAPTER TWO

## Literature Review

### 2.1 Current Problems

Despite the fact that Renewable energy comes with myriad of positive effects to the environment its high penetration to the grid delivers some challenges from Power quality, System Strength and Stability aspects. These aspects are bounded and can impact each other.

Reduction of inertia is frequently faced problem in the stage of transition to Renewable energy sources, which means increased notable deviation from usual frequency (50Hz, with operational limits 49.2-50.5) that also called as ROCOF value (rate of change of frequency) which means rapid change in frequency and can lead to power instabilities Fig.2.1 [8].

When the system's inertia is low, rapid frequency control methods should be applied. Otherwise the problems such as load shedding damage in devices will happen. This in return decreases the reliability of the system appeared by load-shedding [2].

Along with inertia problems, lack of synchronous generators in the system also makes the system weaker means that the system is more sensitive to voltage fluctuations, and can cause generator-faults, and problems in relays [1].

Generally, besides system inertia the notion of system strength was a key to introduce the voltage change level caused by fault current in the grid Usually in weak systems despite the fault current degree is low, the affected voltage change level is massive [1]. The analysis of system strength highlights a requirement for increased reactive power, especially when dealing with larger-scale power generation from renewable sources and systems characterized as weak [69]. Herewith, energy operators may require more system

strength features to make the best use of the existing resources and ensure the security of supply [1]. There are many factors which participate in system's strength evaluation. One of them is Short Circuit Ratio also called as Short Circuit Level. This parameter is utilized to determine the short circuit capacity of equipment or any point of interconnection of devices also called bus to withstand any fault behavior in the system [4,6,7]. According to CREZ studies conducted by Electric Reliability Council of Texas, low SCR levels is main reason leading to high over and/or under voltages in weak grids in addition to low frequency resonances, and instability issues [4,7]. There are many distinct methods of SCR measurement. Voltage issues are the part of Power quality aspect of system stability. Voltage problems that affect stability of the system will be discussed further.

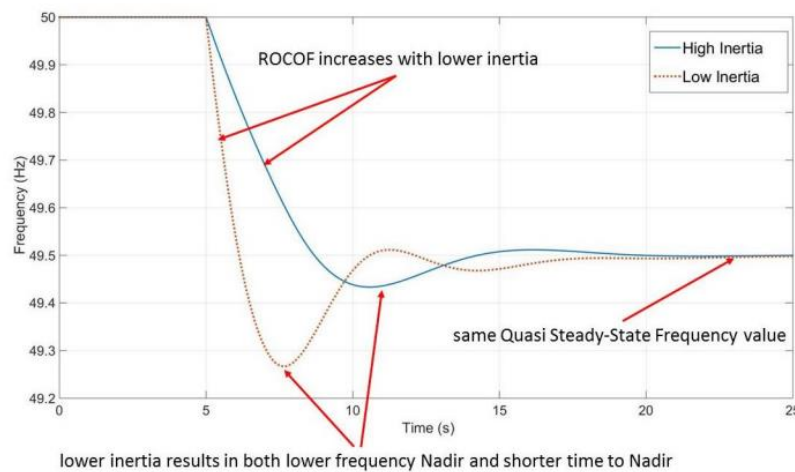


Fig.2.1 Illustration of effects of low inertia on frequency after event [44]

### Short Circuit Ratio which includes main approaches

- Basic or Traditional SCR which is calculated by formula:

$$SCR = S(MVA)/P(MW)$$

here S is calculated at Point of Common Coupling without taking into consideration renewable energy sources.

- There is equivalent circuit based method which is usually used when short circuit level of network bus is shared among Renewable Resources (usually wind power plants). By

this approach, impedance of network becomes less than bus's short circuit level. This brings some advantages such as 1) Improved fault ride-through 2) lower voltage dip 3) enhanced grid support. [9] ESCRI is calculated with following formula:

$$ESCRI = S_i / (P + \sum \Delta(V_i/V_j) * P)$$

$S_i$  In the denominator represents network short circuit apparent power capacity before new source installed,  $P$  – active power of new source and  $\Delta\left(\frac{V_i}{V_j}\right)$ .

- Multi feed SCR is basically proposed by Sun H. et al. to evaluate the short-circuit ratio of new energy from multiple sources system with spatial distribution and temporal variations, which takes into consideration DC/AC rectifier stations, it is more valuable in terms of renewable energy sources [1,9]. And because of analysis complexity it does not have exact formula. Nonetheless, MESCR can't reflect the impact of large capacitor compensations on system stability when a large number of capacitor compensations are installed in the system [1].

- Weighted Short Circuit Ratio (Weighted SCR)

This method is usually used to assess the effect of one renewable source on the short circuit in specific location and was first practically used in Texas for defining operational difficulties of power transmission over main interfaces of IBR [1].

In many analysis, two or more metrics may be used simultaneously for better understanding of the grid's short-circuit characteristics and depending on grid structure, location and regulatory requirements their type may be different [6]. The small SCR in weak system will deteriorate the static stability indirectly impacting Transient stability of Power quality factor as well [6]. According to the IEEE, power quality is the notion of powering and grounding sensitive equipment in a way appropriate for the device's functionality [15]. However, in the case of real system, since the output of the same

collecting station varies, as does the transient stability the short-circuit ratio index cannot adequately describe this occurrence [6].

### **2.1.1 Power quality issues**

Power quality problems are indicators of a poor power grid. [1] Any anomaly in the voltage or current wave causes power quality issues, and the regularity of these issues relies on the system strength, which presents challenges when renewable energy sources utilized [5,10]. Grid outages, electrical device malfunctions, and even a loss of synchronism, which can cause a network breakdown are results of Poor power quality [5]. Within the concept of wind energy, fluctuating active and reactive power outputs at blade-passing frequencies are produced by the pulsing nature of the wind turbine torque. This oscillating behavior deteriorates the power quality in terms of voltage variation at the PCC and occasionally damages the network-connected generators [15].

Power Quality problems cover such concepts as:

- Voltage dip or Voltage sag
- Voltage swell
- Voltage flickers
- Voltage fluctuations
- Harmonics problems
- Voltage transients/spikes

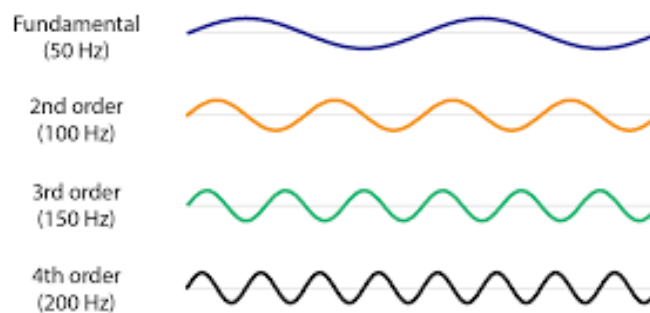
#### **Voltage Sag**

Among all voltage problems **Voltage sag** is the most frequently faced issue, which is a decrease in RMS Value of voltage under a stated threshold from 10 to 90 % caused by sudden change in load or short circuit in the period of time from 0.5 cycles to one minute which is called sustained sag. [5,10] This leads to large inrush current produced after fault

occurred and was cleared that can damage equipment such as converters used in most renewable energy sources.

## Harmonics

As seen from Fig.2.2 harmonics are variation from the nominal frequency by integer multiple. In the terms of green energy, the distortions in the waveforms also called Harmonics also supraharmonics show up when the converters are used to convert DC energy to AC for grid interconnection at very high switching frequency which can diminish the efficiency and lifetime of equipment increasing line losses [25,30,31]. Certain IEEE standards are in place for harmonic measurements restrictions, total harmonic distortion (THD) regulation, and even testing variable speed wind turbines for harmonics in advance of grid connection. Voltage flickers are also caused by fundamental frequency fractions.

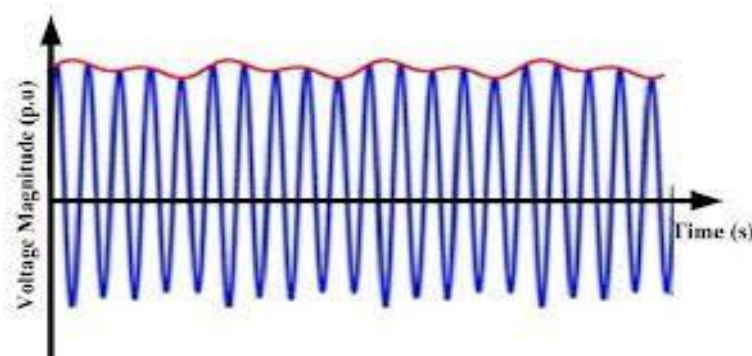


*Fig.2.2 Representation of Harmonics [41]*

## Voltage Flickers

Voltage flickers can be a problem in photovoltaic (PV) systems, causing instability and diminishing the quality of the power supply. Flickers are issues caused by quick and repeated fluctuations in voltage levels with rates that vary between 0.5 to 25 Hz [25]. Changes in sunlight intensity induced by factors such as passing clouds or shade may lead to fast voltage variations in PV systems, resulting in flickering. Controlling voltage

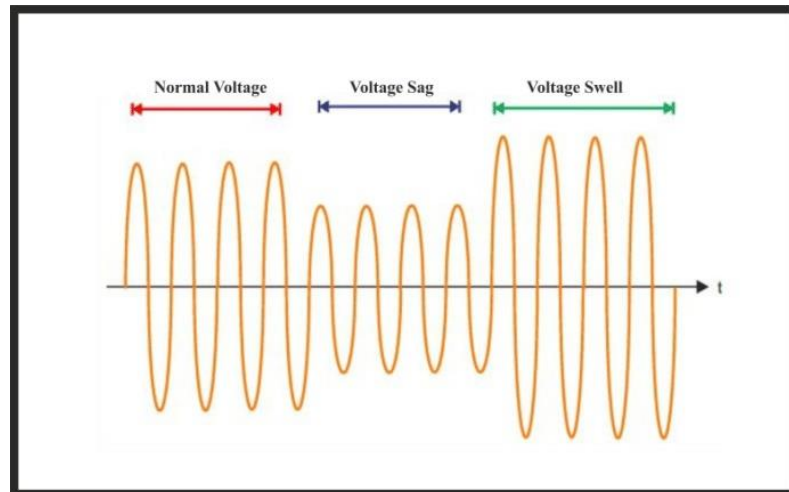
flickers in PV systems is critical for ensuring the PV system and the linked electrical grid operate reliably. It is critical to Follow up with grid norms and standards for dealing with power quality concerns such as flicker. Wind turbines may also produce oscillatory output power, which can cause flickering in the power system network. Tower shadow and turbulence impacts are examples of such factors. International standards such as IEC 61400-21 define measurements for evaluating wind turbine flicker [37]. According to standard wind turbine-induced voltage fluctuation is split into two components: continuous operation and switching operation [25]. Continuous operation flickers are caused by differences in active and reactive power when wind speeds fluctuate, notably in fixed speed wind turbines. Variable speed wind turbines, on the other hand, may reduce these oscillations by adjusting the rotor speed. Switching processes leads to quick changes in power levels as a result of actions such as generator cut-in, cut-out, and switching between wind turbines. When opposed to fixed speed turbines, the impacts of flickers are often less severe in variable speed wind turbines. The dampen fluctuations in aerodynamic torque that spring up as a result of switching operations or wind speed changes can be tackled via variable speed turbines that provide speed control and mitigate voltage flickers [25]. Wind turbine flicker coefficients for both continuous and switching operations are calculated using the 10-minute average wind speed and the network impedance phase angle [25].



*Fig.2.3 Representation of Voltage Fluctuations [39]*

## Voltage Swell

The term "Voltage Swell" describes a quick voltage raise that surpasses the regular tolerance levels. This phenomenon extends for more than one cycle and usually lasts for just a few seconds [29].



*Fig.2.4 Graphical representation of normal, sag and swell voltages [38]*

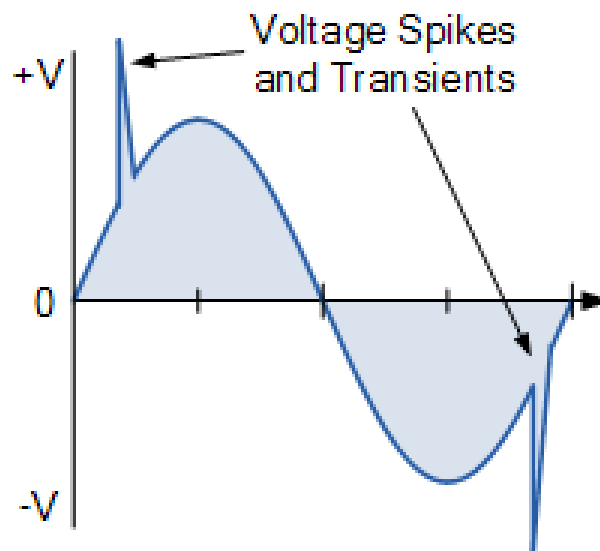
## Voltage Spikes

A voltage spike is a specific kind of transient that is defined as a brief, sudden increase in voltage over the nominal value in an electrical circuit. It is also referred to as a voltage surge or transient voltage. After fast increase in magnitude the voltage again gets back to normal. A variety of things, such as lightning strikes, switching operations, or other sudden changes in the electrical system, can result in voltage spikes. The duration of voltage spikes is usually brief, a mere fraction of a second. Voltage spikes can adversely affect or deteriorate equipment. They also may result in electrical component failure, insulation degradation, or other problems.

## Voltage Transient

A "transient" refers to a sudden and significant alteration in voltage, marked by an abrupt shift in the system's state. These changes are typically triggered by factors like surges and

may occur in steady-state conditions of either both voltage and current, or current and voltage separately [28]. The term "transient" encompasses sudden fluctuations in the Root Mean Square (RMS) value of voltage, encompassing both abrupt increases and decreases.



*Fig.2.5 Voltage Spike [40]*

In order to summarize all voltage problems, their causes and severity the following table 2.1 is created.

Table 2.1 “Power Quality Problems, causes and effects”

| <b>Power Quality Issues</b> | <b>Causes</b>  | <b>Effects</b>   | <b>Severity</b> |
|-----------------------------|--|--|-----------------|
| Voltage Fluctuations        | Load Switching   | Over/undervoltage, flickering in lightning                             | Severe          |
| Voltage Sag/Dip             | Fault in the system, connection of large loads, high network loading, poor wiring, variation of source voltage, inrush current             | Overloading problems   | Moderate        |
| Harmonics                   | If the sinusoidal voltage is applied across the nonlinear load   | Losses in electrical equipment, overheated transformers                | Moderate        |
| Voltage spike               | Connection and disconnection of heavy loads to or from the system, poorly dimensioned power sources or inadequately regulated transformers | Data loss, flickering of lightning, damage of sensitive equipment      | Severe          |
| Transient                   | Capacitor discharge, power system switching, faults in power lines   | Damage in equipment, data loss, impact on equipment’s overall lifespan | Severe          |
| Flicker                     | Fluctuations of supply voltage   | Damage of the equipment on the load side                               | Severe          |
| Voltage Swell               | Decreases in Load voltage, switching operations, or other faults that result an increase in voltage  | Damage of equipment  | Moderate        |

## 2.2 Power Quality Improvements

Flexible Ac transmission systems serves as very crucial element in the solution of power quality issues related to penetration process of renewable energy sources into grid by providing necessary reactive power compensation [16,17]. FACTS devices are mainly divided by shunt and series compensators [18]. The proposed device in this research is static shunt compensator, STATCOM which is not connected to national energy system yet. The reason of STATCOM's wide usage in the power systems of other countries such as Egypt, China, France and etc. can be explained by fast response to dynamic performance of green energy sources due to their unpredictable nature [21]. Apparently, as a name suggests term synchronous implies that STATCOM produces 3 phase voltage as a synchronous generator does and synchronizes with the grid. The term "Static" represents being fully composed by electronic devices [22]. With the existence of static synchronous compensator in the system voltage becomes more smooth by reduced harmonics, sags and swell problems. This stability can be maintained due to capacitive support in case when the actual voltage is less than reference voltage, otherwise inductive support. The reference voltage also known as voltage control point stands for the set-point that is used to adjust and control the voltage in the power system [19]. The basic component of STATCOM is self-commutated converters, in particular Voltage Source Converters (VSC) for the purpose of better economics and performance. As name suggests, in VSC direct voltage has one direction the power polarity change occurs by the current's flow direction change. In Fig.2.6 given the basic form of GTO based VSC, but STATCOM is faster when the switching frequency is high, that's why IGBT utilization and PWM control technique can be more beneficial [22,23]. Other components of STATCOM are transformer along with filter and suitable controller to perform its work properly. In this work Proportional Integral (PI) controller will be discussed inside control mechanism.

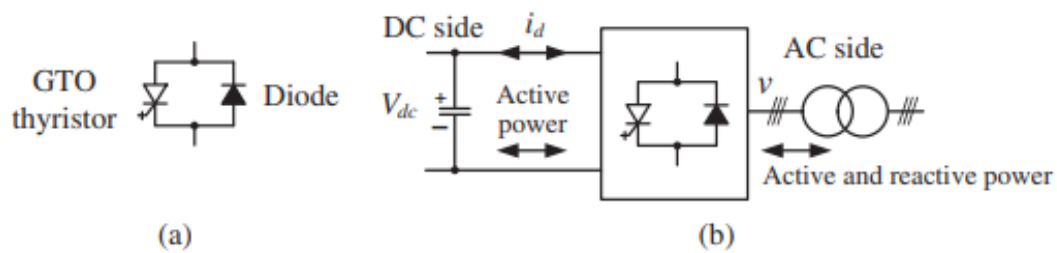


Fig.2.6 GTO based VSC [22]

### 2.3 Control strategies of a STATCOM

In general, the three basic control strategies of a STATCOM are used:

Usually the combination of following three strategies can be observed which leads to similarity with voltage control of synchronous machine [27].

“Constant reactive power” is the strategy when the STATCOM’s reactive power is unchanged. Having in mind that STATCOM is not the most economical source of Q This strategy was developed considering the STATCOM’s larger losses in comparison to passive devices such as Inductor and capacitor [27].

“Voltage control” is the strategy where current control depends on the voltage difference between grid side and reference [27].

“Constant reactive current” is the method which is not used alone but can be applied in addition to other control strategies in order to keep the current limited by max value of it.

The control type similar to synchronous machine is a combination of voltage control in the short term response and then constant reactive power control in the long term control mode. In The steady state regime of STATCOM is in voltage control region and because of possible larger losses that can occur using STATCOM, other reactive-power compensators are usually used instead of it [27].

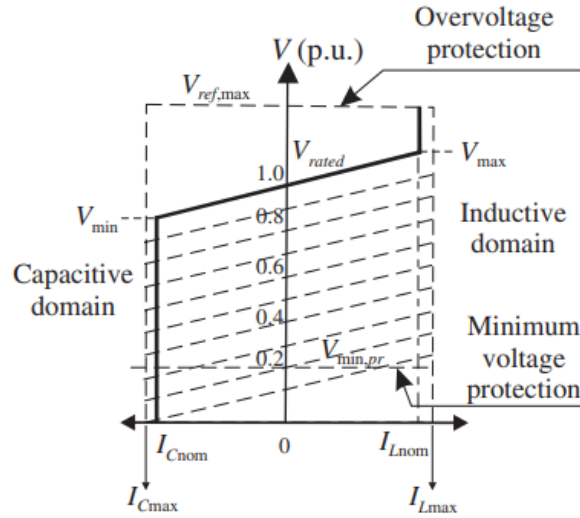


Fig.2.7 V-I characteristic of STATCOM

Fig.2.7 illustrates the V-I characteristic of STATCOM operating in voltage regulation mode characterizing the capacitive and inductive characteristics of the STATCOM. The terms  $I_{Cnom}$  and  $I_{Lnom}$  denote the nominal current values, ensuring prolonged operational stability, while  $I_{Cmax}$  and  $I_{Lmax}$  represent maximum current values for short-term operation until the semiconductor valves approach their thermal limits this is called transient region. Beyond current considerations, operational constraints also encompass voltage limitations, including the maximum reference voltage ( $V_{ref,max}$ ) and the protective minimum voltage ( $V_{min,pr}$ ). Under operational conditions, if  $V > V_{max}$ , The STATCOM operates as a steady reactive current supplier, maintaining a constant reactive current output at  $I_{STATCOM} = I_{Lmax}$ .; conversely, when  $V < V_{min}$ , it acts as a constant reactive current source with  $I_{STATCOM} = I_{Cmax}$ . The voltage is tuned to the reference voltage  $V_{ref}$  as long as the reactive currents stay within the current restrictions established by the converter rating ( $I_{max}, I_{max}$ ). The vector sum  $V = V_{ref} + X_s * I$  (6) defines the STATCOM's V-I characteristic [31]. Where  $V$  denotes positive sequence voltage,  $X_s$  denotes reactance and Slope and  $I$  denotes reactive current [31]. The voltage drop across the inductor is calculated by multiplying two components.

The graph illustrates the significance of the V-rated parameter in a STATCOM (Static Synchronous Compensator), serving as a key factor defining the compensator's capabilities and limitations. V-rated represents the nominal voltage at which the STATCOM is designed to deliver its rated reactive power output. In contrast, V-reference is the reference voltage used in the STATCOM's control system, aligning with the power system's specific requirements.

The control system of the STATCOM aims to maintain the voltage at the intersection with the power system, with V-reference serving as the targeted voltage level. The equations (2.1) and (2.2) describe the active and reactive power output of the STATCOM. In steady-state conditions, the phase angle difference ( $\delta$ ) between output inverter voltage and grid is zero, resulting in only reactive power flow (2.3), (2.4).

$$Q = \left(\frac{V_2}{X}\right) [V_1 \cos\phi - V_2] \quad (2.1)$$

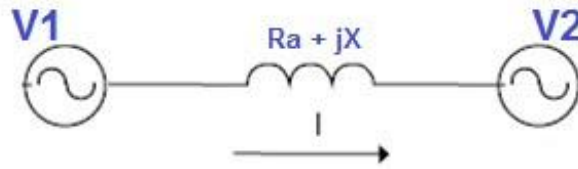
$$P = \frac{V_1 V_2 \sin\delta}{X} \quad (2.2)$$

So the formulas become:

$$Q = (V_2/X)[V_1 - V_2] \quad (2.3)$$

$$P = V_1 V_2 \sin\delta / X = 0 \quad [51]$$

To guarantee dynamic regulation of reactive power, the Voltage Source Converter (VSC) modifies the magnitude of  $V_2$ , the output voltage of the VSC, managing the voltage difference between  $V_2$  and  $V_1$  [31].



Assuming  $R_a = 0$ ,

The Reactive Power Flow  $Q$  is given as

$$Q = (V_2/X)[V_1 \cos \delta - V_2]$$

Fig.2.8 Reactive power flow [51]

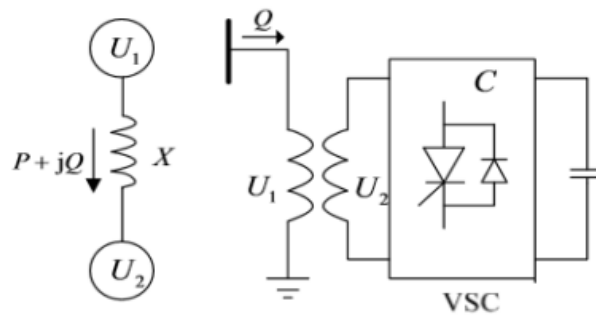


Fig.2.9 Static Synchronous compensator [31]

## 2.4 Comparison with SVC (Static VAR Compensator)

### 2.4.1 Shortly about SVC

Despite the fact that both of STATCOM and SVC work as reactive power compensators. SVC contains thyristor which acts as a switch turning on reactive element by adjusting the firing angle of the thyristors,. Basically, In Static Var Compensators there are components such as thyristor controlled reactors(TCR) and thyristor switched capacitor(TSC). As name suggests both capacitors and inductors are controlled by thyristor's firing angle. In case of TCR it is in connected mode when thyristor is on

conducting mode means TCR can inject or absorb the reactive power in response to changes in voltage in the system.

The aim of TSC in the system is the control of generation of reactive power by controlling capacitor's connection in the system. When thyristor connects or disconnects capacitor based on firing angle the TSC adjusts reactive power output by this compensates reactive power variation. When the voltage in grid side is small reactive power is injected by thyristor being in on mode establishing the connection of capacitor into system. Otherwise, when the power has to be absorbed thyristors are turned off. That in turn means disconnection of capacitor from the system.

#### **2.4.2 The benefits of STATCOM compared to other FACTS devices**

- It encompasses harmonic filtering, power factor correction, rapid voltage control, and reactive power support.
- STATCOM excels in compensating both capacitive and inductive loads, maintaining control over output current within specified capacitive or inductive ranges irrespective of AC system voltage. Notably, it exhibits heightened transient ratings in both capacitive and inductive operating regions, sustaining compensating current even at reduced line voltage.
- The system is capable of regulating output power and reducing power fluctuation through the self-generation and absorption of reactive power.
- The provision of reactive power is not dependent on the actual voltage at the point of interconnection with the grid network. The device's ability to generate a full capacitive output current, even at low system voltage, adds to its commendable features [20].

- The STATCOM's key benefits are its small size, which requires less space for installation, and its better reactive power yield at low voltages. Additionally, from the perspective of dynamic stability, STATCOM imparts stronger damping properties [26]. In case of connection to battery can provide real power as well.

Table 2.2 “Difference between STATCOM and SVC”

| STATCOM   | SVC   |
|---|---|
| Faster(because of electronic device)                  | Tyristor based therefore Slower in speed              |
| Higher losses(because of fast switch)                 | Less losses   |
| Constant Current flows independently on Voltage level | Current is in linear dependency with Voltage          |
| Smaller in size                                       | Captures more place                                   |
| More expensive  | Cheaper but needs additional devices to work properly |

### 2.4.3 Operational Principles

Regarding the difference in operational principles of two devices, there is obvious variance in V-I and Q-V characteristics of STATCOM and SVC (Fig.2.10, Fig.2.11). First of all the transient region in both scenarios corresponds to kind of overload rating means the current can exceed max or min limit in the period of time less than 1 sec only [42]. As seen from Fig.2.10 the current in STATCOM does not depend on the voltage of

the bus whether it reaches the max 1 p.u or goes less. By reaching constant current STATCOM becomes able to dynamically provide and absorb the reactive power, improving overall performance of the system stabilizing the voltage. Fig. 2.11 illustrates constant current in the system and obtained through control algorithms and power electronics where the voltage is constantly monitored and current is set based on desired reactive compensation level.

From here the V-Q characteristics can be obtained. Since the formula is  $Q = V * I$  and the current does not depend on voltage, Q and V have linear dependency.

On the other hand, current in SVC changes linearly with increased or decreased bus voltage. So, from here we can anticipate that Q and V relation here is different from STATCOM case. So it can be concluded that the voltage support in STATCOM is much larger than in SVC which makes it very advantageous. Also the voltage adjustment is easier in STATCOM than in SVC since when the reactive power injected or absorbed increases or decreases the voltage easily.

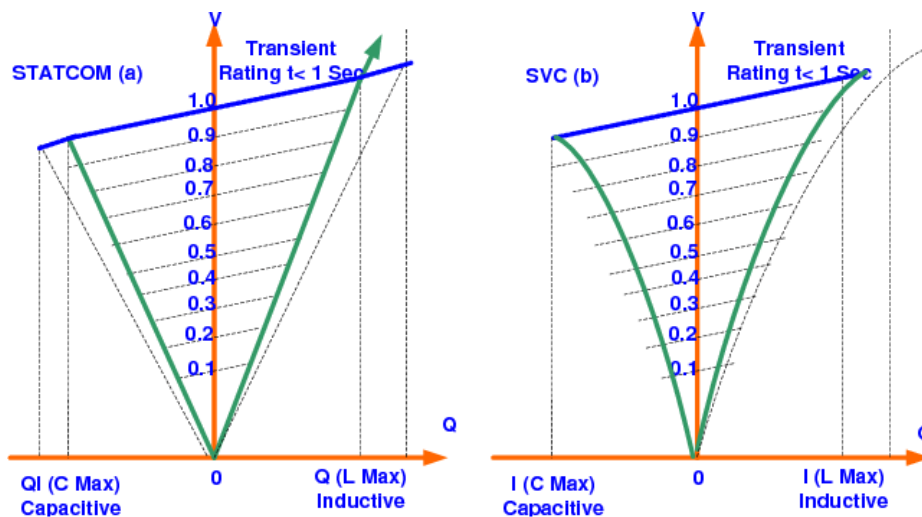


Fig.2.10 V-Q Characteristics of STATCOM and SVC [54]

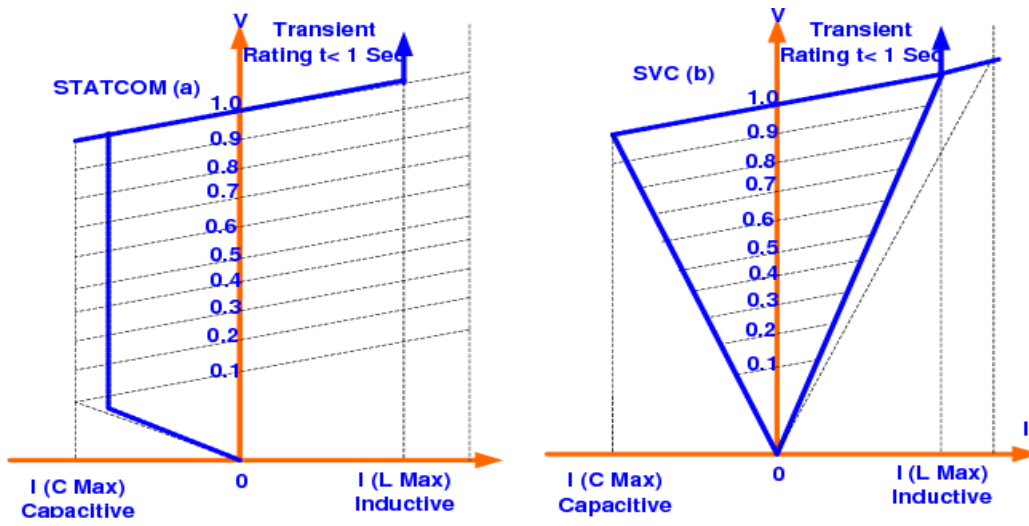


Fig.2.11 V-I characteristics of STATCOM AND SVC [54]

# CHAPTER THREE

## Methodology

### 3.1 Working principle of STATCOM

STATCOM serves as a power delivery and absorption component following procedure: VSC which consists of IGBT transistor as a switch and diode to pass flow in one direction the dc voltage coming from the capacitor by producing  $+V_{DC}/2$  and  $-V_{DC}/2$  voltages where, each phase synchronized and linked to the respective AC system voltage through a relatively minor reactance. This reactance is introduced either by an interface reactor or the leakage inductance of a coupling transformer [50].

The output Voltage of STATCOM is then compared with grid's voltage after sensors observe change in grid voltage. Control system which include controllers such as PI or PID or other methodologies and algorithms that receive the reference voltage and adjust the output value of STATCOM based on this  $V_{reference}$  also called voltage setpoint. The magnitude is important characteristic here because difference between magnitudes determines Reactive Power injection or absorption while phase difference defines active power.

The merit of Pulse Width Modulation here is that the output voltage after control which is  $V_{reference}$  sent to PWM in order to control the voltages in gates of IGBTs, by this way the output voltage of inverter is adjusted (Fig.3.5). And here the adjustment of output voltage affects the polarity of current. By the angle between current and voltage, the reactive power flow is determined. On the other hand, when the output voltage of STATCOM is greater than the grid's voltage in order to synchronize with the grid STATCOM injects the reactive power affecting the voltage in the system. Otherwise it

absorbs the reactive power in order to enhance voltage stability. The reason of this is given in the formulas (3) and (4) in the Chapter 2.3 “Control strategies of a STATCOM”.

There is also the notion of Phase Lock Loop which is used to establish a synchronization in the phase and frequency. The principle of PLL is discussed in the next chapter.

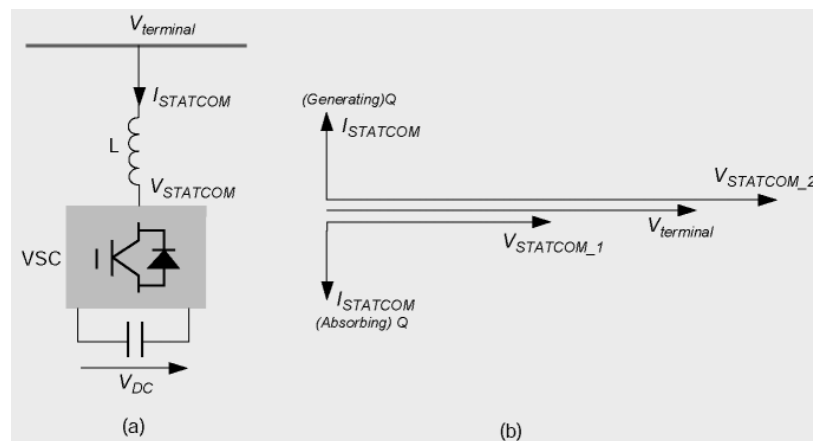


Fig.3.1 STATCOM absorption and injection of reactive power [49]

### 3.2 Phase Lock Loop(PLL)

In grid following VSC the output should synchronize with grid not only by voltage magnitude but also by phase and frequency. When  $f_0=f_{in}$  and  $\Delta F_i=0$  or constant, loop is in locked condition. In order to progress properly the PLL is split into 3 blocks (Fig.2.13): Phase detector takes the input(reference) frequency compares it with output frequency (Oscillator frequency) creates error signal which is passed to low pass filter to maintain error voltage also called as control voltage and this exact voltage then is passed through VCO here the control voltage and frequency are linearly dependent. But this is the general procedure, at the very beginning the process starts at VCO since no output frequency generated yet and VCO runs at the center frequency also called running frequency this stage is called unlocked condition. The purpose of the PLL during this stage is to make the VCO frequency to synchronize with the reference frequency. That's why after the

running frequency is stated it is sent to PD to obtain the error and whole process is repeated. Each time when the error voltage is created through low pass filter VCO either increases or decreases the oscillator frequency (output frequency) until it locks the reference frequency ( $f_{ref}=f_{out}$ ). But before getting locked in no lock condition the input signal should be in the capture range otherwise VCO will not be able to follow it and frequency will be free running and leading to synchronization problems due to PLL struggling to maintain the lock. In addition to this the design parameters of PLL such as filter characteristics, initial parameters and loop bandwidth affect capture range. Therefore, the selection of PLL parameters is crucial for the predefined and expected range of frequencies of the input.

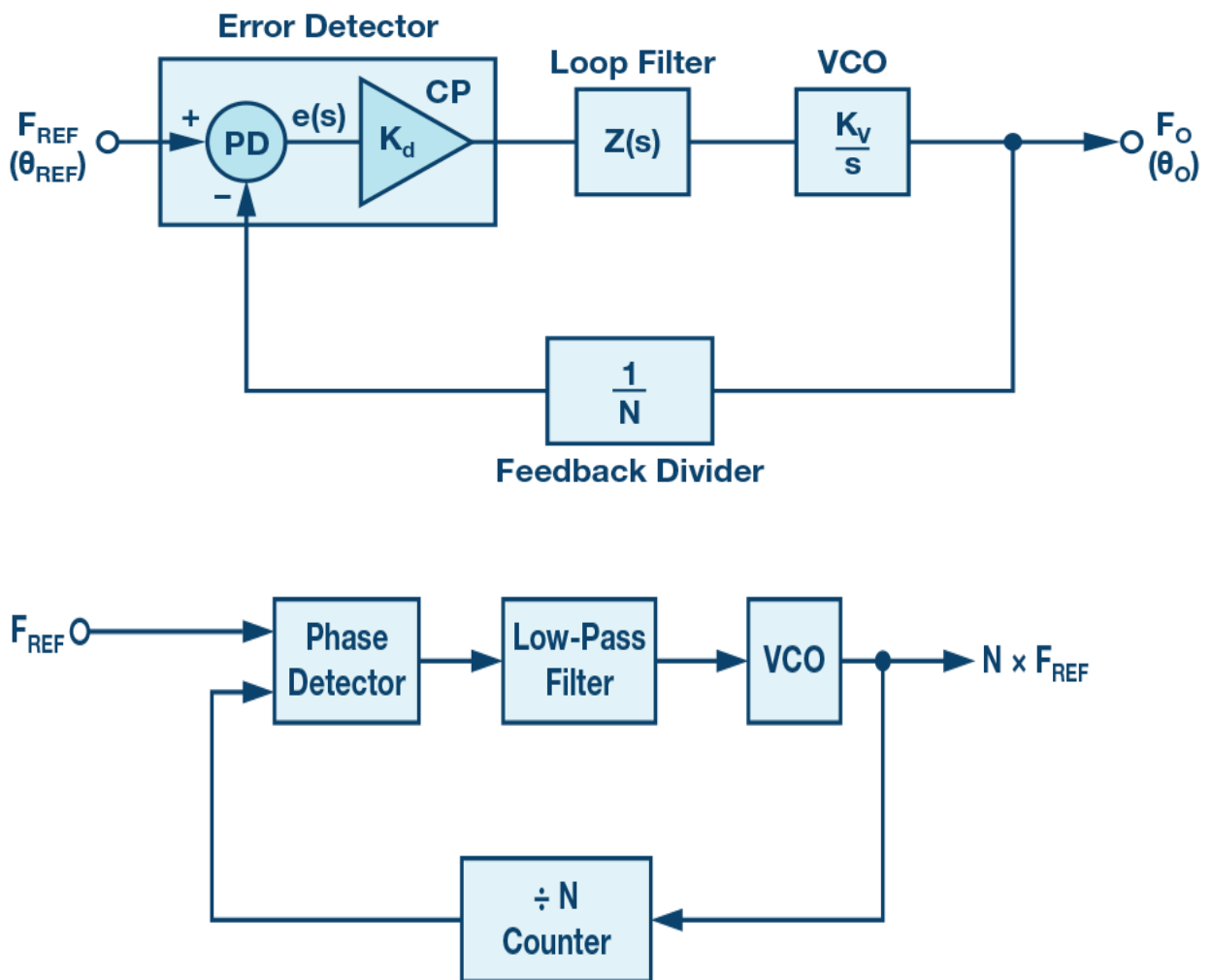


Fig.3.2 Basic PLL representation [35]

Phase Detection process is taking its roots from difference between two phases. Let's say a and b are the given phases which should be compared. So in this case error which is (a-b) is small number very close to 0 and it can be expressed as:

$$(a - b) \approx \sin(a - b) \quad (3.2)$$

Trigonometric equation can be simplified as  $\sin(a - b) = \sin a * \cos b - \sin b * \cos a$  (3.2),

$$\text{Where } \sin a * \cos b = \frac{\sin(a-b)}{2} + \frac{\sin(a+b)}{2} \quad (3.3)$$

The second term of summation components represents high frequency signal which can be eliminated using LPF (Low Pass Filter).

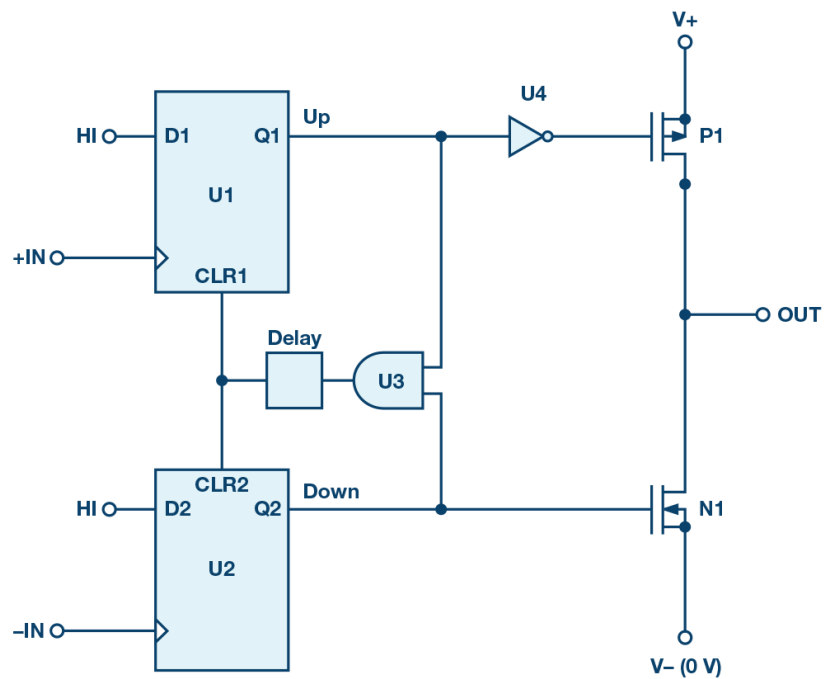


Fig.3.3 Phase Frequency Detector representation in PLL [35 ]

The further detailed PLL control mechanism will be discussed in simulation and results section.

### 3.3 Current Control for STATCOM

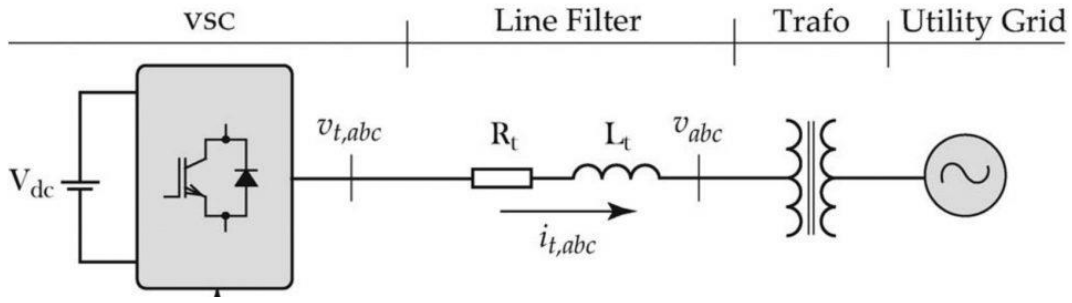


Fig.3.4 VSC connection to the System [55]

This chapter explains the method for controlling STATCOM system . In order to obtain inverter's output voltage  $V_{abc}$  in Point of Common Coupling(PCC) is summed up with  $R_t$   $I_{t,abc}$  and  $L_{t,abc}$  according to Kirkoff Voltage Law (KVL)[56].

$$V_{abc,t} = V_{abc} + L(dI_t/dt) + R_t I_{t,ab} \quad (3.4)$$

Then using Clarke(Eq.3.5) and Park(Eq.3.6) transformation convert 3 phase voltage to DQ voltage.

The equation will become:

$$V_{\alpha\beta,t} = V_{\alpha\beta} + L(dI_{t,\alpha\beta}/dt) + R_t I_{t,\alpha\beta} \quad (3.5)$$

$$V_{dq,t} = V_{dq} + L \left( \frac{dI_{t,dq}}{dt} \right) + j\omega L I_{t,dq} + R_t I_{t,dq} \quad (3.6)$$

When  $V_{dq,t}$  is decomposed to  $V_d$  and  $V_q$ , coupling happens (Eq 3.7 and 3.8). The Fig.3.5 visually represents decoupling by  $-wL$  block multiplied by  $I_q$  to obtain  $V_d$  and  $wL$  by  $I_d$  to obtain  $V_q$ (Eq. 3.9 and 3.10) [56].

$$L \left( \frac{dI_{t,d}}{dt} \right) + R_t I_{t,d} = j\omega L I_{t,q} + V_{d,t} - V_d \quad (3.7)$$

$$L \left( \frac{dI_{t,q}}{dt} \right) + R_t I_{t,q} = -j\omega L I_{t,d} + V_{q,t} - V_q \quad (3.8)$$

The voltage coming from PI controller as an outputs  $V_{c,dq}$  are obtained by the following formulas (Fig.3.5):

$$V_{c,d} = V_{t,d} + L_t \omega I_{t,q} - V_d \quad (3.9)$$

$$V_{c,q} = V_{t,q} - L_t \omega I_{t,d} - V_q \quad (3.10)$$

Merging Eq.3.7 with 3.9 and 3.8 with 3.10, another formula for  $V_{c,dq}$  is obtained:

$$\begin{pmatrix} V_{c,d} \\ V_{c,q} \end{pmatrix} = L_t \begin{pmatrix} \frac{dI_{t,d}}{dt} \\ \frac{dI_{t,q}}{dt} \end{pmatrix} + \begin{pmatrix} R_t & 0 \\ 0 & R_t \end{pmatrix} \begin{pmatrix} I_{t,d} \\ I_{t,q} \end{pmatrix}$$

After decoupling d and q frames, as an output reference voltage is obtained. Further process is described in section 3.1.

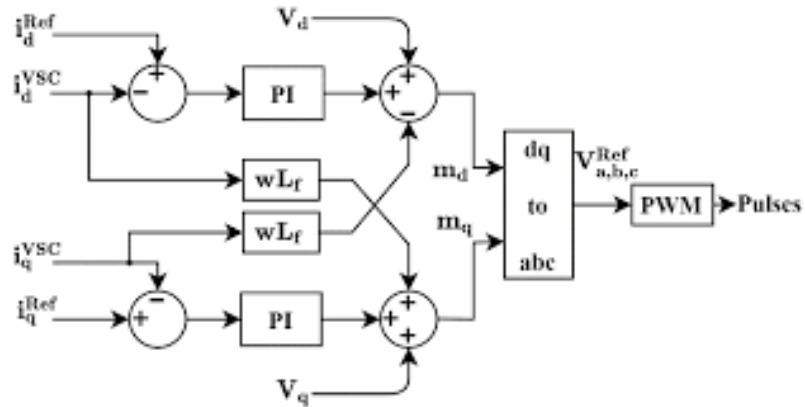


Fig.3.5 Current Control Mechanism [57]

### 3.4 DigSilent PF

DigSilent PowerFactory is a modern software designed to analyze electrical grids. It provides wide range of possibilities such as load flow studies, integration of renewable energy sources that is done in this paper, and in addition to this short circuit analysis can

be made [46]. DigSilent's working principle for numerical techniques is based on Newton- Raphson method. The existence of a libraries for FACTS devices such as STATCOM which are crucial in enhancing power stability and mitigation of voltage problems in the integration of RES to the system make this software even more handy.

# CHAPTER FOUR

## Simulation and Results

### 4.1 Effect of installation of RES to the Voltage and Power

First of all, to show the positive impacts of renewable energy sources penetration to the grid, the solar energy station in Alat Region of Azerbaijan was disconnected from the grid, then connected again. This is the scheme of 2025.

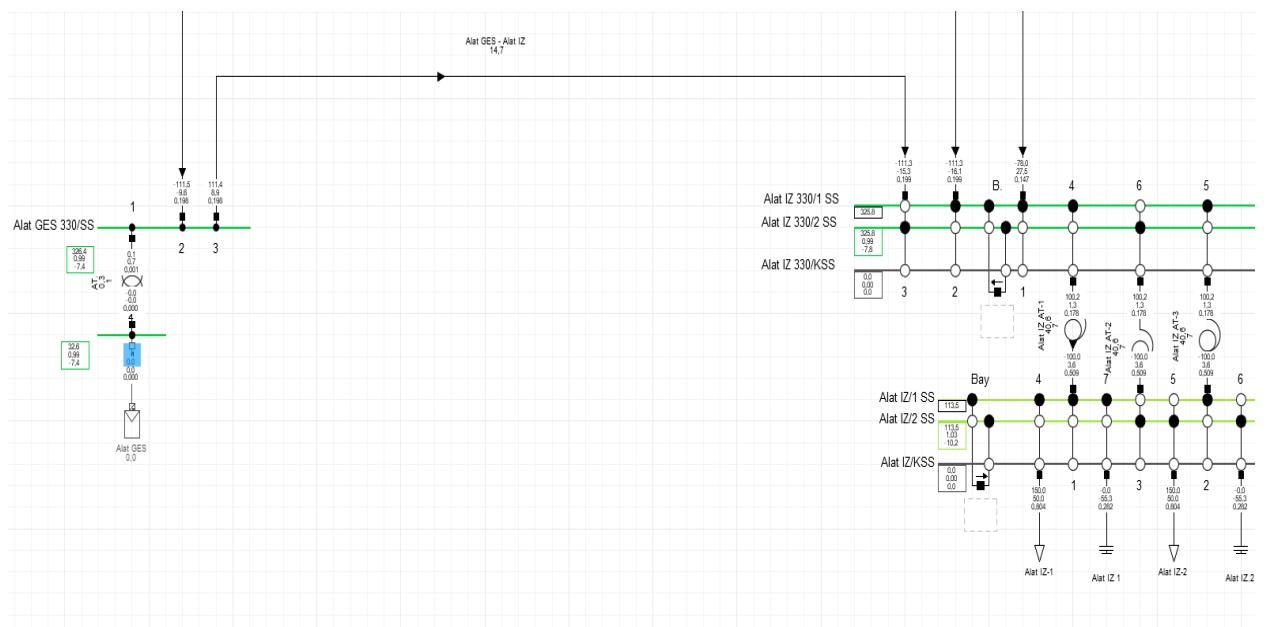
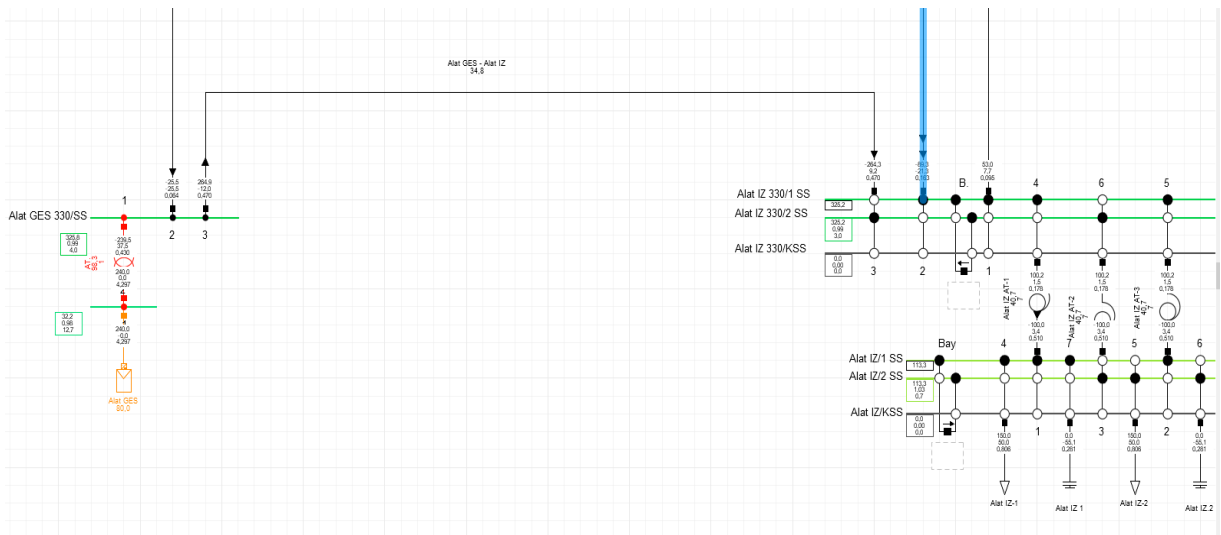


Fig.4.1 ALAT SES connection distracted

As seen from the scheme it is in disconnected mode and provide 0 MW of energy which in terms make the substations Alat Iqtisadi Zones1,2 receive the power to fulfill its need 300 MW (150MW for Zone1 and 150 for Zone2) from the Canub and Qobu stations.



*Fig.4.2 ALAT SES connection established*

However, in case when connection between grid and RES is established it can provide most of the required energy 300MW. It produces 240MW and takes 25.5 MW from outside then the total energy from that is delivered from this substation is 265.4. So this is done to prove that installation of RES in appropriate areas can provide power support which is very crucial with increasing demand for power these days.

#### **4.1.1 STATCOM installation in Xizi region of Azerbaijan**

For visual demonstration purposes of STATCOM installed in Xizi Region of Azerbaijan Fig.4.5 and Fig.4.6 are given. PWM converter in DC side of generation connected to capacitor bank and transformer makes up STATCOM concept. Within the DigSilent Program Fig.4.3 represents IGBT and Diode bridges that make up converter structure.

After the installation the control system of STATCOM is available in Control Block Diagram

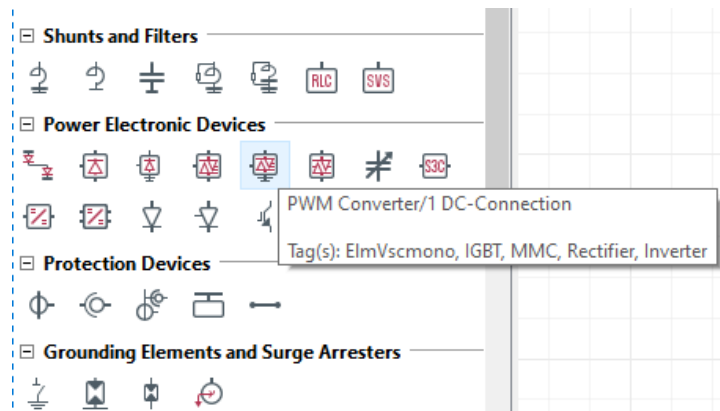


Fig.4.3 PWM Converter in DigSilent

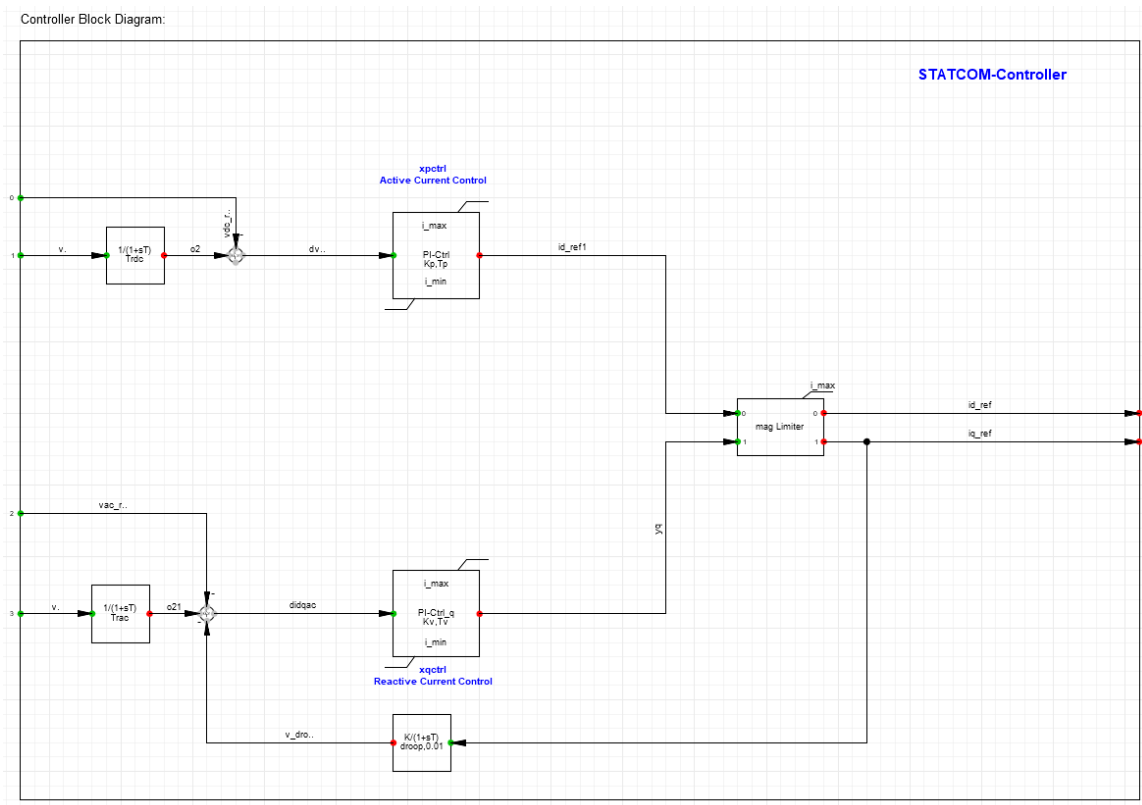


Fig.4.4 Control block diagram

In Fig.4 5 and 4 6 different MVARs are given as set point(Reference) to STATCOM.

The purpose of giving two reactive power levels lies in observation of voltage change in

substations XIZI1 and 2 also increase in reactive power in transmission lines with increasing injected power.

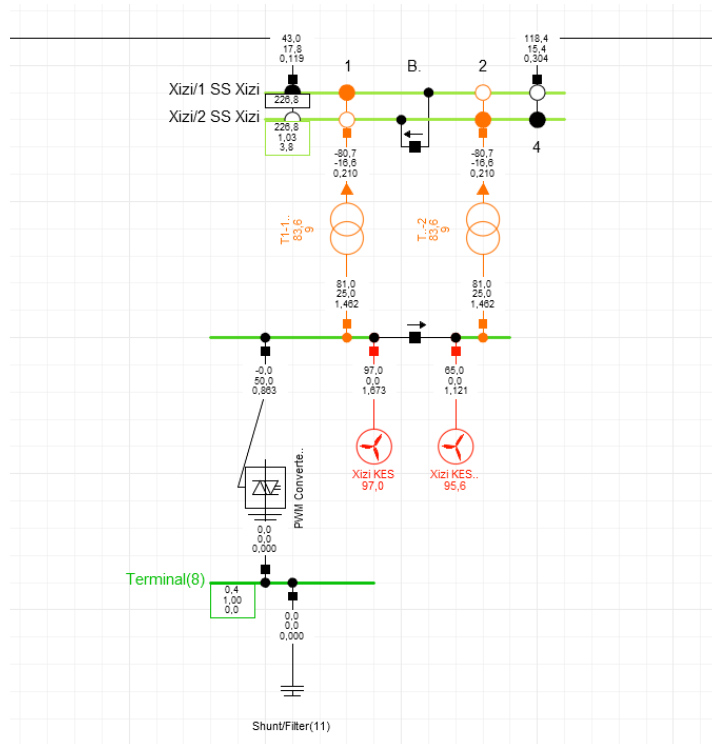


Fig.4.5 STATCOM installation in Xizi with 50MVAR

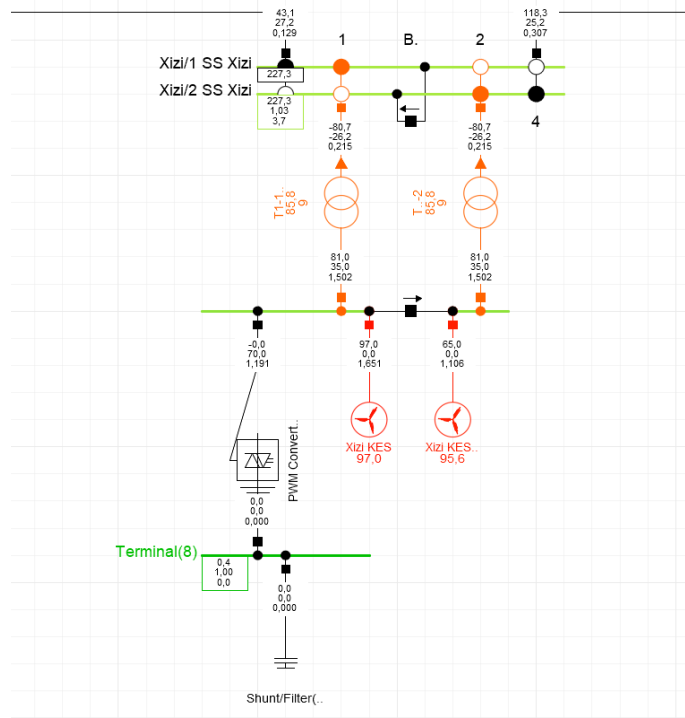


Fig.4.6 STATCOM installation in Xizi with 70MVAR

The parameters for converter to work properly in accordance to the grid are stated in Load Flow → General and Load Flow → Operational Limits, where the reactive power set point (70MVAR in this particular case) and limits for max and min reactive power. For sake of simplicity 220 KV of voltage and reactive power limits which are -100 and 100 MVAR are accepted as -1 and 1 per unit values.

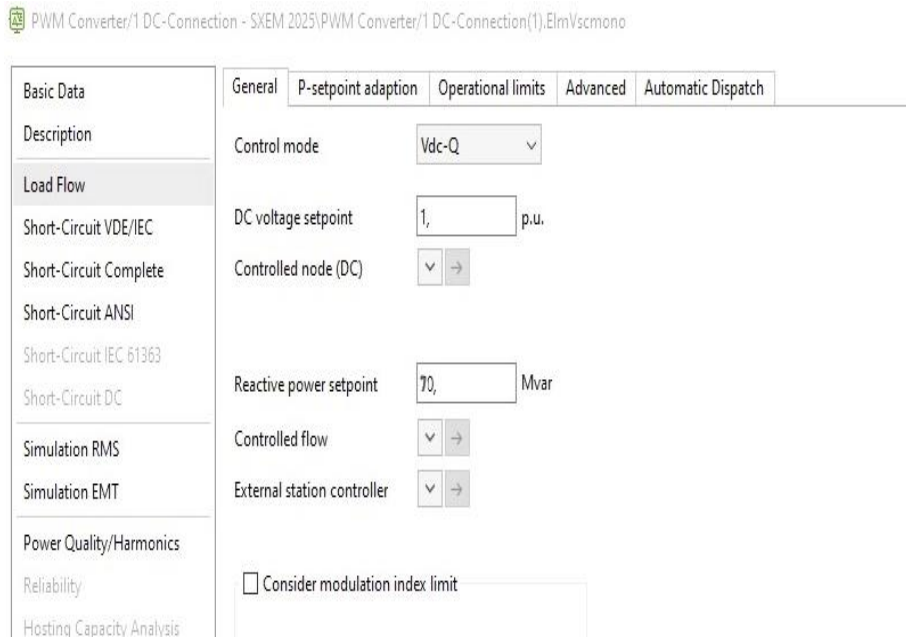


Fig.4.7 Load Flow

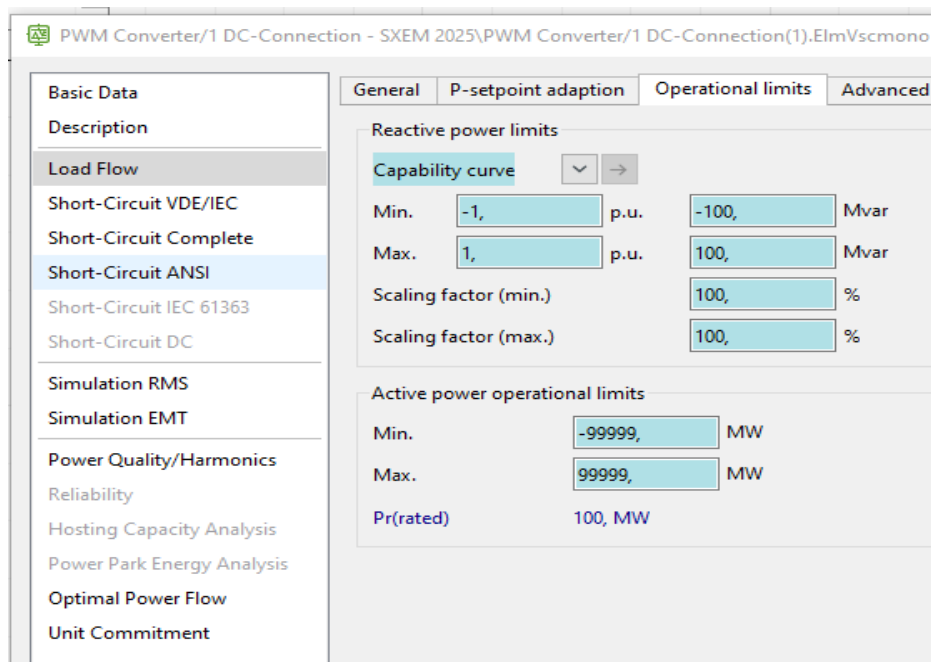


Fig.4.8 Operational Limits of STATCOM

PWM Converter/1 DC-Connection - SXEM 2025\PWM Converter/1 DC-Connection(1),ElmVscmono

| Basic Data                 | General                                 | Advanced  |
|----------------------------|---|---|
| Description                | Name                                    | PWM Converter/1 DC-Connection(1)  |
| Load Flow                  | Terminal AC                             | SXEM 2025\Terminal(73)\Cub_5 Terminal(73)   |
| Short-Circuit VDE/IEC      | Terminal DC                             | SXEM 2025\Terminal(8)\Cub_1 Terminal(8)   |
| Short-Circuit Complete     | Zone                                    | Terminal AC Azerbaijan  |
| Short-Circuit ANSI         | Area                                    | Terminal AC   |
| Short-Circuit IEC 61363    | <input type="checkbox"/> Out of Service |   |
| Short-Circuit DC           | Number of parallel converters           | 1   |
| Simulation RMS             | Converter type                          | Two-level converter   |
| Simulation EMT             |   |   |
| Power Quality/Harmonics    |   |   |
| Reliability                |   |   |
| Hosting Capacity Analysis  |   |   |
| Power Park Energy Analysis |   |   |
| Optimal Power Flow         |   |   |
| Unit Commitment            |   |   |
|                            | Ratings                                 | Modulation  |
|                            | Rated AC-voltage                        | 33, kV  |
|                            | Rated DC-voltage (DC)                   | 0,4 kV  |
|                            | Rated power                             | 100, MVA  |
|                            |   | <input checked="" type="radio"/> Sinusoidal PWM<br><input type="radio"/> Rectangular PWM<br><input type="radio"/> No modulation |

Fig.4.9 Basic Data

As a result of given parameters Capability Curve is obtained where the rated  $P=1$  p.u is given as horizontal blue line and left/ right limits of  $Q$ . Here the reference power is specified as 70 MVAR, therefore this rating is indicated on the x axis ( $Q$  axis) of the curve. Since the STATCOM is installed while steady state operation of the system the angle between grid voltage and inverter's output voltage is 0 which makes active power  $P=0$  (can be calculated with formula given above). That is the reason for point 0.7 be on x axis and not anywhere else.

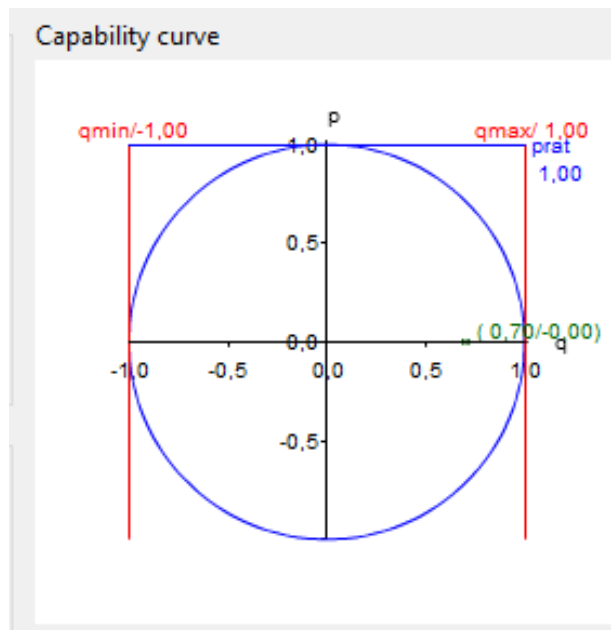


Fig.4.10 Capability Curve

In addition to previous result, in order to prove linear dependency between V and Q depicted in Fig.4.11 different values of reference reactive power are set to obtain corresponding V values. As a result, data was taken from Excel and the line graph was achieved.

Table 4.1 Q-V numerical relation

| Q(MVAR) | (Kv)  |
|---------|-------|
| 0       | 222.3 |
| 10      | 223.0 |
| 20      | 223.8 |
| 30      | 224.5 |
| 40      | 225.2 |
| 50      | 225.9 |
| 60      | 226.6 |
| 70      | 227.2 |
| 80      | 227.9 |
| 90      | 228.5 |



- 1) Inverter Bridge was made up by IGBT, RC branch, inputs from PWM that stand for controlling gate voltage to IGBT. Here  $V_R$ ,  $V_Y$ ,  $V_B$  are the output voltages of inverter.

This is the visual representation of the Inverter structure:

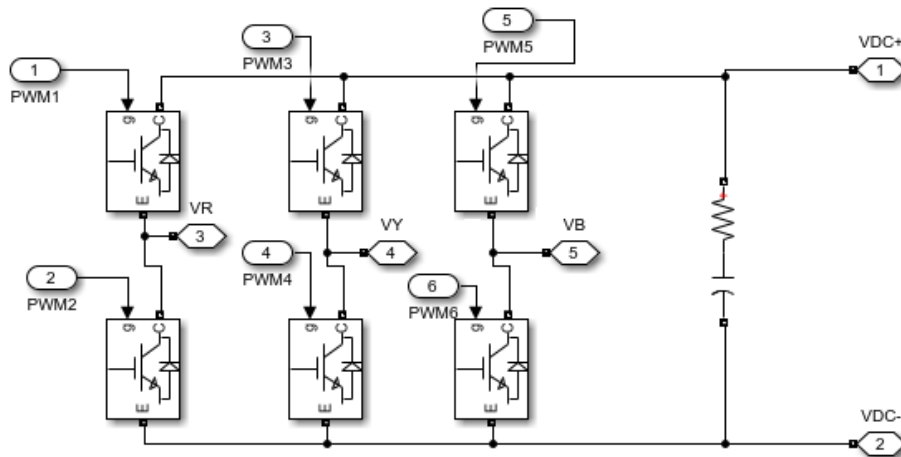


Fig.4.13 Inverter Bridge

- 2) Connect the DC inverter side with grid and load and to decrease harmonics from current flowing from inverter use 3 phase LCL filter. Put V-I measurement blocks to identify each voltage and current coming from inverter, grid and load.

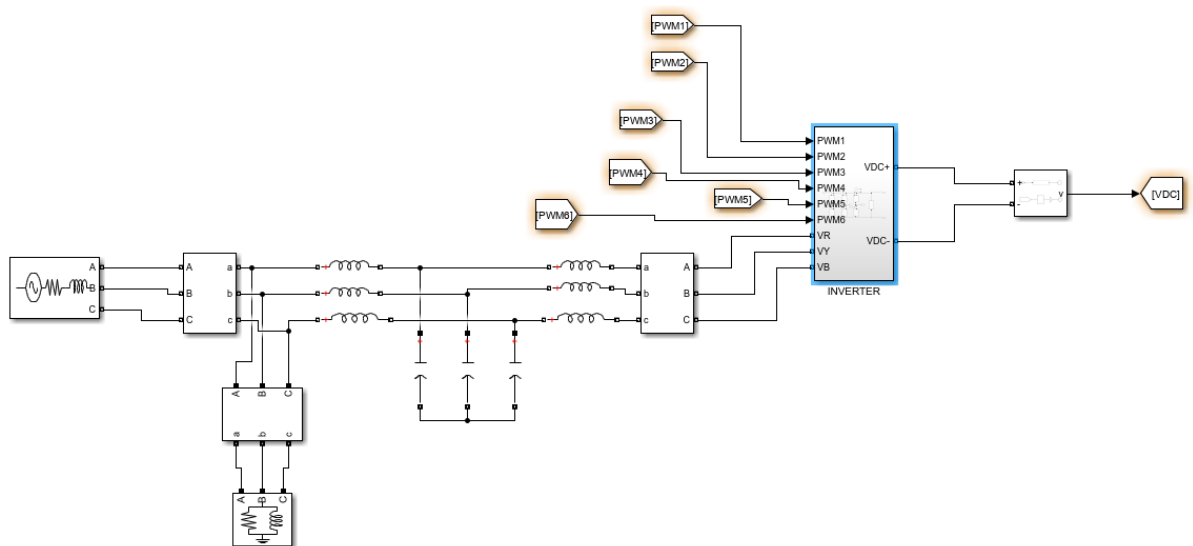
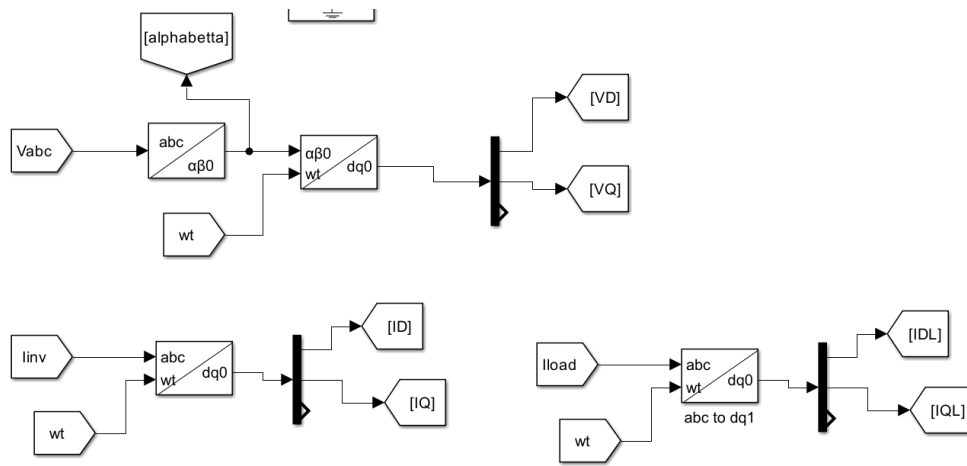


Fig.4.14 Overall circuit with dc side and grid

3) Here in order to implement PLL the 3 phase should be transformed to 2 dimension in voltage and current. Also the chosen components will participate in current and voltage control part from where the output voltage  $V_{ref}$  will be obtained to control PWM. The necessary transformations ( $abc \rightarrow \alpha\beta$  and  $\alpha\beta \rightarrow dq$ ) are done with Clarke and Park methods. However there are ready blocks in DigSilent, therefore no need to implement mathematical formulas.



*Fig.4.15 Voltage and Current transformation to dq frame*

4) Implementation of PLL :

To send reactive power to the grid we use PLL to generate the signal which is 90 degree out of phase with output voltage. As seen from the fig. 4.16,  $U_s$  is the grid's voltage, and this voltage does not align with  $V_d$  (voltage in d frame).  $wt$  is an angle between  $\alpha$  and d axes and its change can reduce angle between  $V_d$  and  $U_s$  to 0. When the  $V_d$  and  $U_s$  are in the same axis this means that q component of voltage became zero ( $U_q$  voltage component of q axis). So therefore reference  $V_q$  value sent to the PI controller is 0. The output obtained is passed through integrator to get  $wt$ .

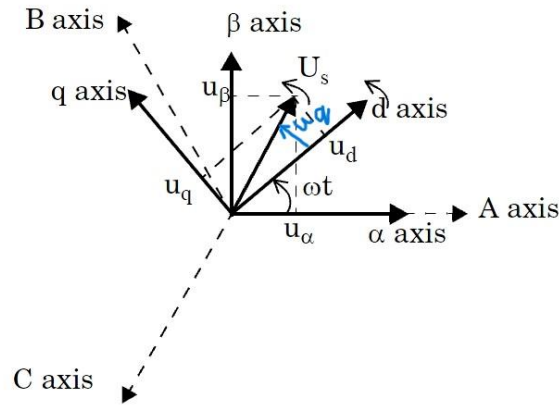


Fig.4.16 dq and  $\alpha\beta$  frame [ 45]

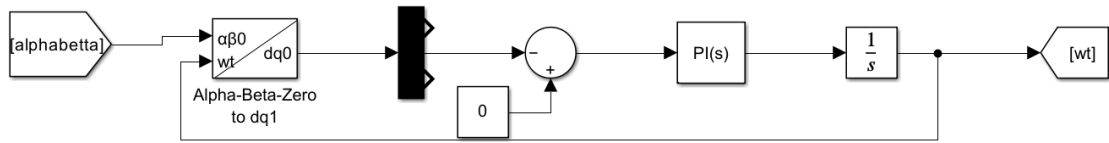


Fig.4.17 PLL

5) Here 600 V of DC voltage sent as reference where  $V_{DC}$  is the rated DC voltage obtained from inverter which approaches 600 after some fluctuations. Error value from there is so tiny can be approximated to 0 at steady state regime. This error value is summed with current in the load and the result is compared to the inverter's output current Decoupling helps us to adjust 3 phase components individually splitting to two axes direct (d) and quadrature (q). Here the cross coupling also can be observed between  $I_q$  and  $V_d$  also  $I_d$  and  $V_q$ . Then in order decouple dependency between d and q axes, Gain blocks( $\omega L_t$ ) are connected to + and - sides of SUM blocks which establish connection between d and q axes. The dq Voltages  $V_{t,d}$  and  $V_{t,q}$  are obtained that vary between  $-V_{dc}/2$  and  $V_{dc}/2$ . In order to achieve integer value of  $V_{t,d}$ ,  $V_{t,q}$  the Gain block with numerical value equal to 2 is added. Dividing these voltages by VDC the signal varying between -1 and 1 is obtained which is modulating signal.

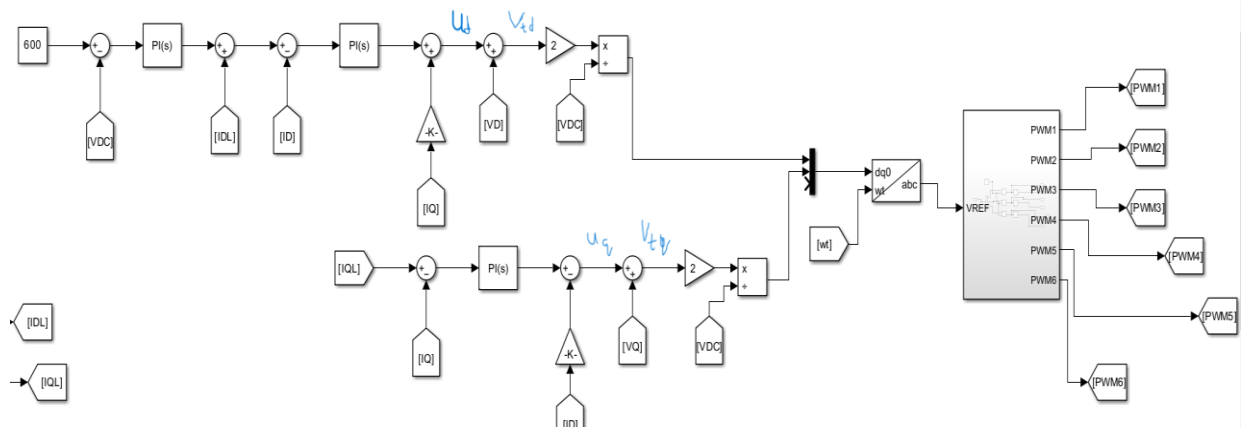


Fig.4.18 Control system

- 6) The triangular signal given in the left upper corner of Fig.4.19 is carrier signal which is generated at a fixed frequency. Here  $V$  reference and carrier signal are continuously compared and based on the result if at a given period the carrier signal is greater than reference voltage (which is the voltage obtained from the control part after dq current control transformation to the voltage and divided by  $VDC$  to obtain signal in the range  $-1$  and  $1$  also called modulation signal. When triangular signal is compared in  $\geq$  block with each phase  $V_Y$   $V_B$  and  $V_R$  (1), the PWM1,3,5 reach on state while PWM2,4,6 are in off state since they are connected to NOT block.

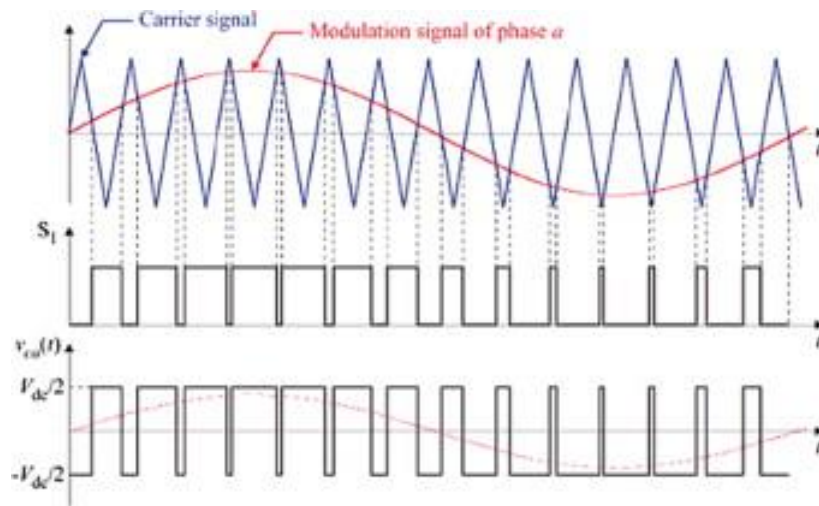


Fig.4.19 Carrier signal and voltage [48]

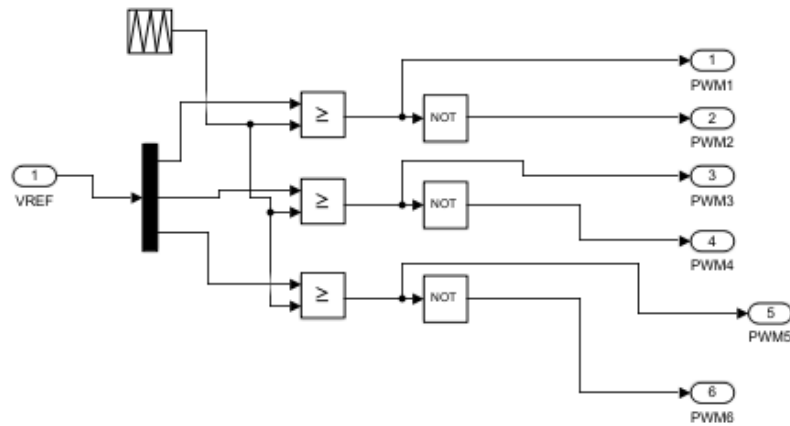


Fig.4.20 Comparison between 3 phase Reference voltage and triangular carrier signal

7) The final step is connection of grid voltage and current to scope 1 to see the final voltage and current received in grid , inverter current and load current to scope 2 where in inverter current the harmonics are observed later reduced by LCL filter and as a result of smooth current wave in the load. Also the waveform of Vdc from the supply side is visually presented.

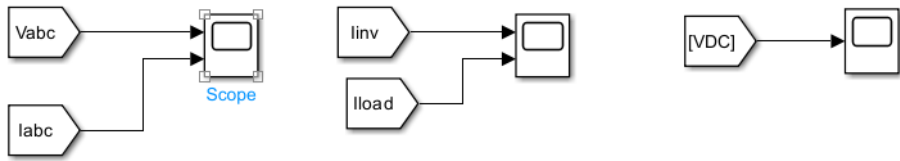
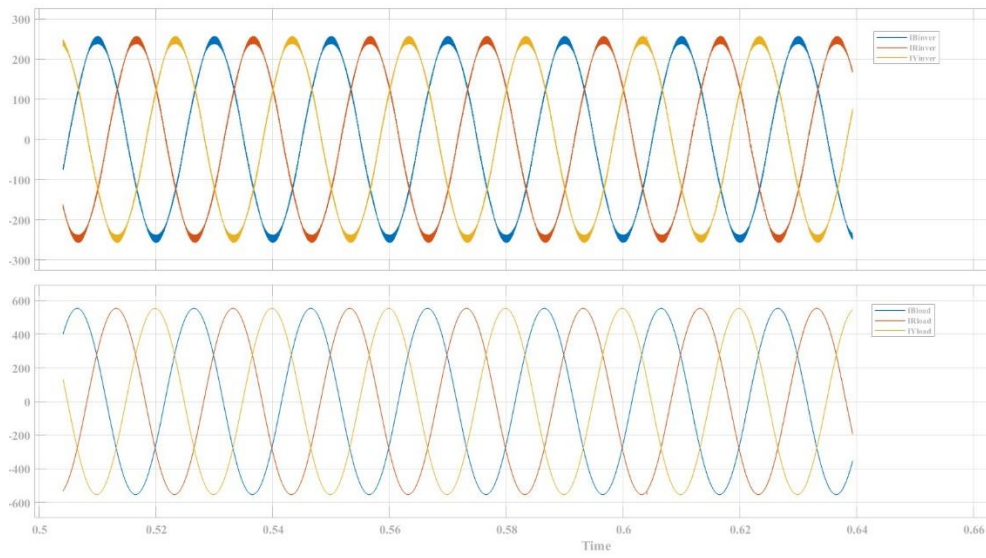


Fig.4. 21 Connection with scope

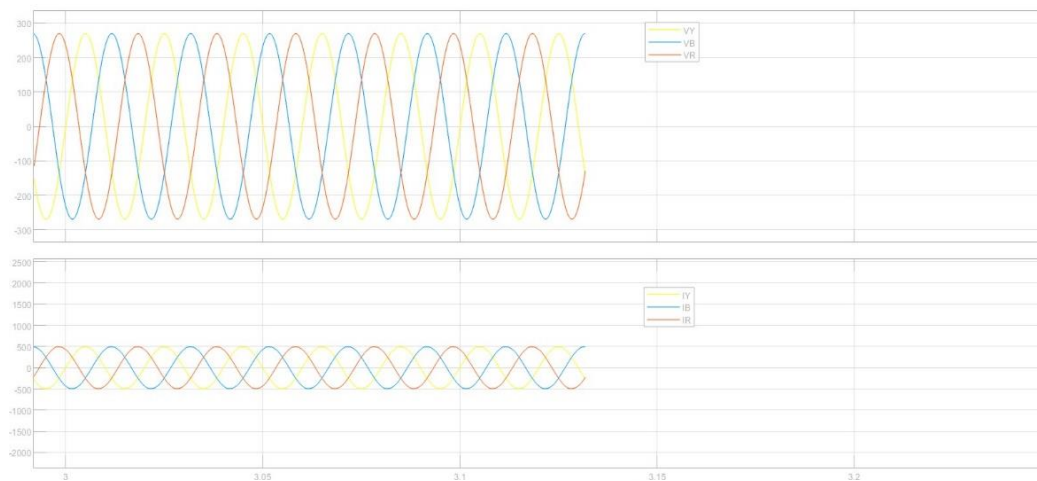
The parameters given to the model are following:

|                            |                     |
|----------------------------|---------------------|
| <b>Rated Power</b>         | <b>100KVA</b>       |
| <b>Grid Voltage</b>        | <b>330V RMS L-L</b> |
| <b>Grid Frequency</b>      | <b>50 Hz</b>        |
| <b>DC Bus Voltage</b>      | <b>600V</b>         |
| <b>Switching Frequency</b> | <b>10 kHz</b>       |

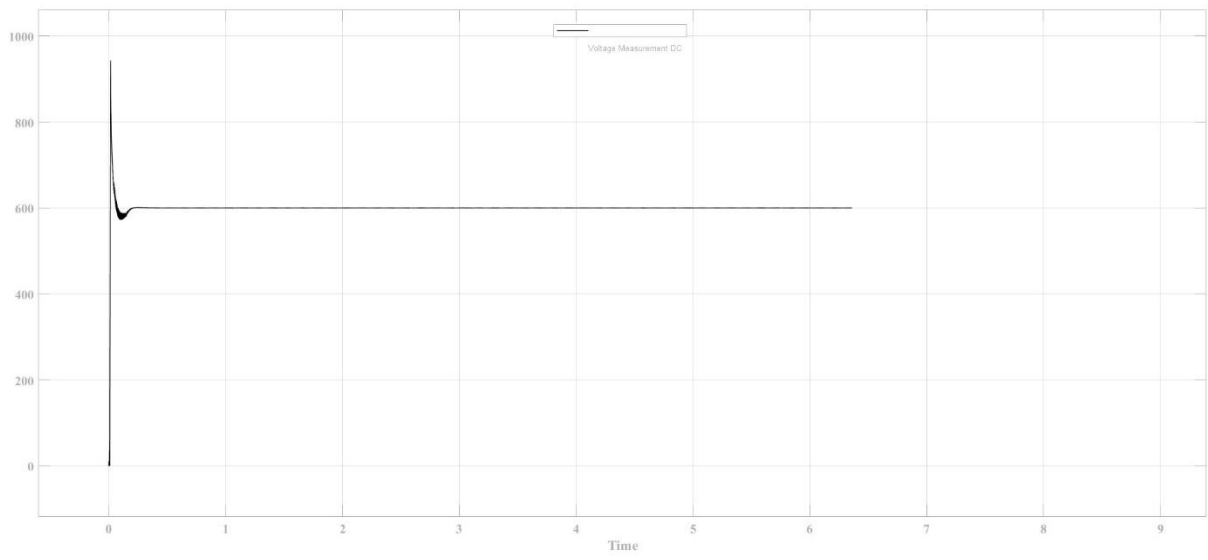
## 4.2 The Results



*Fig. 4 1 The Current flowing from inverter versus current after passing through LCL filter*



*Fig. 4.2 Voltage and Current waves*



*Fig. 4.3 DC voltage*

# CHAPTER FIVE

## Conclusion and Future Work

### 5.1 Conclusion

This paper focuses on the importance of STATCOM for Power quality improvement in addition to PF and grid stability improvement highlighting its advantages. Technical comparison is done between the preferred device and SVC which has the same aim in the system but provides longer response time. The pros and cons of these devices have been discussed in relation to their fundamental operational features.

The contributions of the paper are following:

The study of the basic principles of the STATCOM is carried out as well as the basics of reactive power compensation using a STATCOM.

The voltage and reactive power's linear dependency was presented as a result of simulation. Also the P-Q curve of PWM inverter was obtained at the given set point for reactive power.

Another contribution is the creation of STATCOM model based on predefined ac and dc voltages, system's rated power, frequency and switching frequency, also showing the importance of filters in the STATCOM installation to the system along with the PF correction.

### 5.2 Future Studies

As per obtained results STATCOM's importance in the system was proven, however there are some ways to boost the effect of that device by connecting several devices in parallel. Since STATCOM is expensive enough for economic purposes, results from parallel connection should be compared with those obtained from solely installed

STATCOM to see if connection of several compensators can worth it. In addition to that, some alterations can be applied to the control strategy of compensator. In particular, Fuzzy Logic that is usually implemented to develop the control strategy of an inverter by integrating more sophisticated reasoning and decision making. Apart from that, Whale Optimization Algorithm can be applied for tuning controller. That's why instead of conventional PI controller, fuzzy PI controller with two inputs for better control diversity can be used with WOA to optimize the parameters of Fuzzy PI controller may be beneficial for enhancing overall performance of the system. Whale optimization algorithm (WOA) of PI controllers is for controlling STATCOM. This WOA-PI controllers of SATCOM is applied for a renewable hybrid system to improve the performance of the entire system.

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