



REPUBLIC OF TÜRKİYE  
ALTINBAŞ UNIVERSITY  
Institute of Graduate Studies  
Electrical and Computer Engineering

**POWER QUALITY ENHANCEMENTS IN HYBRID  
GRID USING FACTS DEVICE**

**Mohammed Abdullah Ali AL-ANBAGI**

Master's Thesis

Supervisor

Asst. Prof. Dr. Zaid HAMODAT

Istanbul, 2022

# **POWER QUALITY ENHANCEMENTS IN HYBRID GRID USING FACTS DEVICE**

**Mohammed Abdullah Ali, AL-ANBAGI**

Electrical and Computer Engineering Department

Master's Thesis

ALTINBAŞ UNIVERSITY

2022

The thesis titled POWER QUALITY ENHANCEMENTS IN HYBRID GRID USING FACTS DEVICE prepared by MOHAMMED AL-ANBAGI and submitted on 14/12/2022 has been **accepted unanimously** for the degree of Master of Science in Electrical and Computer Engineering.

---

Asst. Prof. Dr. Zaid HAMODAT

the Supervisor

Thesis Defense Committee Members:

Asst. Prof. Dr. Zaid HAMODAT	Department of Electrical and Electronics Engineering, Altınbaş University	_____
Asst. Prof. Dr. Mesut ÇEVİK	Department of Electrical and Electronics Engineering, Altınbaş University	_____
Asst. Prof. Dr. Abbas UĞURENVER	Department of Electrical and Electronics Engineering, İstanbul Aydın University	_____

I hereby declare that this thesis meets all format and submission requirements of a master's thesis.

Submission date of the thesis to Institute of Graduate Studies: \_\_\_/\_\_\_/\_\_\_

I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Mohammed AL-ANBAGI

Signature

## **DEDICATION**

I dedicate this work to supervisor Dr. Zaid Hamodat, for his support through the journey of writing these pages. Also, my family members and friends. A special feeling of gratitude to my loving wife, for her support and encouragement in my pursuit of education.



## ABSTRACT

### POWER QUALITY ENHANCEMENTS IN HYBRID GRID USING FACTS DEVICE

AL-ANBAGI, Mohammed Abdullah Ali

M.Sc., Electrical and Computer Engineering, Altınbaş University,

Supervisor: Asst. Prof. Dr. Zaid HAMODAT

Date: 12/2022

Pages: 62

This work is studying a hybrid power grid consisting of a photovoltaic power plant as a renewable energy source connected with a conventional power source, and a load. In addition, a Flexible Alternating Current Transmission System FACTS device is used, by contributing to optimal system performance by minimizing power losses and enhancing the voltage profile. This method is utilized to overcome the problems produced by the existence of both reactive and resistive loads at the point of a common coupling. The proposed control strategy controls the FACTS device STATCOM according to dq-control theory, which force the d-axis component of the current to zero, which allows the active component to be taken from the supply while STATCOM also resolve the issues of the harmonic which generated by loads. This strategy will minimize the grid's reactive power output, ultimately increasing transmission capacity and enhancing grid stability.

**Keywords:** D-Q Controller, FACTS, Hybrid Grid, PV Plant, STATCOM.

# TABLE OF CONTENTS

	<u>Page</u>
<b>ABSTRACT .....</b>	<b>vi</b>
<b>LIST OF TABLES.....</b>	<b>ix</b>
<b>LIST OF FIGURES.....</b>	<b>x</b>
<b>LIST OF ABBREVIATIONS .....</b>	<b>xii</b>
<b>LIST OF SYMBOLS .....</b>	<b>xiv</b>
<b>1. INTRODUCTION.....</b>	<b>1</b>
1.1 BACKGROUND.....	1
1.1.1 FACTS devices and capabilities .....	4
1.1.2 Different types of FACTS devices .....	4
1.1.3 The reasons for selecting a STATCOM .....	6
1.1.4 STATCOM's Application.....	7
1.2 MOTIVATION .....	8
1.3 AIMS AND OBJECTIVES.....	8
<b>2. LITERATURE REVIEW.....</b>	<b>9</b>
2.1 RENEWABLE ENERGY .....	9
2.2 FLEXIBLE AC TRANSMISSION SYSTEM (FACTS).....	10
<b>3. METHODOLOGY.....</b>	<b>15</b>
3.1 RENEWABLE ENERGY SOURCE .....	15
3.1.1 Photovoltaic plant configuration .....	15
3.1.2 MPPT techniques .....	17
3.1.3 DC-DC converter .....	22
3.1.4 DC-Link .....	24
3.1.5 DC-AC inverter and filter .....	25
3.1.6 Phase-Locked Loop (PLL) .....	26
3.2 FACTS .....	27
3.2.1 FACTS device model (STATCOM) .....	27

3.2.2	Where the STATCOM is located .....	30
3.2.3	<i>abc</i> to <i>dq</i> Frame Transformation.....	30
3.3	THE PROPOSED SYSTEM WITH CONTROL SCHEME .....	33
3.3.1	Renewable energy source.....	33
3.3.2	STATCOM.....	36
3.3.3	Load.....	37
<b>4.</b>	<b>SIMULATION AND RESULT .....</b>	<b>38</b>
4.1	PV ARRAY PLANT.....	38
4.2	STATCOM.....	41
4.3	LOAD RESULTS .....	43
4.4	GRID RESULTS.....	44
<b>5.</b>	<b>CONCLUSION AND DISCUSSION .....</b>	<b>45</b>
5.1	CONCLUSION.....	45
5.2	FUTURE WORK.....	45
	<b>REFERENCES .....</b>	<b>46</b>

**LIST OF TABLES**

**Page**

Table 3.1: Photovoltaic model characteristics..... 17



## LIST OF FIGURES

	<u>Page</u>
Figure 1.1: Static Var Compensator model and Voltage-Current Characteristics. ....	5
Figure 1.2: Static Synchronous Compensator model and Voltage-Current Characteristics. ....	6
Figure 3.1: Equivalent Circuit diagram of the PV model [35]. ....	15
Figure 3.2: Impact of sun irradiance on photovoltaic characteristic parameters. ....	19
Figure 3.3: Flowchart of Perturb and observe algorithm. ....	21
Figure 3.4: DC-DC Converter Circuit. ....	22
Figure 3.5: Photovoltaic Panels with DC-DC Converter and MPPT. ....	23
Figure 3.6: Representation of phase locked loop (PLL). ....	26
Figure 3.7: STATCOM model .....	27
Figure 3.8: The diagram of the static synchronous compensator controller. ....	29
Figure 3.9: 3-Phase electrical variable in vector representation. ....	31
Figure 3.10: 3-phase electrical variable in <b>abc</b> frame and <b>dq</b> frame. ....	32
Figure 3.11: Illustration of the proposed system configuration. ....	33
Figure 3.12: Photovoltaic system in Simulink. ....	34
Figure 3.13: DC-DC converter with MPPT in Simulink. ....	35
Figure 3.14: LCL filter in Simulink. ....	35

Figure 3.15: STATCOM Capacitor with Inverter in Simulink. ....	36
Figure 3.16: Control Scheme of the STATCOM in Simulink.....	36
Figure 4.1: Output voltage (V) and current (I) of PV system. ....	38
Figure 4.2: Irradiance ( $w/m^2$ ) and output power (watts) of the PV system. ....	39
Figure 4.3: Voltage and current of photovoltaic system before inductor-capacitor-inductor LCL filter.....	39
Figure 4.4: Voltage and current of photovoltaic system with inductor-capacitor-inductor LCL filter.....	40
Figure 4.5: STATCOM's DC voltage.....	41
Figure 4.6: Reactive VAR delivered by STATCOM to the grid.....	41
Figure 4.7: STATCOM's voltage and current before the LCL filter.....	42
Figure 4.8: STATCOM's voltage and current with the LCL filter.....	42
Figure 4.9: Active power absorbed by the load.....	43
Figure 4.10: Reactive power absorbed by the load. ....	43
Figure 4.11: Reactive power delivered by the grid. ....	44
Figure 4.12: Active power delivered/received by the grid.....	44

## LIST OF ABBREVIATIONS

AC	:	Alternating Current
ANN	:	Artificial Neural Network
AVR	:	Automatic Voltage Regulators
CPSS	:	Conventional Power System Stabilizer
DC	:	Direct Current
DG	:	Distributed Generation
FA	:	Firefly Algorithm
FACTS	:	Flexible Alternating Current Transmission System
FLC	:	Fuzzy Logic Control
FOC	:	Fractional Open Circuit
FSC	:	Fractional Short Circuit
GA	:	Genetic Algorithm
IGBT	:	Insulated-Gate Bipolar Transistor
INC	:	Incremental Conductance
LCL	:	Inductor, Capacitor, and Inductor
MOSFET	:	Metal–Oxide–Semiconductor Field-Effect Transistor
MPP	:	Maximum Power Point
MPPT	:	Maximum Power Point Tracking
P&O	:	Perturbation and Observation
PCC	:	Point of Common Coupling
PF	:	Power Factor
PLL	:	Phase Locked Loop
POD	:	Power Oscillation Damping
PSA	:	Particle Swarm Optimization

PSS	:	Power System Stabilizer
PWM	:	Pulse-Width Modulation
SC	:	Soft Computing
SSR	:	Sub-Synchronous Resonance
SSSC		Static Synchronous Series Compensator
STATCOM	:	Static Synchronous Compensator
SVC	:	Static Var Compensator
TCR	:	Thyristor-Controlled Reactor
TCSC	:	Thyristor Series Controlled Capacitor
THD	:	Total Harmonic Distortion
TPSC	:	Thyristor Protected Series Compensation
UPFC	:	Unified Power Flow Controller
VAR	:	Volt-Amps Reactive
VOC	:	Open Circuit Voltage
VSC	:	Voltage Source Converters
VSI	:	Voltage Source Inverter

## LIST OF SYMBOLS

$k$	:	Boltzmann's constant ( $1.83 * 10^{-23}$ J/K)
$E_g$	:	The band gap of silicon material
$I_{pv}$	:	The output current of PV module (A)
$N_p$	:	The number of parallel solar cells in each PV module
$N_s$	:	The number of solar cells series
$R_s$	:	The series resistance of solar cells
$R_{sh}$	:	The shunt resistance of solar cells
$T_r$	:	The reference temperature (25 °C)
$V_{oc}$	:	Open circuit voltage (V)
$V_{pv}$	:	The output voltage of PV module (V)
$A$	:	Ideal factor
$T$	:	Temperature (K)
$q$	:	Electron charge ( $1.6 \times 10^{-19}$ C)

# 1. INTRODUCTION

## 1.1 BACKGROUND

Globally, energy networks are evolving into highly sophisticated technical systems. The overall load rises along with the population development and the regular emergence of a rising number of high-electricity-consumption enterprises, which leads to an increasingly complex distribution system structure. New technologies that enhance different electrical signs are also frequently developed. As a result, there has been a trend toward the construction of tiny networks with their own generation of low power that typically uses renewable energy sources as opposed to the usage of centralized power plants (wind, solar radiation, thermal sources, etc.) The phrase "distributed generation" is used to refer to a class of similar systems. However, additional difficulties arise for network businesses, design firms, and research institutions when it comes to maintaining and updating such dynamic systems. When loads are increased, the power system experiences an increase in losses, which in turn causes a noticeable decline in voltage across all nodes. Electrical networks frequently lose energy during transmission and distribution. Because of the distribution network's lower voltage and higher R/X ratio, it experiences greater power losses than the transmission network. Additionally, power plants must stick to more power generation due to power losses through the journey from generation to the consumer, which increases the consumption of fossil fuels and ultimately results in higher energy prices for the end customer. Up to 70% of all energy losses in the electricity network are attributed to the distribution network, according to the study [1], [2]. Distribution network companies typically focus more on the active power losses that occur because of electrical resistance.

For reactive power compensation devices, the methods of dealing with losses of electrical energy and deviations of voltage levels in electrical networks include change in the transformation ratios of transformers. Depending on the transformer model, it is possible to regulate both load condition, change in the excitation current of generators at power plants and the use of various compensating devices, leading to the redistribution of reactive power flows. Reducing distribution system losses has often been accomplished by the installation of reactive power compensation equipment [3].

Many types of installation of such devices are possible, they change the system parameters in a way to reduce the reactive power which transmitted through the transmission line by providing a capacitive power. By utilizing FACTS devices, voltage and phase angle on the electrical network can be adjusted on a specific section of the electrical system.

Power companies has been used various FACTS devices in the electrical system to achieve the goal which is compensate reactive power. SVC, STATCOM, TCSC, SSSC, and UPFC are common devices. Voltage stabilization is done when the load in the system is increasing above the maximum specific limit. At present, various methods have been proposed to analyze cases and provide a solution. The solutions rely on the recognition of systemic characteristics when the associated Jacobians become unified. Those balance points, also known as unstable stress points, can be statistically tied to the branching of the reference node. Unstable stress points which also called as peak load points. The main two approaches of inductive power reduction are inductive load absorbing and enhancement power quality.

compensation process which comprised of improving the PF of the network, adjusting the active power consumed from the power source, also improving voltage regulation, etc. With large load fluctuations, network stabilization consists in reducing voltage fluctuations in each section power system section especially the transmission section. There are two main types of compensation, series and parallel.

This changes the system characteristics and ensures optimal operation. In recent years, static VAR compensators Including the TCSC and STATCOM static reactive power compensators have been enhanced through the previous years till now. They execute the task of consuming or producing reactive power with a quicker time response excellently, and they classified as flexible alternating current transmission systems. Using these devices makes it possible to increase the transfer of useful power along the long distances and significantly improve power quality by adjusting the main factors which control the electrical network.

TCSC is a FACTS series device, which is able to improve the capacity, reduce the network loss, enhance the network stability, enhance the voltage profile in the transmission

network. It is the best tool to control the power movement in the transmission network. TCSC contains a string of capacitor, inductor, thyristor regulator.

The string compensation capacitor is attached in series along with the transmission line, and TCR is attached parallelly with the capacitor. No associated devices such as a high voltage transformer are required. TCR contains a series of flexible inductor and thyristors [2], [4]. STATCOM allows you to significantly increase the throughput of active power through power lines in continuous operation conditions and significantly enhance the stability of the power system by adjusting parameters such as current, voltage, phase angle and impedance [5].

These devices are in addition to conventional power system control, but due to the speed of the controllers, STATCOM devices can be utilized to increase the stability of the power system through improved damping of power fluctuations. This is achieved by regulating the full power flows and reducing low-frequency fluctuations inside the network. From the perspective of dynamic stability of the power grid, STATCOM provides better damping characteristics than other devices included in the FACTS concept, static thyristor compensators [6], [7]. Due to their design features, such devices are used to manage active and reactive energy adjustment which transmitted in the electrical network, despite other system variables. FACTS device does not have its own active power generation sources on the DC side and cannot deliver active energy to the AC side of the network.

FACTS device includes a three-phase inverter based on IGBTs, DC voltage of the inverter is provided by a DC capacitor, a coupling reactor that links the output of the inverter to the AC source side, and a device coupling transformer to high voltage network. The composition of STATCOM is shown in figure (3). On the capacitor side, The inverter takes full responsibility for generating the three-phase power, and phase sequence synchronization is interfaced with the AC side [8]–[10]. In the event of a voltage phase lagging in the network from the phase on the STATCOM device, it is presented to the power system in the form of a capacitive element and generates reactive power. Otherwise, STATCOM becomes an inductive element and reactive power is consumed from the network.

### 1.1.1 FACTS devices and capabilities

Devices based on FACTS have recently been utilized to regulate power flows and damping oscillations in power systems. It can be used to enhance transmitted power capability, support stable voltage regulation, mitigate power oscillations, and mitigate transient voltage support to prevent network failure. Transient and dynamic stability in photovoltaic power systems could be enhanced by utilizing FACTS devices such as STATCOM. The STATCOM, a member of the FACTS family of devices, can be put to good use in wind farms to keep voltage stable during transients and prevent blackouts. What this means is that a STATCOM is essentially an electrical generator of reactive power.

A transmission line with an impedance of  $Z$ , with transmission power  $S (P + jQ)$  results a voltage drops ( $\Delta V$ ) as shown in Eq. (3.1)

$$\Delta V = \frac{R.P + X.Q}{V} \quad (3.1)$$

According to Eq. 1, the transmitted reactive power ( $Q$ ) is proportional to the voltage difference ( $V$ ). So, an efficient reactive power strategy is necessary for successful voltage control. Dynamic and steady-state assistance can be provided by FACTS devices. They help prevent frequency and voltage drops, and they stabilize power during transients, thus they're useful for a variety of purposes.

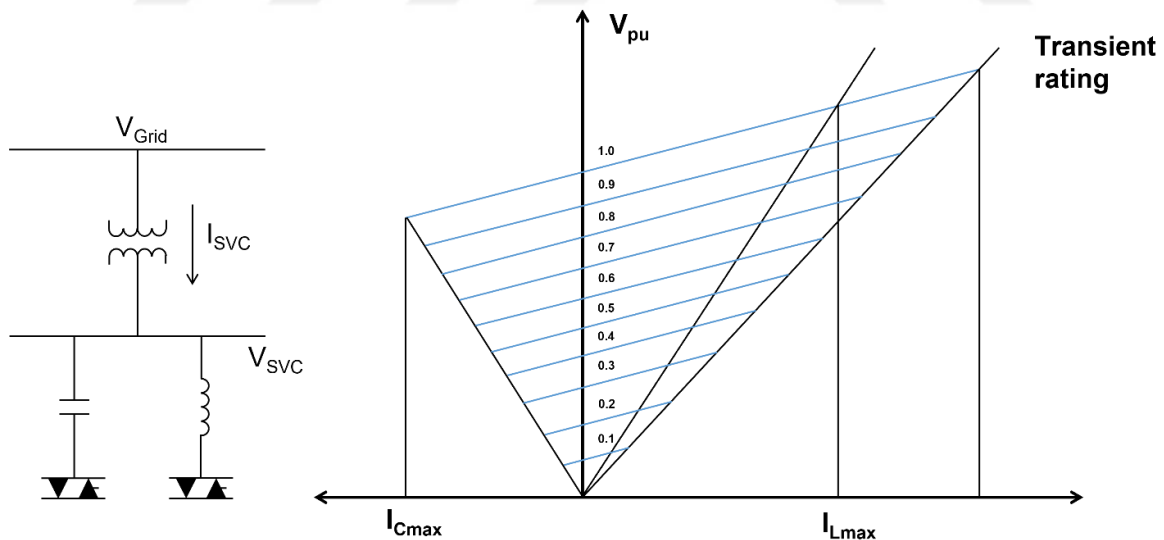
### 1.1.2 Different types of FACTS devices

TPSC and TCSC devices have an effect influence on the dependability of the network but have little effects on the quality of the voltage they produce. Both the SVC and the STATCOM have a moderate effect on the system's overall stability and a significant one on voltage quality. Regarding the power quality, network stability, and support of load flow, the unified power flow controllers UPFC have proven to be highly effective.

The main aim of this thesis is on finding methods to stabilize the system's voltage so that PV plants can be used in compliance with grid regulations. Providing reliable voltage quality throughout the electrical grid is a top priority, and the STATCOM is the most effective tool for doing so.

Shunt-connected reactive power compensation devices, STATCOMs, can generate and/or absorb reactive power, and their output can be adjusted to regulate various aspects of an electrical grid. The voltage can be controlled, and the dynamic stability enhanced by using the static compensator known as STATCOM [11]. Under different operating situations, a STATCOM can provide the necessary reactive power for active voltage control of the network, which in turn increases the network's steady-state stability. The STATCOM's highest inductive production or consumption varies in a linear way with the voltage of the grid, enabling STATCOM to operate at quite low power levels across the entirety of its grid power range.

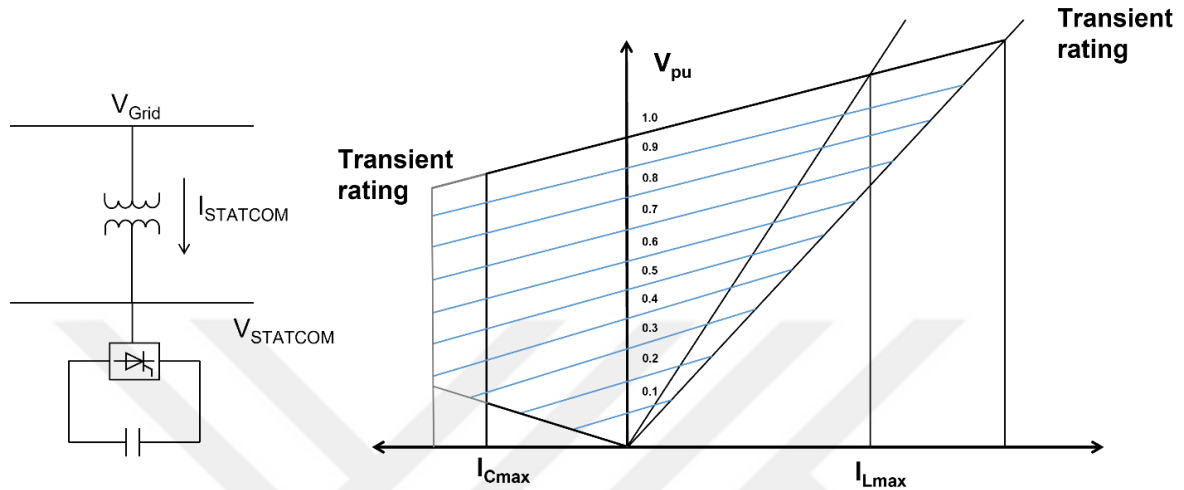
The high SVC compensatory current and high VAR output both drop in a linear fashion with increasing ac system voltage but in inversely proportional ways, respectively. Thus, a higher-rated SVC is needed for the same level of dynamic performance as a STATCOM. Capacitor size and ac system voltage are the two main factors in determining the maximum transient capacitive current that can flow through an SVC. The greatest transient capacitive overcurrent ability of a STATCOM is determined by the power semiconductors' highest turn-off capability [12].



**Figure 1.1:** Static Var Compensator model and Voltage-Current Characteristics.

The Figure above (3.1) depicts the illustrative representation of SVC and V-I characteristics. The representation and V-I features of the STATCOM is shown in Figure (3.2). A STATCOM's primary duty which is offering capacitive power to support and

enhance network stability. so, the first task of utilizing a FACTS device such as UPFC in an electrical power system is to manage the oscillation of different type loads in PCC. As depicted in Figures (3.1) and (3.20), the STATCOM provides superior reactive power regulation compared to the SVC.



**Figure 1.2:** Static Synchronous Compensator model and Voltage-Current Characteristics.

Capacitors which work on a mechanical switching method lack accurate performance especially in a low voltage level, hence, a device with a high switching capability is required for the same goals. Additionally, The SVC working voltage level is the same of the system level, and as a result, FACTS device efficiency is lowered to a low value. The UPFC is very expensive in comparing to its effectiveness and in most cases requires a complicated control method in order to get all the device's capabilities.

### 1.1.3 The reasons for selecting a STATCOM

Because they are a source of reactive power, capacitors are typically linked to renewable sources to increase system voltage. Fixed shunt capacitors which work on a mechanically switching method can increase the stability limit of the network voltage, however, they are not particularly sensitive to voltage changes. Additionally, the network voltage regulation by renewable sources with only the above-mentioned capacitors can exceed the network voltage by 0.05% (1.05 pu). Consequently, for reactive power adjustment, the network could not be dependent only on this type of capacitor.

Thyristor-based SVC has a main feature which is that the adjusting current is independent of the network utility grid at the PCC, which means that network voltage fluctuations do not affect the STATCOM operation [13].

Throughout day duration, the photovoltaic generated power and most of the loads fluctuate endlessly. For the power system to keep the network voltage at a constant value, reactive correction is essential. Reactive loads compensation device, like STATCOM, help minimize reactive power imbalances, which can have severe effects on the power system. STATCOM also has the ability to assist low voltage ride through requirements because of its ability to work in a full capability independently to the voltage.

#### **1.1.4 STATCOM's Application**

STATCOM's major purpose is to provide reactive current compensation and to maintain the bus voltage within acceptable limits. Multiple Canadian jurisdictions make use of STATCOM. STATCOM has been installed by the mining and metallurgical sectors to improve their electricity supply [14]. Due to the use of high-powered motors in the petrochemical industry, the voltage on the feeder decreases [15]. To preserve power dependability and offer high-speed dynamic voltage assistance through different fault scenarios, the service in British Columbia [16] has deployed three 12 MVAR STATCOM units.

Ontario gold mines have utilized the STATCOM technology to aid with their high-power demand or increasing load as a result of expansion [16]. A new mining operation in Ontario necessitates the use of high-powered electrical machinery fed by lengthy cable runs. They have employed six STATCOM units, each rated at 5 MVAR employed to compensate the reactive power in order to adjust voltage [16] to aid their operations. The quick response time of STATCOM guarantees that power performance requirements are met, along with the durability of motors and process equipment, hence ensuring a quick return on investment [16]. Induction motors are the leading source of power loss and poor power performance in mines [17]. Saskatchewan's mine loads have an abundance of induction motors [16]. With an increase in capacity of consumption, services become susceptible to apparatus inefficiency and shutdowns due to insufficient voltage at the PCC. A service has installed many 5.5 MVAR FACTS devices for VAR adjustment towards reduce system influence [16].

## **1.2 MOTIVATION**

Power system oscillation stability has been studied extensively for decades. When there is a power imbalance, the rotor will swing continuously around the steady state value. When major disruptions, like faults, occur in any component of the power system, these persistent oscillations render the system substantially less stable. Consequently, tiny signal stability research is just as crucial as Transient stability research.

It is common practice to employ automatic voltage regulators AVR in power systems to cancel out the oscillations brought on by even minor power system disturbances. However, PSS (Power System Stabilizer) can offer rapid regulation that an automatic voltage regulator cannot. FACTS-based stabilizers outperform CPSS in terms of damping performance (Conventional Power System Stabilizer). Integrating renewable energy sources, testing their compatibility with existing power plants, and learning how the grid reacts to disturbances are all part of the equation.

## **1.3 AIMS AND OBJECTIVES**

- a. Improve the steady-state performance of a multimachine power system.
- b. Study the effect of sun irradiance change on the power generated.

## **2. LITERATURE REVIEW**

### **2.1 RENEWABLE ENERGY**

The renewable energy sources such as solar, wind, and geothermal offer easily accessible, sustainable, green, and abundant energy. Since power outages rise in tandem with rising power consumption, switching to renewable energy sources is becoming increasingly important. A PV system's power generated is subject to substantial short-term and seasonal fluctuations and is dependent on very ephemeral energy sources. There is a need for some sort of energy storage system that can be used as a source of energy during times of low demand and as energy storage during times of high demand. In [18] a PV array shows that the efficiency of the PV array's conversion decreases as a result of external factors. So, in order to maximize energy production, a maximum power point tracking MPPT technique is required to detect the peak power. As shown in the figure 2.1 the system installed in a campus and uses a simple maximum power point tracking method, The obtained results are good tracking efficiency, high response, and the controllability of the generated power in addition to the green energy which means pollution free energy [18].

Planning and evaluating renewable energy integration is becoming increasingly important as renewable energy sources like wind and solar are increasingly used to generate electricity. This is because doing so requires a deep look into the operational economics of the energy system. Calculating the maximum renewable integration capacity for a renewable energy grid can help independent government system operators and investors make planning and operational decisions that support a higher penetration of renewable energy. A method in [19] is proposed to model a technical methodologies and evaluation points supporting integration planning and evaluation of renewable sources. [19] concludes to standardize models that used in the construction of renewable energy plants, as well as medium and long-term models to describe production, operation, and characteristics of energy systems in the production simulation for planning, also standardize the evaluation of criteria for the integration of renewable energy.

## 2.2 FLEXIBLE AC TRANSMISSION SYSTEM (FACTS)

In the past, under low load conditions, different type of reactors were used to regulate the system voltage, while under heavy load conditions, different type of capacitors were used to regulate voltage level [20]. However, resonance issues, a slower response time to transient situations, and active power loss in the reactors make the operation of standard compensators limited in terms of their ability to transmit data [21]. Since power demand is rising and more and more decentralized power sources are being connected to the grid, power quality has become a key issue. Because of this, power system issues such voltage instability, power flow variations, voltage fluctuation, and harmonics distortion became more common. In [22] a shunt FACTS device is used that compensates reactive power with a Thyristor-based LC filter and a VSC-based inverter operating at a low DC link voltage, this study proposes a method for improving the voltage profile. It concludes that the hybrid STATCOM, which can extend the compensation range with less DC link voltage and improve the power quality in the system since it operates reliably under a wide variety of load conditions.

An enhanced power quality has been a continuous necessity and challenging task for any electric distribution system [23]. In [24] address the challenges introduced in case of non-linear devices connected with PCC, which provides a systematic way for building a basic control for VSC-STATCOM at PCC. So that the source provides active power (watts) only and the STATCOM can satisfy the harmonic and reactive current requirements of the non-linear load, which is connected, the suggested strategy works in a way that the source q-axis component of the current minimize to zero or near that value. Different optimization methods are used to fine-tune different loops of the PI controllers. The DC capacitor voltage of the STATCOM showed a very slight fluctuation, suggesting improved system performance. In all three examples taken into consideration, the THD of the adjusted supply current were likewise discovered to be below the IEEE-519 standard's upper and lower bounds. It was also emphasized that the suggested STATCOM control may provide reactive power through voltage drop scenario. In this manner, it was discovered that the performing of the suggested STATCOM control approach with adjusted controllers was acting adequately.

In [25], a high increase in renewable energy sources shows new challenging issues such as voltage fluctuation, harmonic noise, reactive power demand, etc. Intelligent FACTS devices, as a solution, are used to overcome the abovementioned problems, an energy storage system such as a supercapacitor is utilized for a grid-connected solar plant. For operation efficiently, a voltage controller and a d-q axis controller are both utilized. [25] concludes that the proposed method increases the ability to address power systems issues.

For the purpose of providing high response and a steady voltage in a solar-wind hybrid grid, in [26] two paralleled techniques, genetic and bacteria foraging, are employed to tune the gain parameter of PI controllers in the STATCOM control circuit. The comparison of the outcomes revealed that the STATCOM tuned with Genetic algorithm and Bacteria foraging algorithm was more successful. The voltage swell caused by the shift in reactive power has been overcome and a better dynamic response has been attained by achieving the best settings for PI controller gains.

[27] presents a tabu search-based algorithm for identifying and sizing FACTS devices in a microgrid. The functionality of the microgrid is enhanced by the joint placement of various types of devices. To guide the search in the correct track, Tabu Search makes use of many indexes. The derived solutions exhibit a decent voltage profile and objective function values. The choice of the position and size of FACTS in a grid is a challenging issue, and its resolution necessitates the use of optimization methods that enable considering the interactions between the various components. The findings obtained demonstrate that every component of the microgrid is operating within its design parameters, and the optimization model has significantly improved.

A discussion of the impact of a battery energy storage system based on STATCOM performance is provided in [28]. A notable enhancement in voltage profile is seen when STATCOM is in use. It effectively addresses problems like voltage sag-swell, harmonic distortion, and voltage profile. After the STATCOM is connected to the system, the current and voltage at the source side are seen to be in phase. As a result, the evacuated substation can maintain a power factor close to unity PCC. In fact, STATCOM ensures electricity quality standards at close-by wind farm substations. As a result, forced trips of connecting lines between the pooling and evacuation substations can be prevented, improving the plant load factor and long-term earnings.

In [29], In order to reduce sub-synchronous resonance SSR in a steam turbine-driven synchronous generator coupled to a series compensated transmission line, this work proposes a new control strategy for a STATCOM which based on a connection between a photovoltaic plant which works together with the STATCOM. The Photovoltaic farm can use all its inverter capacity for SSR minimization at night to function as a STATCOM. When a system problem occurs during the day that causes SSR, the solar farm automatically stops producing active power as usual and delivers all its available capacity of the inverter working as Photovoltaic-STATCOM to prevent Sub synchronous resonance. The solar farm resumes producing real power normally once the sub-synchronous resonances are dampened. By replacing or reducing the need for an expensive FACTS device, the proposed Photovoltaic-STATCOM technology can achieve the same goal. Additionally, this technology is significantly more affordable than a standard SVC or STATCOM of a comparable scale. According to the studies, this type of integration of photovoltaic and a FACTS device can effectively minimize the hazardous sub-synchronous resonance in the connected sources. Potentially, With the photovoltaic-STATCOM control, the installation of a pricy FACTS device attached to the output terminal for the identical reason might be avoided. Because Photovoltaic solar farms are a competitor in the market, Generally, the operator of a synchronous generator might not even wish to share any classified info about rotor disturbances with other generating owners.

The fuzzy-controlled STATCOM is introduced in [30], for the enhancement of grid-connected wind energy conversion systems and non-linear load power quality. It aids in enhancing the system's voltage profile. By dramatically lowering the THDs in the voltages and currents on the source and load sides, the fuzzy regulated STATCOM has improved the grid power quality. As a result, fuzzy controlled STATCOM performs better than the traditional controller. A STATCOM's rating determines how much reactive support it can offer. Therefore, a STATCOM with a high enough rating must be offered.

A hybrid wind and photovoltaic system model has been presented in [31]. This kind of solution is particularly advantageous and practical for remote or island locations where grid integration is not very cost-effective. Due to the unpredictability of the renewable energy availability, however, the alone operation of either photovoltaic or wind energy systems does not offer a highly stable source of electricity production. As a result, a variety

of wind and solar power generation systems can create a very promising and dependable supply of electricity. Power quality issues, such as harmonic production and the reactive power adjustment that disrupt the power distribution system, are brought on by the connecting of power electronic equipment to DG systems. The total harmonic distortion THD at various wind speeds has been calculated to assess the power quality of the system. By utilizing D-STATCOM, the hybrid system's power quality has been enhanced.

In [32], Since energy is delivered into the grid from various sources, grid-connected or hybrid system have caused an energy imbalance. The energy that is given to the consumer is of lower quality as a result. To overcome the mentioned issue, static compensators (STATCOM) are now required. It acts swiftly and makes an effort to improve power supply quality by dampening power fluctuations. The most up-to-date innovation in this area of study recommends utilizing STATCOM hybrid models that make use of capacitors that are controlled mechanically, Overall, the system is found to be efficient, with harmonic distortion dropping on the supply side and the load side. Having the hybrid STATCOM attached means that the supply harmonics were dampened. The degradation in supply is intended to be mitigated by the fuzzy logic controller included in the system.

A unique control introduced for photovoltaic system which is a STATCOM in [33], or Photovoltaic-STATCOM, for the purpose of reducing POD in power system. When the suggested control is activated, the solar farm temporarily (a matter of seconds) stops its actual power producing function and instead uses its full inverter ability to work like a STATCOM to minimize PODs if power fluctuations are detected as a result of a system disturbance. As soon as power oscillations are suppressed, Maintaining the damping function, the renewable energy system approaches to improving to its post level of actual power output. The resulting repair time is far less than what is required by grid codes. As the sun goes down, the solar farm uses all its inverter capacity to carry out POD. In systems that display both local inertial and inter-area oscillatory modes, the suggested control offers a significant boost in power transmission capacity. The proposed device is less expensive than a traditional one and would be to provide POD in the same area. With this innovative control, solar farms can earn additional cash by supplying POD, while transmission utilities can save substantial sums of money.

An integrated new inverter called PV-STATCOM is introduced in [34], enabling the photovoltaic system's inverter to function as a dynamic reactive power adjuster. The device can be used to regulate voltage during crucial system requirements. The system runs on the entire inverter capacity at night. During a critical system interruption during the day, the intelligent inverter ceases providing real power and releases its whole inverter capability for STATCOM operations. Once the disturbance is eliminated and the requirement for power system management is satisfied, the photovoltaic system returns to its post power output.



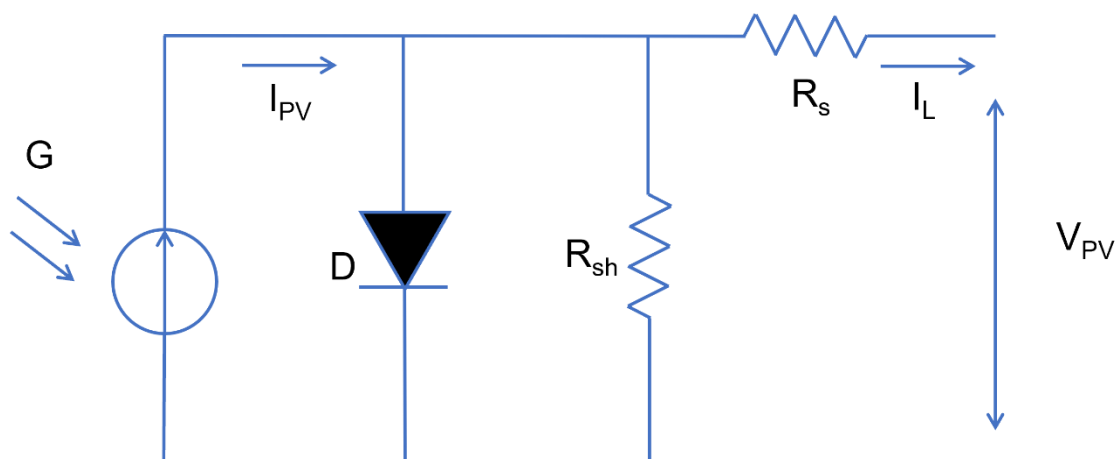
### 3. METHODOLOGY

#### 3.1 RENEWABLE ENERGY SOURCE

The most overflowing source of energy is solar energy, which may even be used under cloudy conditions. The rate at which the Earth absorbs solar energy is much greater than the rate at which people use energy. For a wide range of applications, solar systems can provide heat, cooling, natural lighting, power, and fuels. Solar technologies can use photovoltaic panels or solar radiation-concentrating mirrors to turn sunlight into electrical energy. Solar panels are now not only accessible, but frequently the cheapest source of electricity because to a sharp decline in the cost of solar panel production over the past ten years. Solar panels come in a range of colors according to the type of substance being used their production and have an average age of thirty years.

##### 3.1.1 Photovoltaic plant configuration

PV P-N junction composed of semiconducting material or other manufacturing alloys is used to construct solar cells. This PV solar cell can transform the electromagnetic energy of the sun or solar radiation into electricity. PV module is comprised of PV solar cells linked in series and parallel to produce the desired voltage and current. A PV solar cell is portrayed as a source of current coupled to other electrical components. Figure (3.1) depicts the PV solar cell equivalent circuit model.



**Figure 3.1:** Equivalent Circuit diagram of the PV model [35].

There are several ways to model PV solar cells. MATLAB - Simulink is the most popular and effective simulation environment for performing PV modeling work [36]. All PV module parameters can be obtained by reviewing the manufacturer's datasheet. The mathematical formulae for the PV module are as follows [37]:

$$I_{ph} = \frac{[I_{sh} + K_i(T - 298)]xG}{1000} \quad (3.1)$$

Where  $I_{ph}$  is the photovoltaic current and  $I_{sh}$  is the solar cell's short-circuit current (A) under standard test conditions (STC),  $k_i$  is the solar cell's short current temperature coefficient (A/°C), and G is the solar irradiance (W/m<sup>2</sup>).

The reverse saturation current  $I_{rs}$ , the saturation current  $I_0$ , and the output current ( $I_{pv}$ ) equations of PV module are:

$$I_{rs} = \frac{I_{sh}}{\left[ \exp \left( \frac{qV_{oc}}{N_s k A T} \right) - 1 \right]} \quad (3.2)$$

$$I_0 = I_{rs} \left[ \frac{T}{T_r} \right]^3 \exp \left[ \left( \frac{qE_g}{Ak} \right) \left( \frac{1}{T_r} - \frac{1}{T} \right) \right] \quad (3.3)$$

$$I_{pv} = N_p I_{ph} - N_p I_0 \left[ \exp \left\{ \frac{(q(V_{pv} + I_{pv} R_s))}{N_s A k T} \right\} - 1 \right] \quad (3.4)$$

Where the parameters of the photovoltaic panel as shown in the table (3.1) below:

**Table 3.1:** Photovoltaic model characteristics.

Parallel strings	47
Series-connected modules per string	10
Maximum Power (W)	213.15
Cells per module	60
Open circuit voltage $V_{oc}$ (V)	36.3
Short-circuit current $I_{sc}$ (A)	7.84
The voltage at maximum power point $V_{mp}$ (V)	29
Current at maximum power point $I_{mp}$ (A)	7.35
Temperature coefficient of $V_{oc}$	-0.36099
Temperature coefficient of $I_{sc}$	0.102

### 3.1.2 MPPT techniques

Recent technological advancements have made it easier and less expensive to generate power using photovoltaic PV systems, making photovoltaic electricity the predominant source of renewable energy. Increasing the efficiency of photovoltaic systems is of greatest priority as the demand for these systems grows. The technique in which the system delivers a high power is called MPPT technique, these techniques have been advanced through time to improve the effectiveness of the generated power from photovoltaic PV systems with fluctuating conditions such as solar irradiance in the area, environment temperature, and cleanliness of the PV panel [38].

Many techniques have been presented to achieve the above goal and work as MPPT, the majority of these methods are SC and traditional procedures [39] – [41]. The most well-known soft computing approaches are ANN, PSA, FLC, GA, and FA [42]. SC approaches employ adaptable algorithms that do not require modeling a specific mathematical system under consideration. Therefore, this approach may quickly adapt to various application with no need for a controller update. Additionally, SC techniques can effectively manage the non-linear change in irradiance and temperature, it is considered as a benefit for this

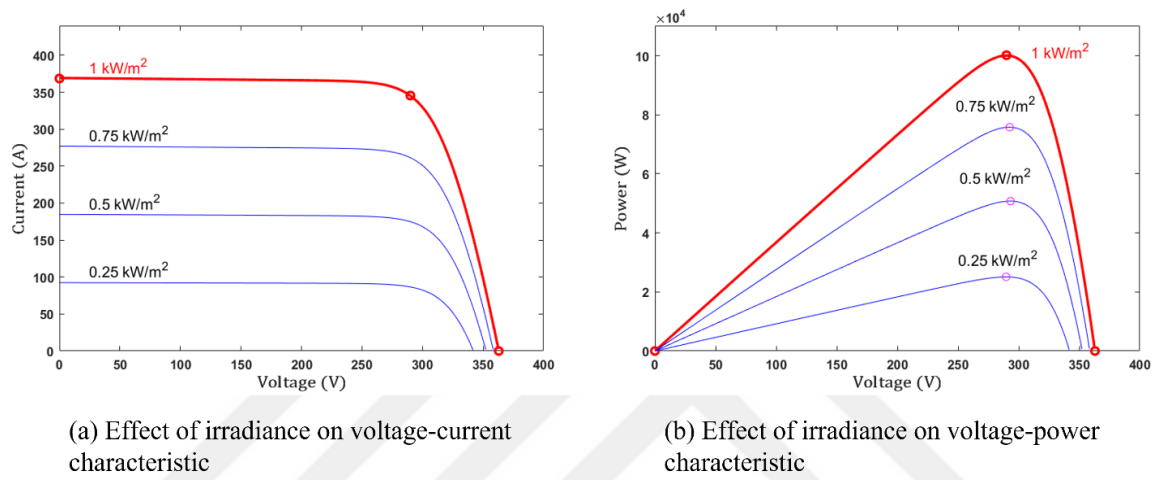
approach over conventional ones [43]. SC approaches were not widely used in photovoltaic energy system for the features such as expensive application costs and complicated architecture.

Current and voltage sensors are used in the conventional MPPT systems. The duty cycles of power converters are determined by MPPT controllers which measure the current and voltage of the photovoltaic and depending on the generated energy. Profitable, chasing irradiance velocity, and quantity of oscillation at constant-state maximum power point distinguish widely employed traditional MPPT techniques MPP, FOC, FSC approaches are among those that are somewhat complex but lack precision [44], [45]. FOC approach employs a relationship between maximum power point operating of  $V_{mp}$  and  $V_{oc}$  of photovoltaic strings that is roughly linear, with a proportional constant  $K$ . The experimented  $V_{oc}$  of the photovoltaic panel is employed to calculate the operational voltage recommendation point as a reference point, and this reference point held unchanged till the following sampling process. This is the primary cause of the FOC method's inaccuracy [46]. The Incremental Conductance INC approach was first presented in 1993, and there have been numerous enhancements since then. The INC process is built on the power-voltage curve gradient. This technique can only detect the MPP under uniform irradiation [47], [48]. The MPP can be tracked using the fraction of incremental and instantaneous conductance.

Because of its basic construction and low price, P&O is the highly used MPPT technique along with the whole MPPT processes [49]–[51]. However, this approach fails when varied irradiance levels are applied to panels in an array. Strong chasing period and great steady-state oscillations are other significant issues with this technology [52].

The standard P&O approach takes constant iteration step size. Large iteration step sizes result in quicker chasing, but also in steady-state oscillations around maximum power point. Small enough move sizes may be used to dampen oscillations, albeit at the expense of poor tracking. P&O approaches with variable iteration step sizes were developed to address this trade-off. These methods provide the use of bigger step size for faster tracking as the generated power of photovoltaic panel approaches MPP and smaller step for fewer oscillation when the generated power is close to MPP.

The power output of photovoltaic panel varies according to the amount of sun irradiance and the temperature of the environment. Figure (3.2) illustrates the influence of sun irradiance on the output of the photovoltaic panel as shown in curves of voltage-power and voltage-current. It has been determined that for a certain quantity of irradiation, there exists a precise value for voltage and current that provides the maximum possible power. This moment is known as MPP ( $V_{MPP}$ ,  $I_{MPP}$ ). Although it is displayed here only for irradiance, MPP might vary based on variables such as temperature and weather conditions.



**Figure 3.2:** Impact of sun irradiance on photovoltaic characteristic parameters.

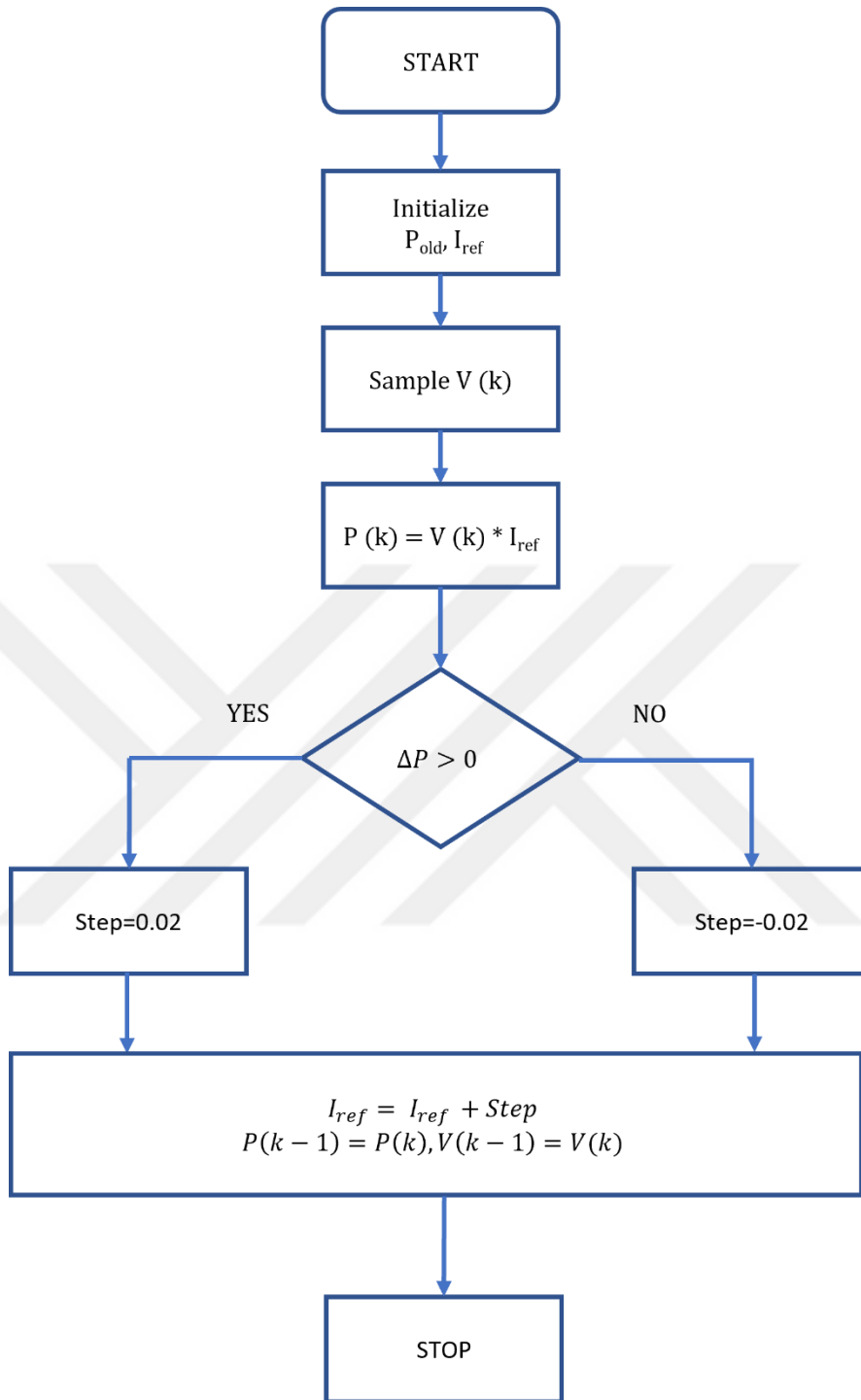
MPPT algorithms confirm that the maximum amount of power is extracted from variable-term photovoltaic systems. This is often accomplished through taking readings of voltage and current and monitoring output power of the photovoltaic string and comparison them to the reference rates. There have been several MPPT approaches created [53], [54], but P&O is considered one of the most well-established and widely employed. This is particularly due to simplified construction and simplicity of operation.

Figure (3.3) depicts the flow chart of the standard P&O approach. This procedure calculates the change inside photovoltaic string and the generated energy across successive time duration. Photovoltaic string generated power of the present duration is matched with the readings of the earlier duration. The algorithm selects whether to enhance or reduce the current  $I_{ref}$  based on this comparison. If the output power is growing, the direction of the current change is not altered. When the difference between successive cycles for power is negative, the way of difference for the current is inverted. Because of the current unrest is

constant throughout each time duration, steady-state power output fluctuates about its maximum value.

When the step size is fixed, achieving the *MPP* rapidly and limiting oscillation across the *MPP* is contradictory goals. Using a bigger step size expedites *MPP* attainment, but also increases the power loss caused by steady-state oscillations. In contrast, selecting a small step size may reduce energy cost close to the *MPP*, but tracking needs extended time. In case that a short time for tracking and a small number of oscillations across *MPP* are required, fixed step P&O processes must be changed in a way to accept varying step size each time duration based on the operating point. These techniques of MPPT have been created in last years. The P&O technique developed to address the issues follows.





**Figure 3.3:** Flowchart of Perturb and observe algorithm.

### 3.1.3 DC-DC converter

Boost converters are frequently employed in renewable energy applications such as photovoltaic and wind. Because the power production of these types of sources is fundamentally irregular, it is essential to account for its impact to improve the overall system productivity. A converter helps to improve the overall efficiency of the system. A boost converter is an electronic device that increases the voltage of a low-voltage DC source. Additionally, it regulates the amount of energy taken from the solar panel and applies a constant voltage to the output [55]. Photovoltaic panels exhibit nonlinear output and obvious oscillations in voltage which are called ripples, which prevents electrical equipment from directly utilizing Photovoltaic output power. DC-DC converters are utilized to control the power output of Photovoltaic systems. The output operating point of a boost converter is controlled by the switching equipment's switching speed and the frequency of switching devices [56]. Benefit from switching methods, the output voltage of the DC converter can be changed up and down (boost-buck), simultaneously (boost-buck) (buck-boost). In this work, Figure (3.4) shows that a boost DC-DC converter is utilized. By toggling the MOSFET (G), voltage level conversion is attained. MPPT is accomplished whenever the controller algorithm modifies and adjusts the duty cycle value (D) of the PWM unit which generates pulses for the switching device IGBT in the DC converter power converter to control the dc voltage of photovoltaic panels [57].

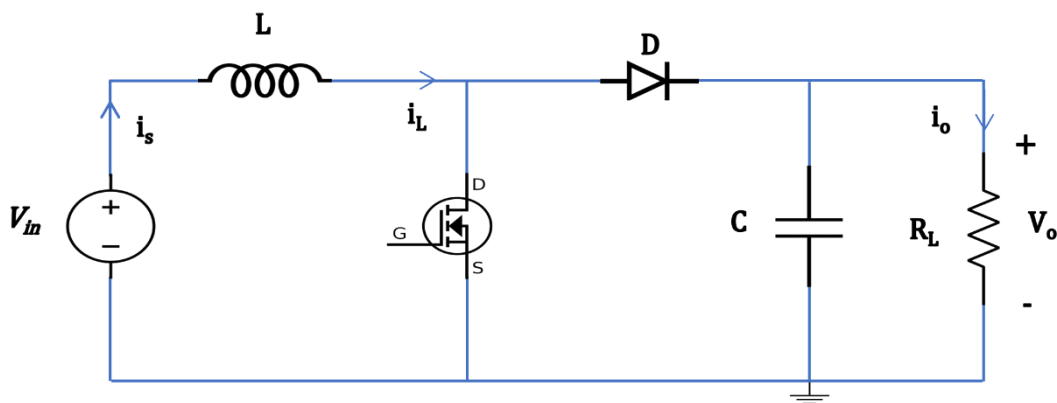
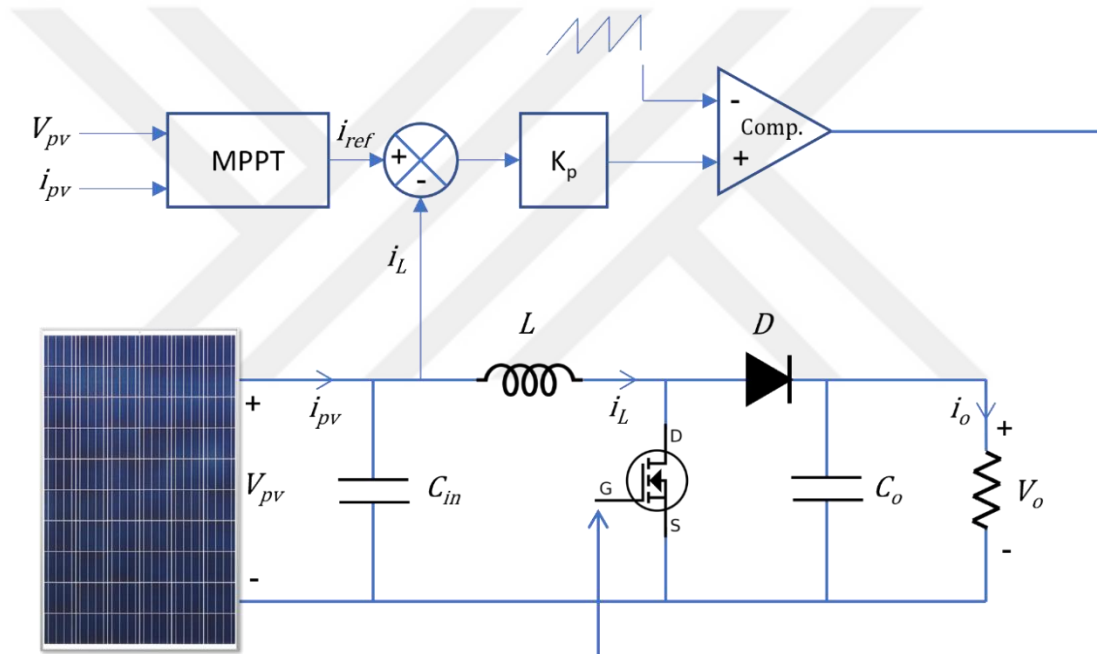


Figure 3.4: DC-DC Converter Circuit.

In the figure below the proposed scheme of DC-DC converter in addition to the MPPT method. Error is determined by deducting  $i_{ind}$  from  $i_{ref}$ . Previous duty cycle, error, and

proportional controller  $k_p$  are utilized to determine the duty cycle, The duty cycle must remain between 0 and 1. Nevertheless, the slip amount might be too large to handle this variety, particularly for the duration of the ascent. To maintain the duty cycle within the specified range, the error is increased by a coefficient. This constant has been selected as the ideal number that will never cause duty cycle to exceed its boundaries.  $k_p$  is set for the system to 0.01. Figure (3.5) depicts the system under investigation with the proposed MPPT approach.



**Figure 3.5:** Photovoltaic Panels with DC-DC Converter and MPPT.

### 3.1.4 DC-Link

Typically, an electrolytic capacitor serves as the DC-link capacitor, often referred to as power decoupling. As bus connection capacitors, electrolytic capacitors have been frequently utilized in inverter designs. For many years, electrolytic capacitors were the typical for strongly operated inverter bus link capacitors. Electrolytic capacitor design has stayed substantially unchanged over the years. The low cost per farad of electrolytic capacitors has made them appeal [59]. The DC-link capacitor is an essential part to achieve a long operating duration for the converter; therefore, it should be checked and, where possible, replaced with film capacitors. The DC-link capacitance of the inverter has been decreased by replacing electrolytic capacitors with more trustworthy, although more costly and larger film capacitors.

The difference between an electrolytic capacitor and a film capacitor is that the life of an electrolytic capacitor depends on its temperature. Due to their long lifespan and broad operating temperature range, film capacitors are a logical option. Since film capacitors are significantly more expensive per farad than electrolytic capacitors, the capacitance must be decreased to make the price reasonable. A smaller capacitance, in contrast, reduces the DC-link's ability to decouple power, which may result in DC-link voltage fluctuations that distort the inverter's output current to the grid. The transient DC fluctuation is caused by the quick increase/decrease of input power into the DC-link capacitor. This can be avoided by employing a current controller with a very fast response time. DC fluctuation is not a significant factor to consider while developing a VSI for solar applications. The grid-side double-line frequency ripple power is responsible for the second component, known as the AC fluctuation of the DC-link voltage-current reference signal, which can be substantially skewed due to the connection of a double-frequency vibration component across the control loop of the DC voltage. The capacitance of the bus connection is utilized in DC-to-AC inverters to eliminate inductance impacts which may be caused by the DC voltage source against the bridge. The leakage inductance is reduced by the capacitor of the bus-link, Eq. (3.5) of the inverter power bridge.

$$C_{dc} = \frac{p_{out}}{2\pi f \Delta v_{dc} v_{dc}} \quad (3.5)$$

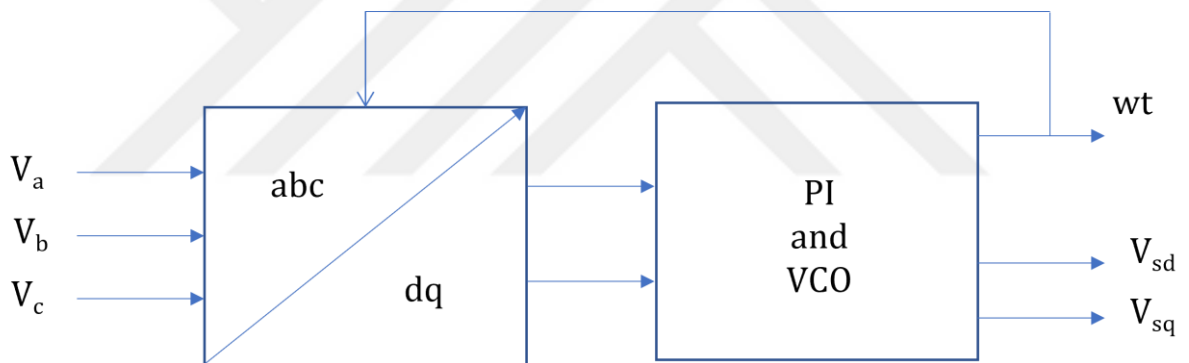
### 3.1.5 DC-AC inverter and filter

Switch Mode DC-AC inverters use pulse width modulation to create sinusoidal alternating current from direct current input. Both the value and frequency of the inverter's AC output could be changed. Voltage source inverters are inverters that accept an input from a DC voltage source (VSIs). Square-wave inverter, single-phase inverter, and PWM inverter with voltages elimination are the three available types of inverters [58]. The most prevalent type of inverter used in solar systems is a PWM inverter, which modifies the DC link current to keep a steady DC-link voltage. Both the control signal and the output voltage waveform must be sinusoidal to generate a sine output voltage waveform with the required frequency. And the wave form to which it is being compared has a triangular waveform. The switching frequency is normally fixed. There exists a more detailed example of DC-AC switch mode inverters [59]. Multilevel inverters have several benefits, such as less filter requirements at the same duty ratio, lower voltages or harmonic currents, and fewer electromagnetic fields [60]. Due to recent improvements in microprocessor technology, it is now simple to regulate multilevel inverters. Popularity has increased, especially in high-power settings. Modern inverters, on the other hand, need the inclusion of additional components, such as switching devices, capacitors, gate controllers, and more complex circuit topologies [60].

As previously indicated, solar PV electricity is frequently converted using a VSI system before being put into the grid. A suitable filter placed between the VSI system, and the network can reduce the harmonics inherent to the inverter's output voltage, thereby protecting the grid operator's power quality. The inductor L, inductor-capacitor LC, and inductor-capacitor-inductor LCL filters are the most prevalent filters, and each has its own advantages and disadvantages.

### 3.1.6 Phase-Locked Loop (PLL)

The phase-locked loop's function is to resolve the components of grid voltage, then deliver the rotational frequency, and the two components of voltage (direct and quadrature) for the location of the connection PCC. Various control frames in the photovoltaic power system use this information to control the system's production control signal. To avoid cross-coupling between active and reactive power, Phase-locked loop determines the rotation speed of the grid side vector by translating the result to  $dq$  reference component, after that, forcing voltage amplitude part to zero. Figure (3.6) illustrates how a proportional-integral PI controller accomplishes this objective. To get a quick settling time,  $(k_p)$  and  $(k_i)$  which are the main parameters of the controller were successively adjusted.



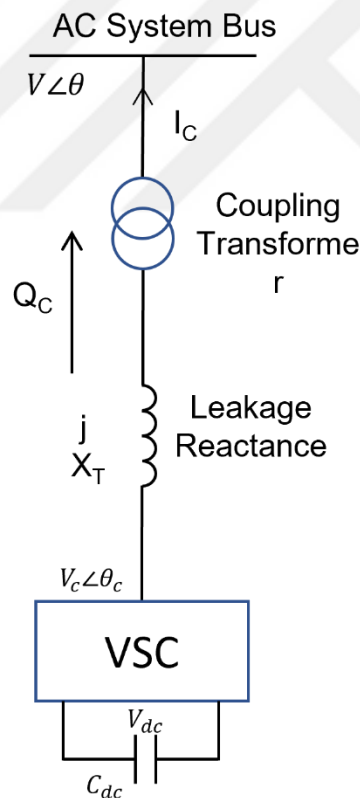
**Figure 3.6:** Representation of phase locked loop (PLL)

## 3.2 FACTS

Power electronics elements are combined with conventional power system components (such power transformer, reactor, switch, and capacitor) to create various schemes and combinations of FACTS devices (such as various types of transistors and thyristors).

### 3.2.1 FACTS device model (STATCOM)

The Figure below (3.7) depicts an illustrative fundamental schematic model of a FACTS device STATCOM coupled to power grid through a transformer. Maximum current compensation does not affect by network voltage value, allowing the device to operate with full capacity Regardless of the network voltage. The benefits of a STATCOM include variable voltage management for power features enhancement, rapid response, and application with fluctuating loads of large magnitude.



**Figure 3.7:** STATCOM model

The output of the controller's reactive power is controllable and is proportional to the voltage magnitude difference ( $V_c - V$ ) and provided by Eq. (3.6)

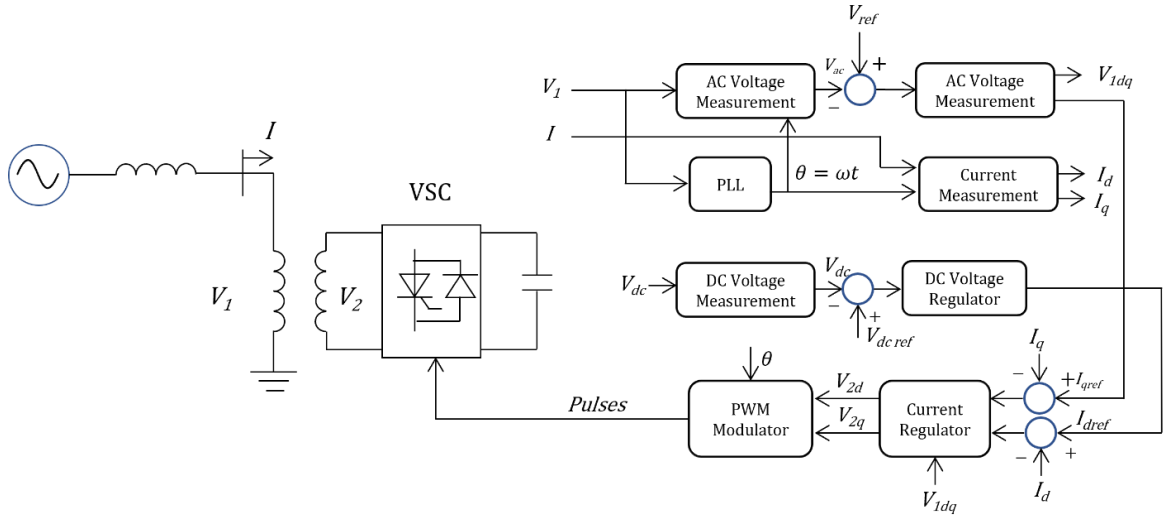
$$Q_c = \frac{V(V_c - V)}{X} \quad (3.6)$$

STATCOM's primary components include a step-down transformer, an inverter which consists of H-bridge installation of DC capacitor with IGBT and diode, and High-frequency filters. By regulating the magnitude of the output voltage with consideration to the phase shift of the VSC's output voltage, this system's control system keeps the level of the point voltage constant. By properly regulating  $i_q$ , it is possible to achieve reactive power exchange. The error in voltage is utilized to evaluate the reference for the active power to be replaced by the inverter.

STATCOM is a SVC with variable output whose output can be altered in order to keep and regulate electric network parameters. The STATCOM is a component of power electronics which is utilized for the active regulation of reactive power and grid stability. The reactive output power of the compensator is modified in order to regulate the voltage of the transmission terminals at a specific value, hence preserving the required power flows during potential system faults and contingency.

STATCOM can respond to temporary disturbances at a high speed and with superior performance in a low voltage condition compared to other compensators. The highest compensation current which is provided by the STATCOM is independent on the voltage of the network. Overall, a STATCOM delivers flexible voltage management, dampens oscillations in the network, and enhances the temporary stability of the system. Manipulating the phase angle regulates the capacity of the current which transfers between the STATCOM and the grid.

STATCOM is selected to be like a source of reactive power support due to its capacity to continually alter its susceptance though responding quickly and delivering power assistance at a particular point. The diagram of the STATCOM controller is depicted in Figure (3.8).



**Figure 3.8:** The diagram of the static synchronous compensator controller.

Adjusting the phase and amplitude of the STATCOM output permits regulation of transmission network between the network and the STATCOM.  $i_{dref}$  and  $i_{qref}$  are the reference currents in ( $dq$ ) components necessary to calculate the quantity of the reactive power to be supplied by the FACTS device as shown in Eq. (3.7) and Eq. (4.8).

$$P_{inj} = V_i(i_d \cos \theta_i + i_q \sin \theta_i) = v_d i_d + v_q i_q \quad (3.7)$$

$$Q_{inj} = V_i(i_d \sin \theta_i - i_q \cos \theta_i) = -v_d i_d + v_q i_q \quad (3.8)$$

where  $i_d$  and  $i_q$  are the system's references as  $d$  – axis and  $q$  – axis components. The control parameter is STATCOM's supplied current, and system's injected reactive power.

STATCOM ratings are based on numerous characteristics, the majority of which are regulated by the quantity of reactive power which is required by the system to improve network performance especially through common electrical system fault and to decrease losing connection of other network gear which may lose the sync with the grid. Even though the final capacity of the STATCOM is defined by the economics of the system, the capacity chosen will be adequate for the system to stabilize following temporary system disturbances. The size of the STATCOM is also determined by the failure types from

which the system is supposed to recover. For instance, a 3-phase impedance fault with low impedance demands STATCOM with a superior capability, whereas short circuit faults with high impedance require devices with low ratings to maintain the system during fault and aid in its recovery after fault. The current rating of the converter and the capacitor's size also determine STATCOM's capabilities.

Using a coupling transformer, the STATCOM could be attached to any voltage rating system. The device in the VSC is fixed versus overvoltages in the DC-link capacitor banks to reduce damages, also avoid having to resist big sparks during inverse overvoltage.

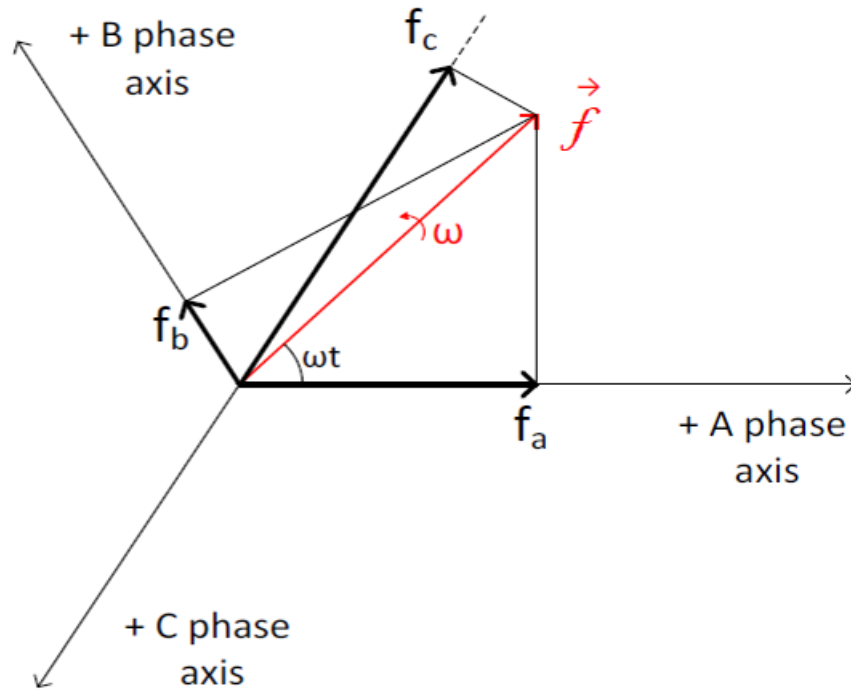
### 3.2.2 Where the STATCOM is located

According to simulation studies, STATCOM offers efficient voltage assistance for the network to which it is attached. For different reasons, the STATCOM is located at the nearest point or feasible to the load bus. So, the support should be near to the location where is required. Second, in the examined test system, the load bus is the optimal placement for the STATCOM since the voltage change effect is greatest at this place.

The position of the STATCOM is determined by a measurable calculation of advantages. Reduced losses and greater maximum transfer capacity are the primary advantages of having a STATCOM in the network. Typically, the location of STATCOM is determined by its location in the network that requires compensation. Placing a STATCOM at a specific point in the network will decrease the reactive power movement over transmission line, hence decreasing the losses  $I^2R$  of the line. Transporting reactive power at lower voltage in network operating near to the limit of stability may be inefficient. In addition, the transmission line power factor limiting factors will influence the overall amount of reactive power transfer possible. Since the ratio  $(\frac{\Delta V}{V_{nom}})$  would be greater for PCC during fault condition, suppliers and compensation device are continually placed at nearest point to the consumers.

### 3.2.3 *abc* to *dq* Frame Transformation

Voltage, current, and flux linkage, the three phase electrical variables, this can be described as a trajectory. Figure illustrates the vector form of momentary three phase components in a fixed *abc* reference frame (3.9) [61], [62].



**Figure 3.9:** 3-Phase electrical variable in vector representation.

The space vector  $\vec{f}$  is denoted by Eq. (3.9) :

$$\vec{f}(t) = \frac{2}{3} \left( f_a(t) + f_b(t)e^{j\frac{2\pi}{3}} + f_c(t)e^{-j\frac{2\pi}{3}} \right) \quad (3.9)$$

Where  $f_a(t)$ ,  $f_b(t)$  and  $f_c(t)$  shown in Eq. (3.10), (3.11), and (3.12)

$$f_a(t) = A \cos(\omega t) \quad (3.10)$$

$$f_b(t) = A \cos\left(\omega t - \frac{2\pi}{3}\right) \quad (3.11)$$

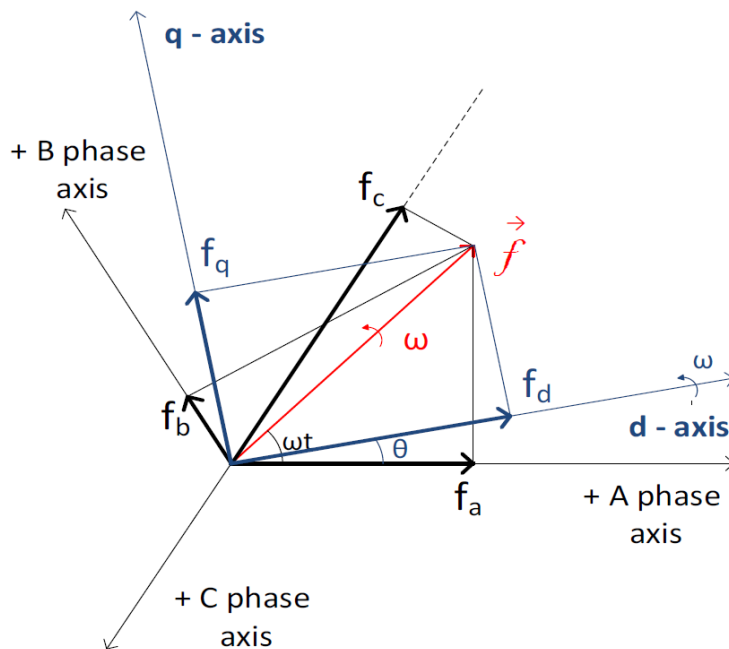
$$f_c(t) = A \cos\left(\omega t - \frac{4\pi}{3}\right) \quad (3.12)$$

The variable  $A$  is the amount of physical quantity and  $\omega$  is the rotational velocity of that quantity (377 rad/sec). it spins with a velocity of relative to a fixed structure of reference. the three-phase variable of a stationary  $abc$  reference frame could translate in to double

form quantities in a rotating  $d - axis$  and  $q - axis$  components. This  $dq$  structure spins at the equal rate as the vector of space. The transformation occurs as follows in Eq. (3.13) and Eq. (3.14) [63]:

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ -\sin(\omega t) & -\sin\left(\omega t - \frac{2\pi}{3}\right) & -\sin\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} f_a(t) \\ f_b(t) \\ f_c(t) \end{bmatrix} \quad (3.13)$$

where the components of space vector along direct and quadrature axes are  $f_d$  and  $f_q$  respectively.



**Figure 3.10:** 3-phase electrical variable in  $abc$  frame and  $dq$  frame.

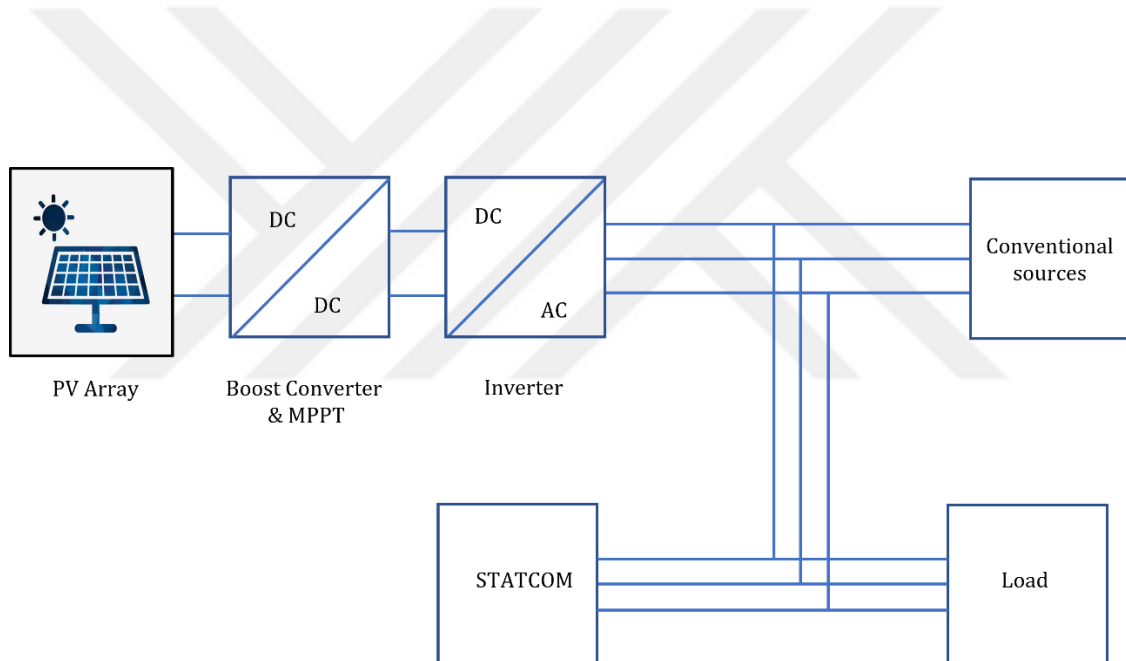
The transformation results in  $f_d$  and  $f_q$  being DC Features. The space trajectory  $f(t)$  may therefore represented as in Eq. (3.14):

$$f(t) = (f_d + jf_q)e^{j\omega t} \quad (3.14)$$

Figure (3.10) displays the space trajectory  $f(t)$  in  $abc$  terms and  $dq$ . The instant angle between the axes is denoted by  $\theta$ . The  $dq$  coordination spins with velocity in velocity of  $\omega = \frac{d\theta}{dt}$ .

### 3.3 THE PROPOSED SYSTEM WITH CONTROL SCHEME

The simulation is done with support of MATLAB Simulink. Figure (3.11) below, shows an illustration of the entire proposed system, which contains a 100 KW photovoltaic plant, a conventional source, a STATCOM, and a load.

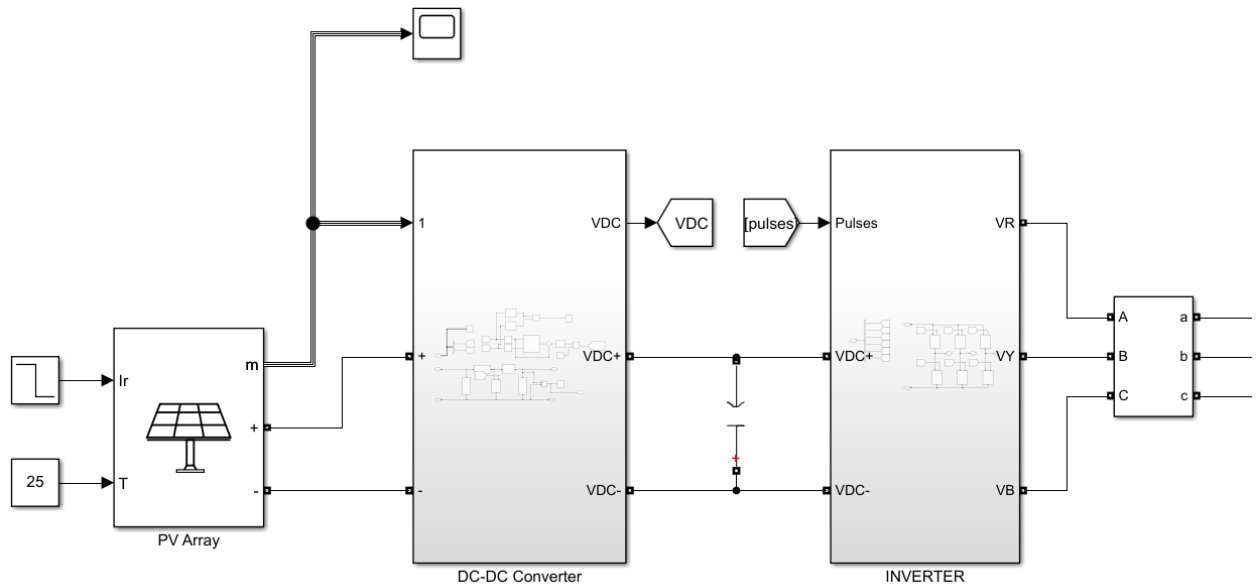


**Figure 3.11:** Illustration of the proposed system configuration.

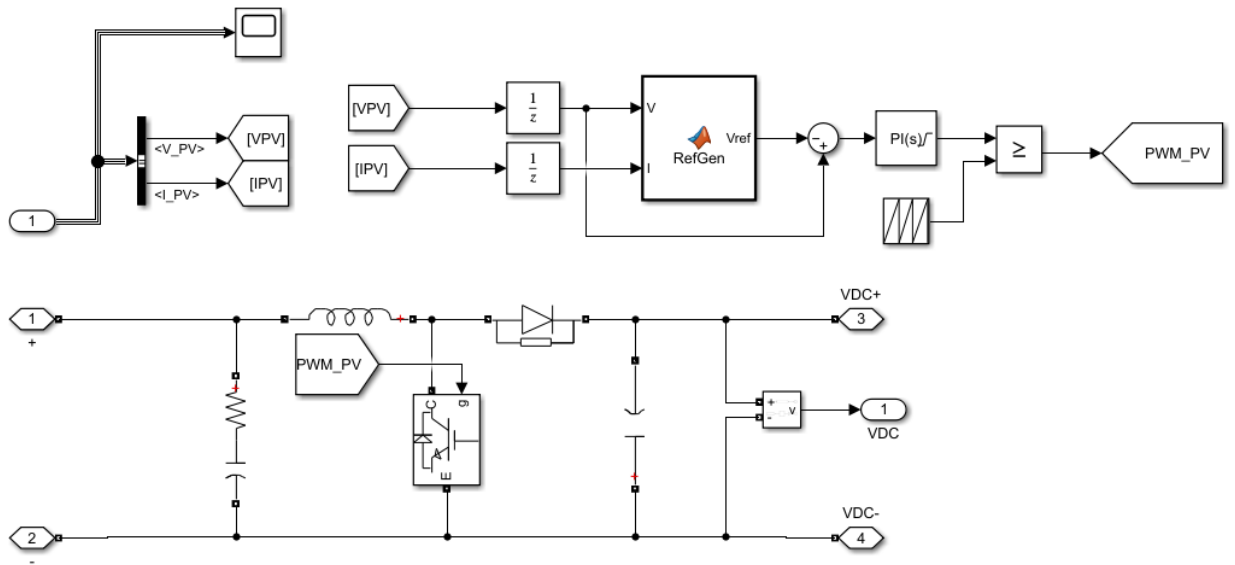
#### 3.3.1 Renewable energy source

The main part of the system is a 100 KW photovoltaic array plant, connected with a DC-DC converter with a MPPT algorithm to supply an inverter. The inverter delivers the power of the photovoltaic plant to the network. The Figure (3.12) below reveals the

configuration of the different parts. Also, the control scheme which is shown in Figure (3.16). the DC-DC converter with the MPPT algorithm is illustrated in Figure (3.13), with controller arrangement of DC converter.

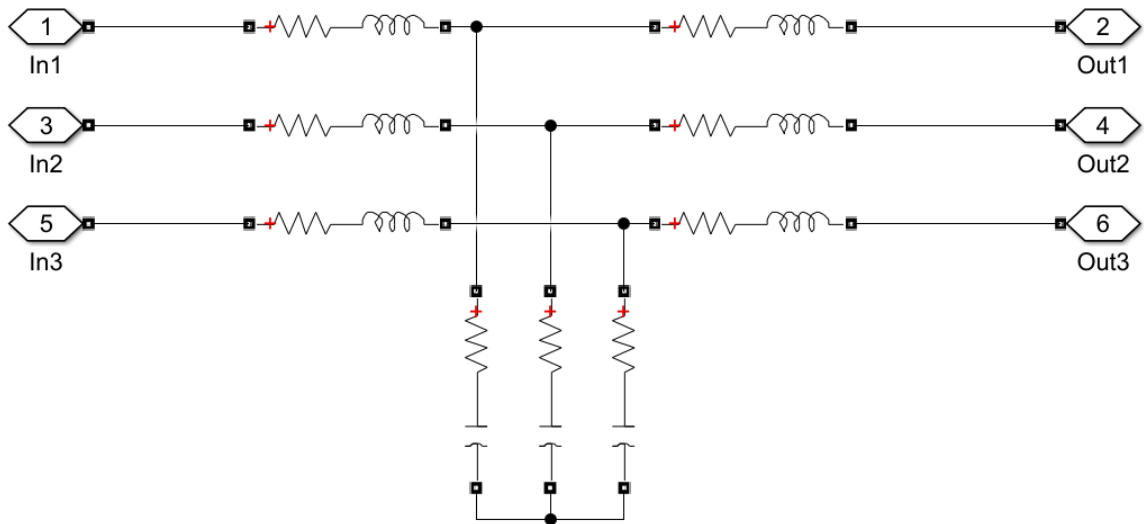


**Figure 3.12:** Photovoltaic system in Simulink.



**Figure 3.13:** DC-DC converter with MPPT in Simulink.

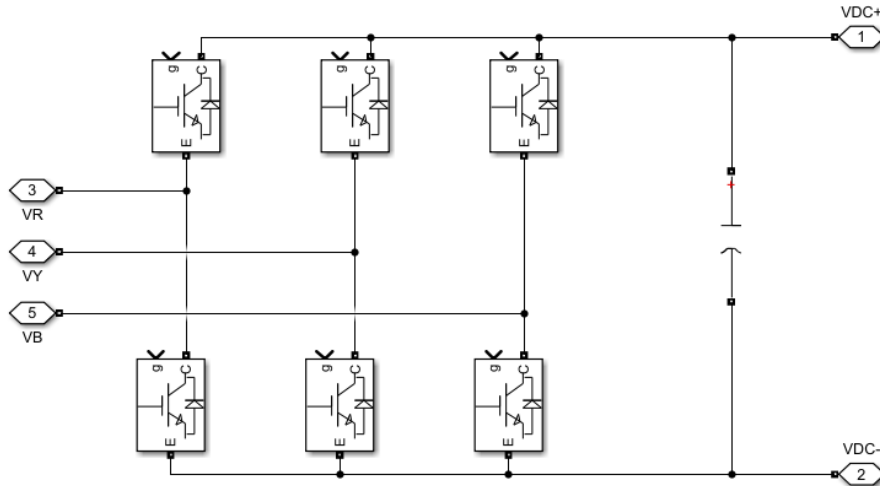
Then, the AC power filtered by a LCL filter, as shown in the Figure (3.14). Which reduces the impact of harmonic distortions.



**Figure 3.14:** LCL filter in Simulink.

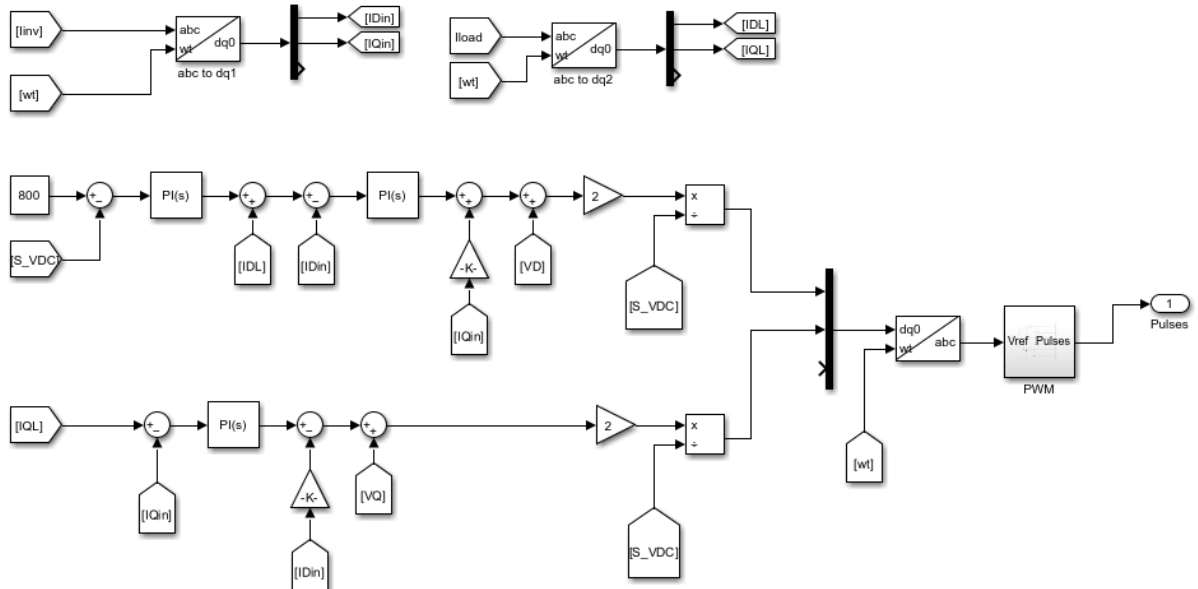
### 3.3.2 STATCOM

The STATCOM system is shown in Figure (3.15), which consists of a capacitor and IGBTs, attached to the main grid through LCL-filter which tries to decrease the harmonic distortions.



**Figure 3.15:** STATCOM Capacitor with Inverter in Simulink.

The controller diagram of the STATCOM is shown in Figure (3.16) below,



**Figure 3.16:** Control Scheme of the STATCOM in Simulink.

### 3.3.3 Load

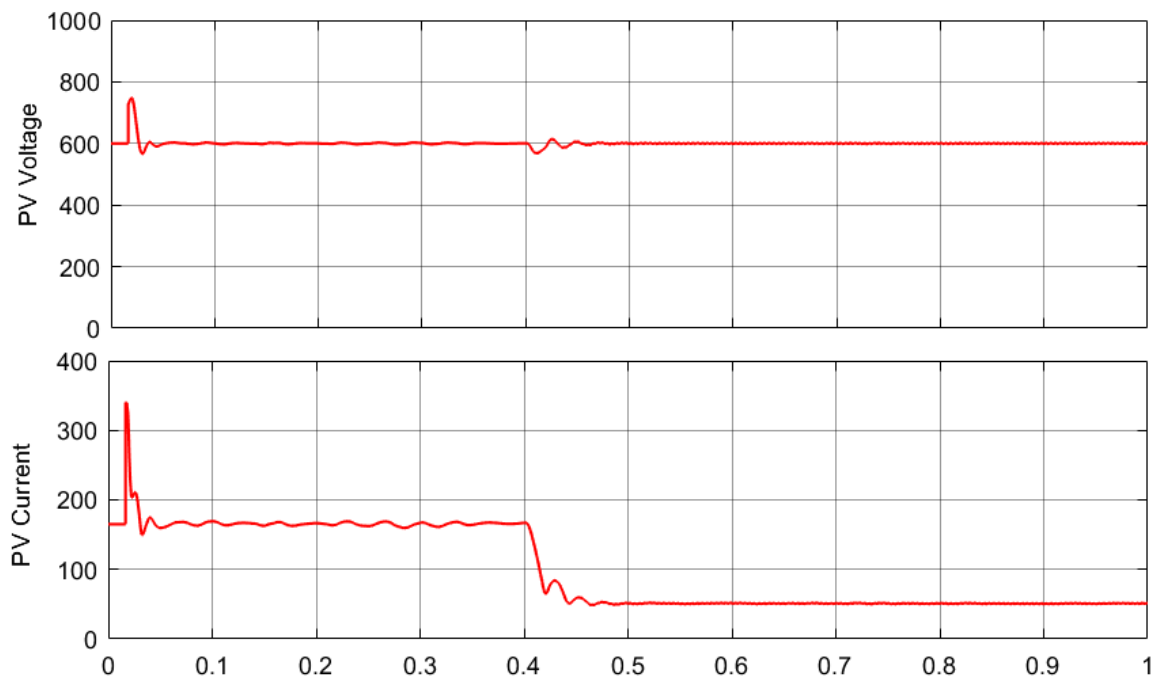
The simulated grid-connected PV system contains both nonlinear and linear demands. Current and voltage sine waves are represented by a waveform. Consider a waveform in which the voltage and current are represented by pure, 50 Hz sine waves. When a linear load is present, the waveforms of the current and voltage appear identical. Nonlinear loads have an impedance that fluctuates in response to the applied voltage. Due to the alteration in impedance, the current will no longer be sinusoidal. Harmonic characteristics of these non-sinusoidal currents create voltage distortion in the power supply and connected devices.

## 4. SIMULATION AND RESULT

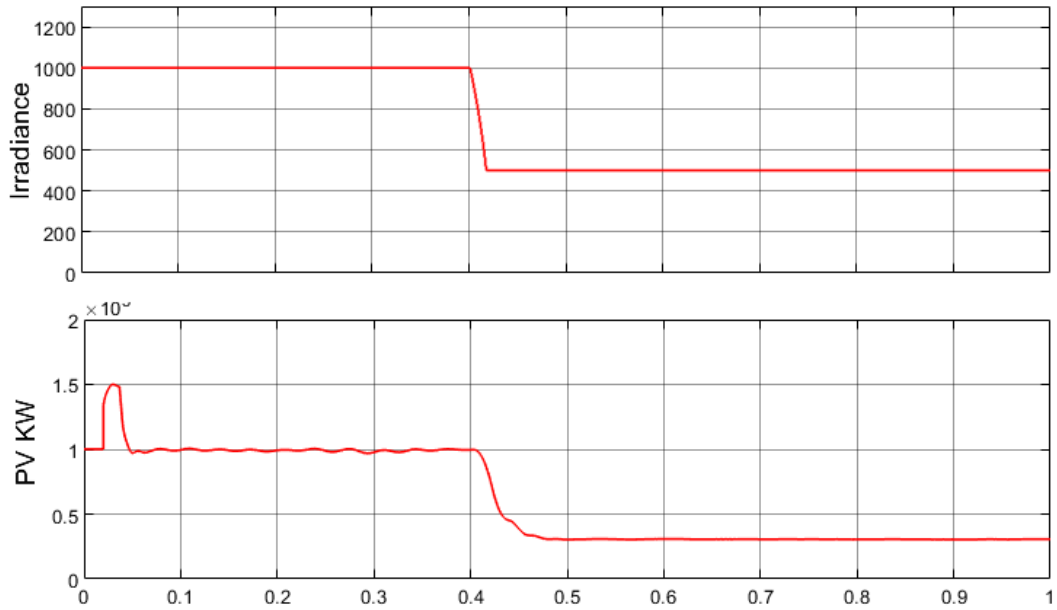
Modeling and simulating a grid-connected photovoltaic plant with a STATCOM by the MATLAB software. Many scenarios or conditions were utilized to get the conclusions and non-linear loads, wherein in the starting duration the solar system functions at full power and so supplies the loads with the necessary energy. The remainder of the energy is introduced into the network. In the middle of the simulation time, the solar system capacity decreased to a specific amount that supply the loads without increasing the capacity going to the grid, the solar system does not function at night or when there are clouds, thus the network supplies the necessary energy to the loads.

### 4.1 PV ARRAY PLANT

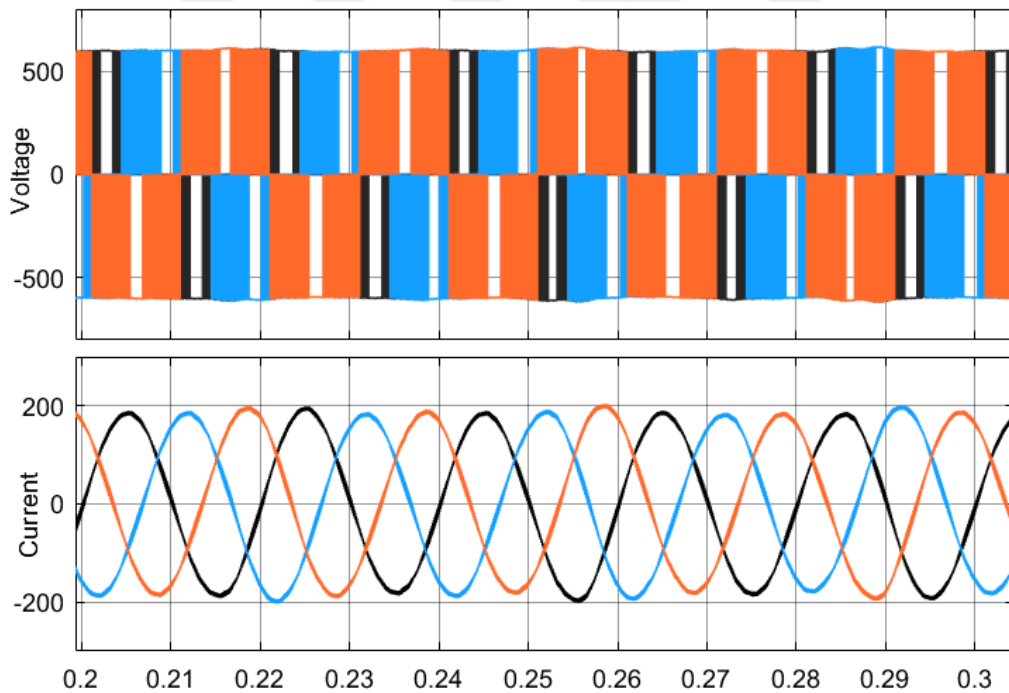
The photovoltaic plant is designed and simulated utilizing MATLAB software. The grid-connected solar energy system is comprised of 47 parallel strings, with each string delivering 2.13 kW of rated power and the 47 parallel strings total 100 kW of nominal capacity. As the whole PV plant contains a DC-DC boost converter.



**Figure 4.1:** Output voltage (V) and current (I) of PV system.

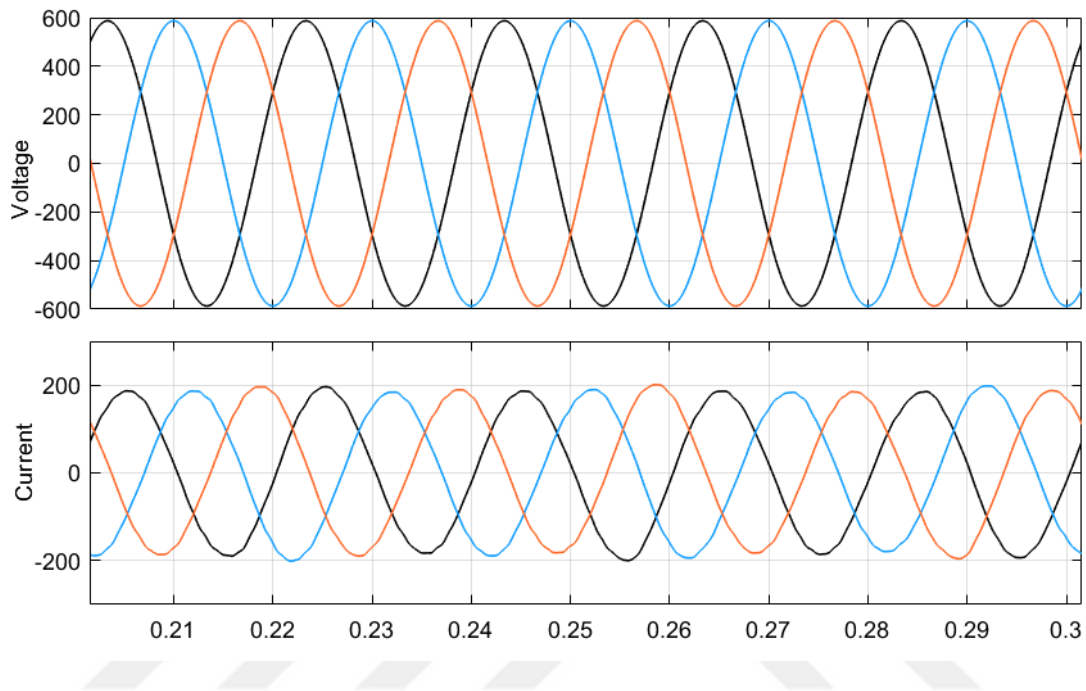


**Figure 4.2:** Irradiance ( $w/m^2$ ) and output power (watts) of the PV system.



**Figure 4.3:** Voltage and current of photovoltaic system before inductor-capacitor-inductor LCL filter.

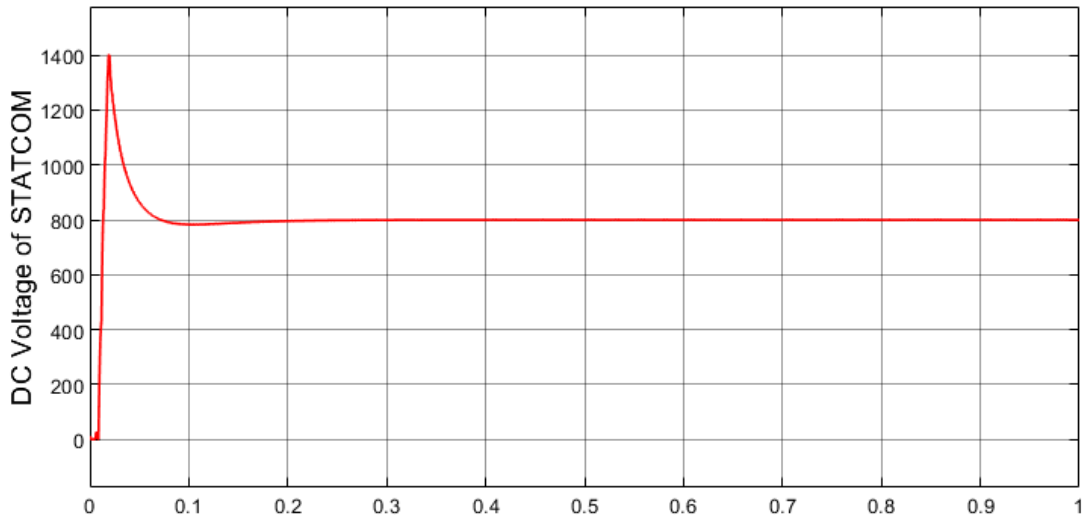
Figure (4.3) depicts the output voltage and current waveforms of the inverter based on the method stated within Section 3, harmonics are clearly present in both voltage and current, which required treatment. The LCL filter is used to overcome this issue. Figure (4.4) shows the output voltages after passing directly through the LCL filter.



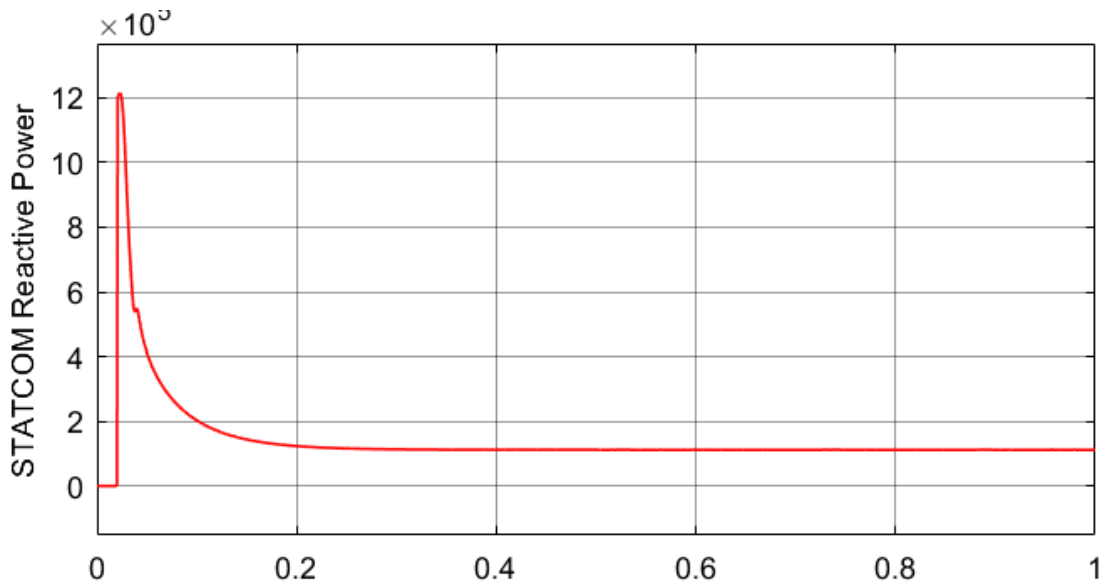
**Figure 4.4:** Voltage and current of photovoltaic system with inductor-capacitor-inductor LCL filter.

## 4.2 STATCOM

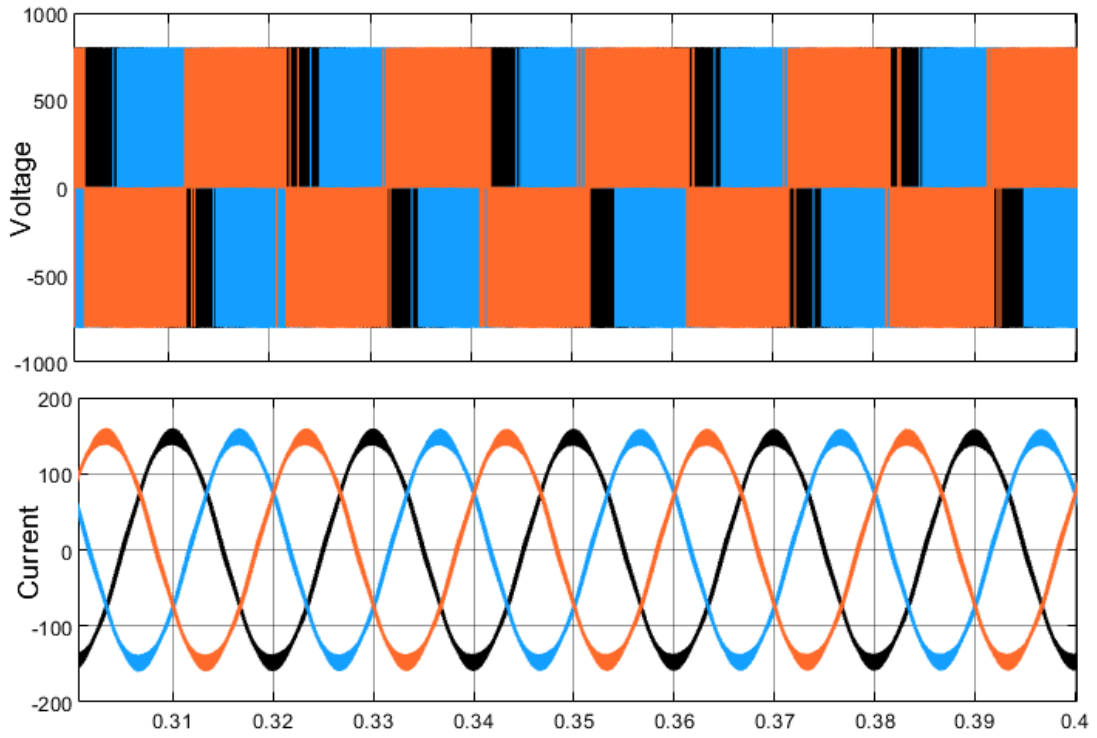
The DC voltage of the STATCOM's capacitor is displayed in the figure below (4.5), which remains constant through the simulation duration and does not change. Figure (4.6) shows the STATCOM's reactive power (delivered and received) by the.



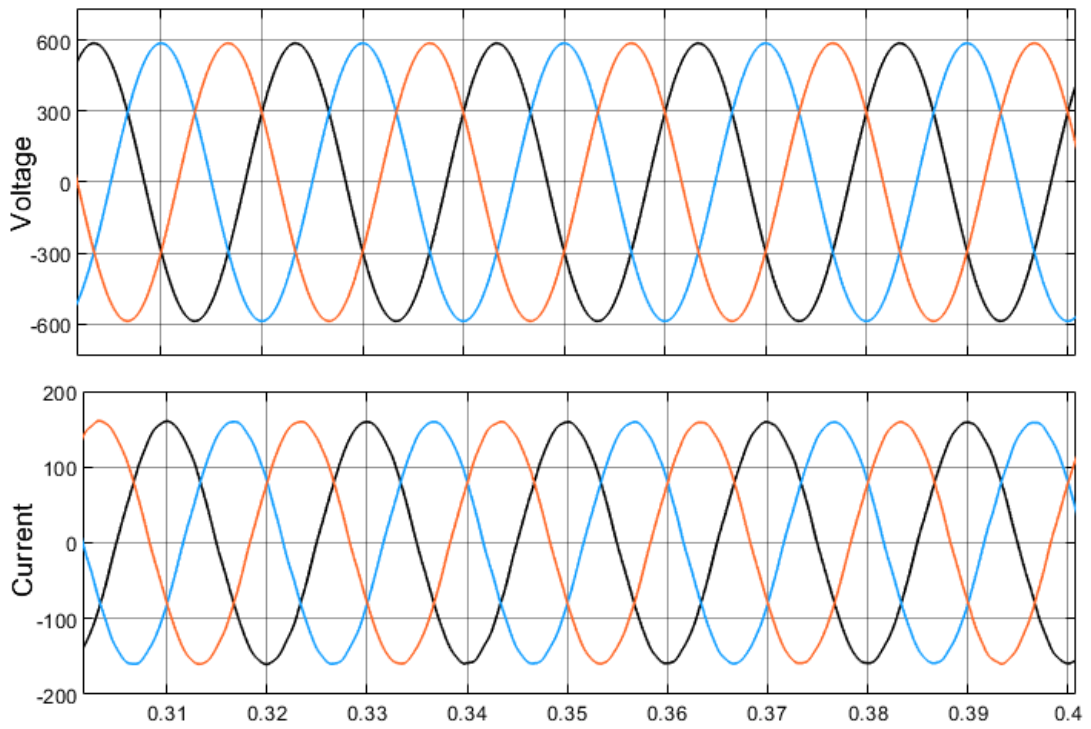
**Figure 4.5:** STATCOM's DC voltage.



**Figure 4.6:** Reactive VAR delivered by STATCOM to the grid.



**Figure 4.7:** STATCOM's voltage and current before the LCL filter.



**Figure 4.8:** STATCOM's voltage and current with the LCL filter.

### 4.3 LOAD RESULTS

The load consumes a constant power despite the source of that generation, at the first, the load receives its power from the photovoltaic array plant, but when the sun irradiance decreases to its 50%, the load starts to treat this deficiency from the conventional power system.

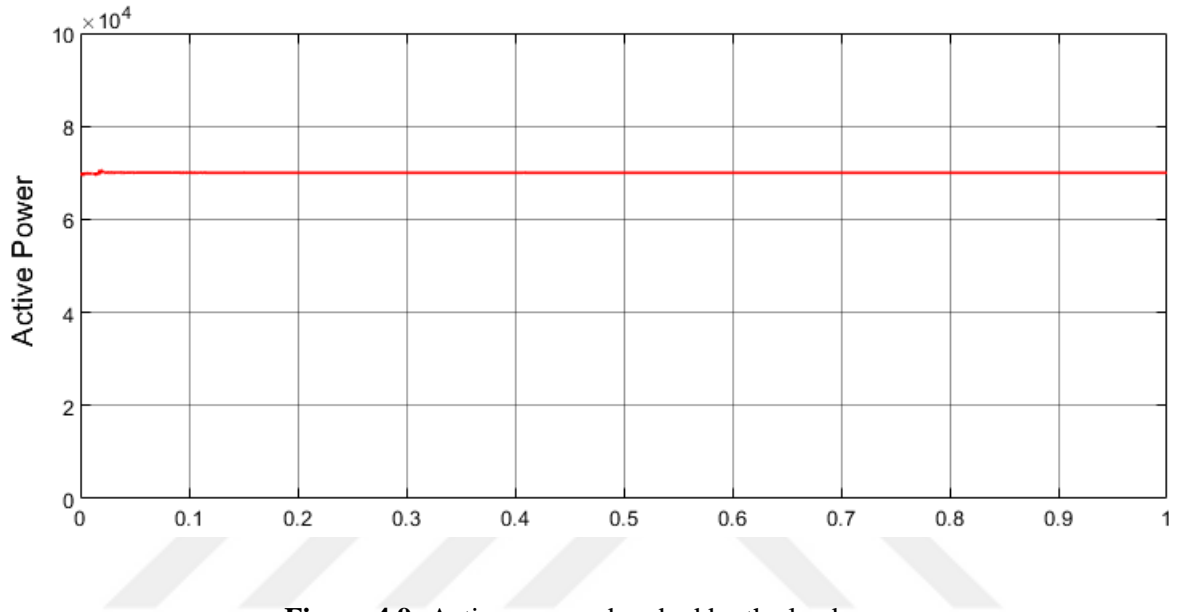


Figure 4.9: Active power absorbed by the load.

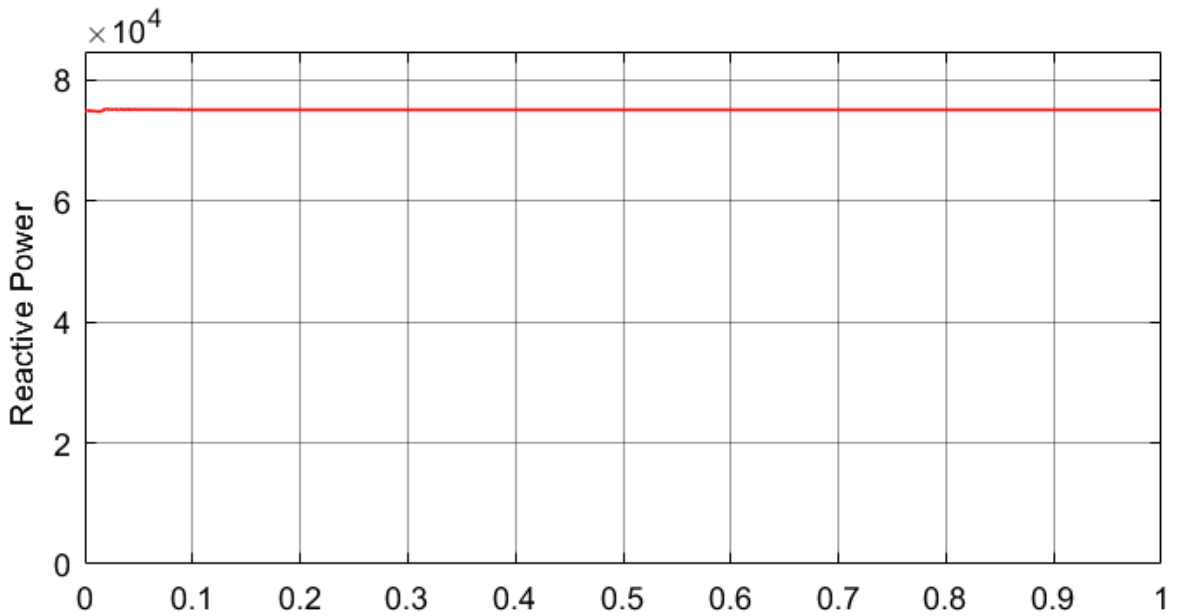
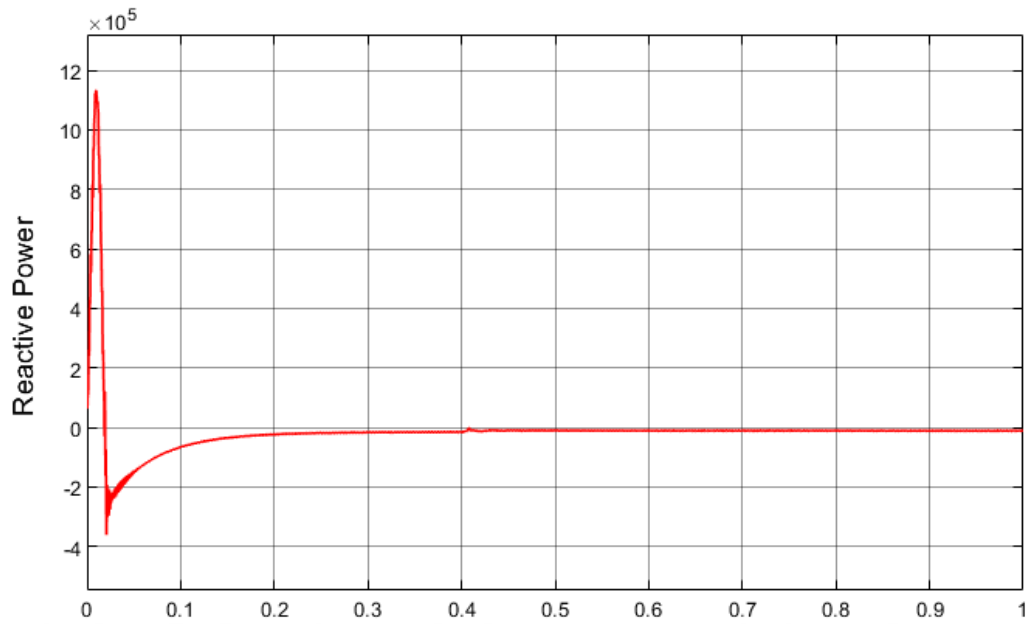


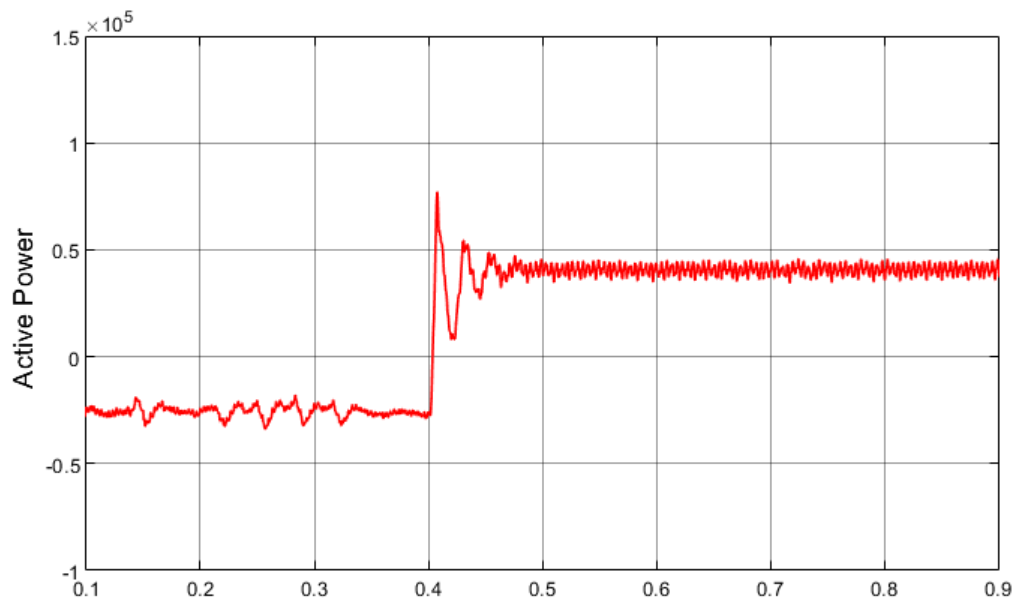
Figure 4.10: Reactive power absorbed by the load.

#### 4.4 GRID RESULTS

Through the simulation, the grid receives power from the photovoltaic plant. but at 0.4 of the simulation time, the sun irradiance was decreased to 0.4 of its value which make the power generated by the renewable energy source decreased. So, the direction of power inversed.



**Figure 4.11:** Reactive power delivered by the grid.



**Figure 4.12:** Active power delivered/received by the grid.

## **5. CONCLUSION AND DISCUSSION**

### **5.1 CONCLUSION**

The presented work is oriented to power compensation of inductive loads and an integration of a photovoltaic energy to the network, the utilizing of a STATCOM to minimize the effects of increasing use of inductive loads, application of intelligent control in oscillation damping using FACTS STATCOM. With the application of the methodology proposed in this work also to combine the renewable energy source into the network and find a way to operate together under the same criteria. Adding renewable energy sources, for instance wind turbine or photovoltaic solar plant that produce no greenhouse gas emissions and reduces some types of air pollution is currently an objective.

Stable responses were obtained for nominal operating conditions and low load, obtaining the shortest settling time when the system is at points close to the nominal operating condition. The effectiveness of heuristically adjusted STATCOM oscillation controllers, which provide compensation for the reactive load.

### **5.2 FUTURE WORK**

According to the results and information compiled in this thesis, some criteria are established to be used as a reference in upcoming works connected to integrate a renewable energy source grid-connected with a FACTS device to achieve voltage regulation, reactive power compensation, and stability, such as:

- a. Apply intelligent control in FACTS devices STATCOM, which allows active and reactive power controls.
- b. Adding a different renewable energy source like wind energy or hydropower source.
- c. Apply the proposed methodology in large-scale systems with real characteristics, to evaluate their behavior and performance considering FACTS devices.

## REFERENCES

- [1] R. J. Sarfi, M. M. A. Salama, and A. Y. Chikhani, "A survey of the state of the art in distribution system reconfiguration for system loss reduction," *Electric Power Systems Research*, vol. 31, no. 1, pp. 61–70, Oct. 1994, doi: 10.1016/0378-7796(94)90029-9.
- [2] R. A. Gallego, A. J. Monticelli, and R. Romero, "Optimal capacitor placement in radial distribution networks," *IEEE Transactions on Power Systems*, vol. 16, no. 4, pp. 630–637, 2001, doi: 10.1109/59.962407.
- [3] R. Natesan and G. Radman, "Effects of statcom, sssc and upfc on voltage stability," in *Thirty-Sixth Southeastern Symposium on System Theory, 2004. Proceedings of the*, pp. 546–550. doi: 10.1109/SSST.2004.1295718.
- [4] Snehal B. Sahare and U. G. Bonde, "Transient Stability Enhancement in Multi-Machine Power System by using Power System Stabilizer (Pss) and Static Var Compensator (Svc)," *International Journal of Engineering Research and*, vol. V9, no. 02, Feb. 2020, doi: 10.17577/IJERTV9IS020068.
- [5] A. Kazemi, V. Vahidinasab, and A. Mosallanejad, "Study of STATCOM and UPFC Controllers for Voltage Stability Evaluated by Saddle-Node Bifurcation Analysis," in *2006 IEEE International Power and Energy Conference*, Nov. 2006, pp. 191–195. doi: 10.1109/PECON.2006.346644.
- [6] A. Sode-Yome, N. Mithulananthan, and K. Y. Lee, "Static Voltage Stability Margin Enhancement Using STATCOM, TCSC and SSSC," in *2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific*, pp. 1–6. doi: 10.1109/TDC.2005.1547141.
- [7] C. A. Cañizares, C. Cavallo, M. Pozzi, and S. Corsi, "Comparing secondary voltage regulation and shunt compensation for improving voltage stability and transfer capability in the Italian power system," *Electric Power Systems Research*, vol. 73, no. 1, pp. 67–76, Jan. 2005, doi: 10.1016/j.epsr.2004.06.005.

- [8] Heinz. K. Tyll and F. Schettler, "Power system problems solved by FACTS devices," in *2009 IEEE/PES Power Systems Conference and Exposition*, Mar. 2009, pp. 1–5. doi: 10.1109/PSCE.2009.4840205.
- [9] R. Dehini, C. Benachaiba, and A. Bassou, "Simulation of Distribution Static Compensator (D-STATCOM) to Improve Power Quality," *Arab J Sci Eng*, vol. 38, no. 11, pp. 3051–3058, Nov. 2013, doi: 10.1007/s13369-012-0461-5.
- [10] C.-F. Chang, "Reconfiguration and Capacitor Placement for Loss Reduction of Distribution Systems by Ant Colony Search Algorithm," *IEEE Transactions on Power Systems*, vol. 23, no. 4, pp. 1747–1755, Nov. 2008, doi: 10.1109/TPWRS.2008.2002169.
- [11] N.G. Hingorani and L. Gyugyi, *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*. New York: Wiley-IEEE Press, 1999.
- [12] W. Zhang, "Optimal Sizing and Location of Static and Dynamic Reactive Power Compensation," 2007.
- [13] M. Molinas, S. Vazquez, T. Takaku, J. M. Carrasco, R. Shimada, and T. Undeland, "Improvement of transient stability margin in power systems with integrated wind generation using a STATCOM: an experimental verification," in *2005 International Conference on Future Power Systems*, 2005, pp. 6 pp. – 6. doi: 10.1109/FPS.2005.204256.
- [14] "MMC." <https://www.siemens-energy.com/global/en/offerings/power-transmission/portfolio/high-voltage-direct-current-transmission-solutions/hvdc-plus.html> (accessed Sep. 28, 2022).
- [15] B. Singh, S. S. Murthy, and S. Gupta, "A Stand-Alone Generating System Using Self-Excited Induction Generators in the Extraction of Petroleum Products," *IEEE Trans Ind Appl*, vol. 46, no. 1, pp. 94–101, 2010, doi: 10.1109/TIA.2009.2036519.
- [16] "ABB Datasheet." <https://new.abb.com/ca> (accessed Sep. 28, 2022).

- [17] B. Singh, S. S. Murthy, and R. S. R. Chilipi, "STATCOM-Based Controller for a Three-Phase SEIG Feeding Single-Phase Loads," *IEEE Transactions on Energy Conversion*, vol. 29, no. 2, pp. 320–331, 2014, doi: 10.1109/TEC.2014.2299574.
- [18] P. Jaiswal, S. K. Srivastava, and K. B. Sahay, "Modeling & simulation of proposed 100 KW solar PV array power plant for MMMUT Gorakhpur," in *2016 International Conference on Emerging Trends in Electrical Electronics & Sustainable Energy Systems (ICETEESES)*, Mar. 2016, pp. 261–266. doi: 10.1109/ICETEESES.2016.7581391.
- [19] Y. Li, Y. Chi, X. Wang, X. Tian, and J. Jianqing, "Practices and Challenge on Planning with Large-scale Renewable Energy Grid Integration," in *2019 IEEE 3rd Conference on Energy Internet and Energy System Integration (EI2)*, Nov. 2019, pp. 118–121. doi: 10.1109/EI247390.2019.9062091.
- [20] J. Dixon, L. Moran, J. Rodriguez, and R. Domke, "Reactive Power Compensation Technologies: State-of-the-Art Review," *Proceedings of the IEEE*, vol. 93, no. 12, pp. 2144–2164, Dec. 2005, doi: 10.1109/JPROC.2005.859937.
- [21] R. A. Otto, T. H. Putman, and L. Gyugyi, "Principles and Applications of Static, Thyristor-Controlled Shunt Compensators," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-97, no. 5, pp. 1935–1945, Sep. 1978, doi: 10.1109/TPAS.1978.354690.
- [22] R. Adware and V. Chandrakar, "Power Quality Enhancement through Reactive Power Compensation Using Hybrid STATCOM," in *2022 Second International Conference on Power, Control and Computing Technologies (ICPC2T)*, Mar. 2022, pp. 1–5. doi: 10.1109/ICPC2T53885.2022.9777006.
- [23] S. Chattopadhyay, M. Mitra, and S. Sengupta, *Electric Power Quality*. Dordrecht: Springer Netherlands, 2011. doi: 10.1007/978-94-007-0635-4.
- [24] S. M. Tripathi and P. J. Barnawal, "Design and Control of a STATCOM for Non-Linear Load Compensation: A Simple Approach," *Electrical, Control and Communication Engineering*, vol. 14, no. 2, pp. 172–184, Dec. 2018, doi: 10.2478/ecce-2018-0021.

- [25] M. M. Afzal *et al.*, “A Comparative Study of Supercapacitor-Based STATCOM in a Grid-Connected Photovoltaic System for Regulating Power Quality Issues,” *Sustainability*, vol. 12, no. 17, p. 6781, Aug. 2020, doi: 10.3390/su12176781.
- [26] H. Bakir and A. A. Kulaksiz, “Modelling and voltage control of the solar-wind hybrid micro-grid with optimized STATCOM using GA and BFA,” *Engineering Science and Technology, an International Journal*, vol. 23, no. 3, pp. 576–584, Jun. 2020, doi: 10.1016/j.jestch.2019.07.009.
- [27] O. A. Coronado de Koster, J. S. Artal-Sevil, and J. A. Dominguez-Navarro, “Multi-type FACTS location in a microgrid,” in *2020 Fifteenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Sep. 2020, pp. 1–5. doi: 10.1109/EVER48776.2020.9243070.
- [28] S. Kirmani and B. Kumar, “Power quality improvement by using STATCOM control scheme in wind energy generation interface to grid,” *IOP Conf Ser Earth Environ Sci*, vol. 114, p. 012001, Jan. 2018, doi: 10.1088/1755-1315/114/1/012001.
- [29] R. K. Varma and R. Salehi, “SSR Mitigation With a New Control of PV Solar Farm as STATCOM (PV-STATCOM),” *IEEE Trans Sustain Energy*, vol. 8, no. 4, pp. 1473–1483, Oct. 2017, doi: 10.1109/TSTE.2017.2691279.
- [30] J. Kumar, A. K. Jaiswal, A. Agarwal, and N. Singh, “Power Quality Improvement of a Grid Connected Wind Energy Conversion System Using Fuzzy Logic Controlled STATCOM,” in *2022 2nd International Conference on Power Electronics & IoT Applications in Renewable Energy and its Control (PARC)*, Jan. 2022, pp. 1–6. doi: 10.1109/PARC52418.2022.9726548.
- [31] T. S. Saradhisatwik, Gankidinishma, U. Hemanthchandra, V. Sailaja, and R. Mahalakshmi, “Power Quality Improvement in Solar Powered Standalone System using D-STATCOM,” in *2022 4th International Conference on Smart Systems and Inventive Technology (ICSSIT)*, Jan. 2022, pp. 593–596. doi: 10.1109/ICSSIT53264.2022.9716537.
- [32] M. Hans and V. Kamble, “Implementation of Hybrid STATCOM System for Power System Performance Enhancement,” in *2020 International Conference on Smart*

- Electronics and Communication (ICOSEC)*, Sep. 2020, pp. 1050–1054. doi: 10.1109/ICOSEC49089.2020.9215337.
- [33] R. K. Varma and H. Maleki, “PV Solar System Control as STATCOM (PV-STATCOM) for Power Oscillation Damping,” *IEEE Trans Sustain Energy*, vol. 10, no. 4, pp. 1793–1803, Oct. 2019, doi: 10.1109/TSTE.2018.2871074.
- [34] R. K. Varma and E. M. Siavashi, “PV-STATCOM: A New Smart Inverter for Voltage Control in Distribution Systems,” *IEEE Trans Sustain Energy*, vol. 9, no. 4, pp. 1681–1691, Oct. 2018, doi: 10.1109/TSTE.2018.2808601.
- [35] H. Patel and V. Agarwal, “MATLAB-Based Modeling to Study the Effects of Partial Shading on PV Array Characteristics,” *IEEE Transactions on Energy Conversion*, vol. 23, no. 1, pp. 302–310, Mar. 2008, doi: 10.1109/TEC.2007.914308.
- [36] I. H. Altas and A. M. Sharaf, “A Photovoltaic Array Simulation Model for Matlab-Simulink GUI Environment,” in *2007 International Conference on Clean Electrical Power*, May 2007, pp. 341–345. doi: 10.1109/ICCEP.2007.384234.
- [37] N. Pandiarajan, R. Ramaprabha, and R. Muthu, “Application of Circuit Model for Photovoltaic Energy Conversion System,” *International Journal of Photoenergy*, vol. 2012, pp. 1–14, 2012, doi: 10.1155/2012/410401.
- [38] R. Gules, J. de Pellegrin Pacheco, H. L. Hey, and J. Imhoff, “A Maximum Power Point Tracking System With Parallel Connection for PV Stand-Alone Applications,” *IEEE Transactions on Industrial Electronics*, vol. 55, no. 7, pp. 2674–2683, Jul. 2008, doi: 10.1109/TIE.2008.924033.
- [39] B. Subudhi and R. Pradhan, “A Comparative Study on Maximum Power Point Tracking Techniques for Photovoltaic Power Systems,” *IEEE Trans Sustain Energy*, vol. 4, no. 1, pp. 89–98, Jan. 2013, doi: 10.1109/TSTE.2012.2202294.
- [40] M. A. Eltawil and Z. Zhao, “MPPT techniques for photovoltaic applications,” *Renewable and Sustainable Energy Reviews*, vol. 25, no. C, pp. 793–813, 2013,

[Online].

Available:

<https://EconPapers.repec.org/RePEc:eee:rensus:v:25:y:2013:i:c:p:793-813>

- [41] A. Reza Reisi, M. Hassan Moradi, and S. Jamasb, "Classification and comparison of maximum power point tracking techniques for photovoltaic system: A review," *Renewable and Sustainable Energy Reviews*, vol. 19, pp. 433–443, Mar. 2013, doi: 10.1016/j.rser.2012.11.052.
- [42] J. P. Ram, T. S. Babu, and N. Rajasekar, "A comprehensive review on solar PV maximum power point tracking techniques," *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 826–847, Jan. 2017, doi: 10.1016/j.rser.2016.09.076.
- [43] Z. Salam, J. Ahmed, and B. S. Merugu, "The application of soft computing methods for MPPT of PV system: A technological and status review," *Appl Energy*, vol. 107, pp. 135–148, Jul. 2013, doi: 10.1016/j.apenergy.2013.02.008.
- [44] D. Baimel, S. Tapuchi, Y. Levron, and J. Belikov, "Improved Fractional Open Circuit Voltage MPPT Methods for PV Systems," *Electronics (Basel)*, vol. 8, no. 3, p. 321, Mar. 2019, doi: 10.3390/electronics8030321.
- [45] H. A. Sher, A. F. Murtaza, A. Noman, K. E. Addoweesh, K. Al-Haddad, and M. Chiaberge, "A New Sensorless Hybrid MPPT Algorithm Based on Fractional Short-Circuit Current Measurement and P&O MPPT," *IEEE Trans Sustain Energy*, vol. 6, no. 4, pp. 1426–1434, Oct. 2015, doi: 10.1109/TSTE.2015.2438781.
- [46] Hyeong-Ju Noh, Dong-Yun Lee, and Dong-Seok Hyun, "An improved MPPT converter with current compensation method for small scaled PV-applications," in *IEEE 2002 28th Annual Conference of the Industrial Electronics Society. IECON 02*, pp. 1113–1118. doi: 10.1109/IECON.2002.1185428.
- [47] Jiyong Li and Honghua Wang, "A novel stand-alone PV generation system based on variable step size INC MPPT and SVPWM control," in *2009 IEEE 6th International Power Electronics and Motion Control Conference*, May 2009, pp. 2155–2160. doi: 10.1109/IPEMC.2009.5157758.

- [48] A. Ali, W. Li, and X. He, "Simple Moving Voltage Average Incremental Conductance MPPT Technique with Direct Control Method under Nonuniform Solar Irradiance Conditions," *International Journal of Photoenergy*, vol. 2015, pp. 1–12, 2015, doi: 10.1155/2015/479178.
- [49] M. A. Elgendy, B. Zahawi, and D. J. Atkinson, "Assessment of Perturb and Observe MPPT Algorithm Implementation Techniques for PV Pumping Applications," *IEEE Trans Sustain Energy*, vol. 3, no. 1, pp. 21–33, Jan. 2012, doi: 10.1109/TSTE.2011.2168245.
- [50] T. Esmam and P. L. Chapman, "Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques," *IEEE Transactions on Energy Conversion*, vol. 22, no. 2, pp. 439–449, Jun. 2007, doi: 10.1109/TEC.2006.874230.
- [51] A. O. Baba, G. Liu, and X. Chen, "Classification and Evaluation Review of Maximum Power Point Tracking Methods," *Sustainable Futures*, vol. 2, p. 100020, 2020, doi: 10.1016/j.sftr.2020.100020.
- [52] N. Karami, N. Moubayed, and R. Outbib, "General review and classification of different MPPT Techniques," *Renewable and Sustainable Energy Reviews*, vol. 68, pp. 1–18, Feb. 2017, doi: 10.1016/j.rser.2016.09.132.
- [53] S. Mohanty, B. Subudhi, and P. K. Ray, "A New MPPT Design Using Grey Wolf Optimization Technique for Photovoltaic System Under Partial Shading Conditions," *IEEE Trans Sustain Energy*, vol. 7, no. 1, pp. 181–188, Jan. 2016, doi: 10.1109/TSTE.2015.2482120.
- [54] M. A. Ghasemi, A. Ramyar, and H. Iman-Eini, "MPPT Method for PV Systems Under Partially Shaded Conditions by Approximating I–V Curve," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 5, pp. 3966–3975, May 2018, doi: 10.1109/TIE.2017.2764840.
- [55] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications, and Design.*, 3rd ed. New York: John Wiley and Sons, 2002.

- [56] I. Khan, "20 - Gate Drive Circuitry for Power Converters," in *Power Electronics Handbook (Second Edition)*, Second Edition., M. H. Rashid, Ed. Burlington: Academic Press, 2007, pp. 543–558. doi: <https://doi.org/10.1016/B978-012088479-7/50038-9>.
- [57] M. A. A. Mohd Zainuri, M. A. Mohd Radzi, A. C. Soh, and N. A. Rahim, "Adaptive P&O-fuzzy control MPPT for PV boost dc-dc converter," in *2012 IEEE International Conference on Power and Energy (PECon)*, Dec. 2012, pp. 524–529. doi: [10.1109/PECon.2012.6450270](https://doi.org/10.1109/PECon.2012.6450270).
- [58] R. I. Putri, S. Wibowo, and M. Rifa'i, "Maximum Power Point Tracking for Photovoltaic Using Incremental Conductance Method," *Energy Procedia*, vol. 68, pp. 22–30, Apr. 2015, doi: [10.1016/j.egypro.2015.03.228](https://doi.org/10.1016/j.egypro.2015.03.228).
- [59] M. Milosević, "Decoupling Control of d and q Current Components in Three-Phase Voltage Source Inverter," 2003.
- [60] N. Odeh, T. Grassie, D. Henderson, and T. Muneer, "Modelling of flow rate in a photovoltaic-driven roof slate-based solar ventilation air preheating system," *Energy Convers Manag*, vol. 47, no. 7–8, pp. 909–925, May 2006, doi: [10.1016/j.enconman.2005.06.005](https://doi.org/10.1016/j.enconman.2005.06.005).
- [61] C. Schauder, "Vector analysis and control of advanced static VAR compensators," in *International Conference on AC and DC Power Transmission*, 1991, pp. 266–272.
- [62] bin Wu, Y. Lang, N. Zargari, and S. Kouro, *Power conversion and control of wind energy system*. IEEE Press, 2011.
- [63] P. Krause, O. Wasynczuk, and S. Sudhoff, *Analysis of Electric Machinery and Drive Systems*. Hoboken, NJ, USA: John Wiley & Sons, Inc., 2013. doi: [10.1002/9781118524336](https://doi.org/10.1002/9781118524336).