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STATCOM based Control Schemes for Grid-Connected Solar Energy Systems to Improve Power Quality

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Abstract— With the increase in demand for electricity due to increase in population and industrialization, the generation of power to meet the demand is really a challenge nowadays. It has become necessary to utilize renewable energy resources like wind, biomass, hydro co-generation to meet the energy needs etc. In this suggested scheme we have developed a model with grid integrated solar energy generating system and nonlinear load in MATLAB/SIMULINK. Injecting solar energy into the power grid affects the quality of electricity. The most important power quality problems are voltage swelling, voltage swelling, harmonics, flicker, weak power factor by the source, etc. the performance of a Solar Energy and, therefore, the quality of electricity is determined. The project proposes the STATCOM control plan for grid-connected Solar power systems to increase power quality. The bang-bang controller was developed for STATCOM based on the hysteresis current control scheme. STATCOM has been merged with Common Coupling (PCC) to reduce power quality issues. In this proposed scheme, the FACTS device STATCOM (static compensation) is connected at the PCC with the battery power storage system (BESS) to alleviate power quality problems. The Battery Energy Storage System is integrated to support the real power source during Solar power fluctuations, also it helps rapid injection of reactive power at PCC.
Keywords: Solar Energy, power quality, STATCOM, Electric grid, IGBT, PWM etc.

I. INTRODUCTION

In day to day observation it is evident that the voltage dip is the major factor that causes disturbance in obtaining a quality power. A voltage dip is a short time (10 ms to 1 minute) event that occurs whenever there is reduction in the magnitude of the r.m.s voltage. It is viewed with two parameters, depth/magnitude and duration. The magnitude of the voltage dip range between 10% to 90% of nominal voltage (which corresponds to 90% to 10% remaining voltage) and with a duration of half a cycle to 1 min. The voltage dip in a three phase system affects both the phase-to-ground and phase-to-phase voltages. A large increase of the load current, like starting a motor or energizing a transformer cause a fault in the utility system which results in a voltage drop over the network impedance. The voltage drops close to zero of the faulted phases at the fault location.

The voltage in the non-faulted phases is more or less unchanged. The voltage dips occur more often and cause severe problems and economical losses, due to the disturbances, flicker, harmonics etc., from end user equipment as the main power quality problems. One of the most common causes to voltage dips on overhead lines is Faults due to lightning. If the losses due to voltage dips are at considerable limit, mitigation actions can be suggested which is profitable for the customer and even in different cases of utility. Each mitigation action must be carefully planned and evaluated because there is no any standard solution which would work for every site.

In transmission and distribution systems there are different ways to mitigate voltage dips, swell and interruptions. At present, a wide range of latest technology, very flexible controllers are incorporated on newly available power electronics components are available for custom power applications. The most effective devices that use VSC principle are the distribution static compensator and the dynamic voltage restorer. The power quality issues are associated with respect to the Solar power generation, transmission and distribution network, such as voltage sag, swells, flickers, harmonics etc. One of the simple methods of running a PV generating system is to use the induction generator connected directly to the grid system. Although it causes disturbances into the distribution network, it has excellent advantages of cost effectiveness, robustness and requires reactive power for magnetization. The change of Solar Energy causes the variation in active power and will affect the absorbed reactive power and terminal voltage of an induction generator. In Solar Energy generation system under normal operating condition a trusted control scheme is required to ensure the proper control over the active power production.

A battery energy storage system is required to compensate the fluctuation generated by Solar Energy.

In this paper a STATCOM based control technology has been proposed for commercial Solar Energy for improving the power quality which can technically manage the power level associated with it. The proposed STATCOM control scheme for grid connected Solar Energy generation for power quality improvement has following objectives. Unity power factor at the source side, Reactive power support only from STATCOM to Solar Energy & Load and Simple bang-bang controller for STATCOM to achieve fast dynamic response. The latest Solar Energy generating systems are installed with pulse controlled inverters. Due to the improvement in switching techniques, the voltage and current at the point of common connection can be made in sinusoidal form and at unity power factor to improve the power quality at PCC.

II. OBJECTIVES

The main goal is to use recent technological advancements to increase the reliability of motor applications. High-efficiency induction motors are utilized in many different industrial applications, and this project offers easy administration and continuous surveillance of these motors. By ensuring system reliability, anomalous situations may be quickly identified and fixed.

Given that AC equipment account for roughly 90% of industrial utilization, tracking economic data becomes critical. The regular upkeep of induction devices is essential for increasing industrial output. Proactive steps to avoid system failure and safeguard large horsepower engines from excessive expenses are critical.

The project's precise aims are as follows:

- Monitor and operate an induction motor via an LCD display, allowing for safe and cost-effective data transfer in industrial areas.
- Use automated and manual control techniques to start and stop the induction machine, preventing system faults.
- Determine the voltage, current, frequency, acceleration, and heat of the induction motor's coil.

III. PROPOSED SYSTEM

Fuzzy Logic Controller is designed to improve the STATCOM injects current of varying magnitude and frequency at a common coupling point that compensates for the harmonic and reactive part of the load and induction generator current so that the source current is harmonic-free and in phase with the voltage of the source. This improves power factor and power quality. To achieve these objectives, the grid voltages at a point of common coupling are detected and synchronized in generating the reference current to the inverter. The suggested integrated grid system is implemented in MATLAB / SIMULINK to improve power quality at the point of common coupling (PCC) as shown in Fig.1. The grid-connected system in Fig.1 consists of a Solar power generation system and battery power storage system with STATCOM.

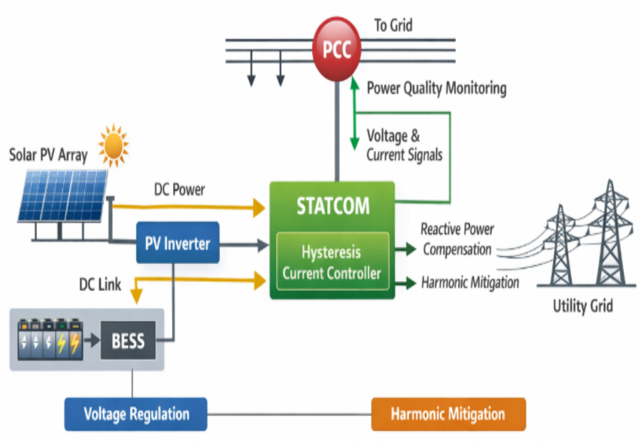

Fig.1: Grid-connected system for power quality improvement

A. Solar Energy Generating System

- The solar PV array converts solar irradiance into DC electrical power.
- The PV inverter converts the generated DC power into AC power suitable for grid interconnection.

- A common DC link is maintained between the PV inverter, STATCOM, and Battery Energy Storage System (BESS).
- The BESS absorbs or supplies real power to stabilize the DC-link voltage during solar power fluctuations.
- The STATCOM is connected in shunt at the Point of Common Coupling (PCC).
- Voltage and current signals at the PCC are continuously measured for power quality monitoring.
- These signals are processed to detect harmonic distortion and reactive power imbalance.
- Based on the detected errors, reference compensating currents are generated.
- A hysteresis current controller compares actual STATCOM currents with reference currents.
- Appropriate switching pulses are generated for the STATCOM inverter.
- The STATCOM injects compensating currents into the grid.
- Reactive power demand of the PV system and loads is supplied locally by the STATCOM.
- Harmonic currents generated by the PV inverter and nonlinear loads are effectively mitigated.
- Voltage profile at the PCC is regulated within permissible limits.
- Unity power factor is maintained at the grid interface.
- The coordinated operation of STATCOM and BESS ensures stable, reliable, and high-quality power delivery to the utility grid.

B. BESS-STATCOM

- STATCOM is a 3-Phase voltage source inverter with capacitor at DC link and connected at a point of common coupling.
- STATCOM injects a controlled amount of compensating current at a point of common coupling. To ensure that rapid injection or absorption of inverter current it is very important to sustain the DC link capacitor voltage constant.
- To regulate and maintain the DC link capacitor voltage constant Battery Energy Storage System is installed at a point of common coupling along with STATCOM.
- BESS helps to keep the DC link capacitor voltage constant which in turn helps STATCOM to either inject or absorb the reactive power at a point of common coupling.
- Also in case of any power fluctuation occurs in the system BESS supports the exchange of real power at a point of common coupling.

C. System Operation

- Power network model of the proposed grid connected system is shown in Fig.2. The system consists of solar energy generation system and battery energy storage system with STATCOM.
- To voltage regulation, the battery energy storage system (BESS) is worked as an energy storage element. The BESS will naturally sustain DC capacitor voltage constant and is best suited in STATCOM since it quickly injects or absorbed reactive power to stabilize the grid system.
- BESS can be used to level the power variation by charging and discharging operation. The battery is connected in parallel with the DC-link capacitor of STATCOM.

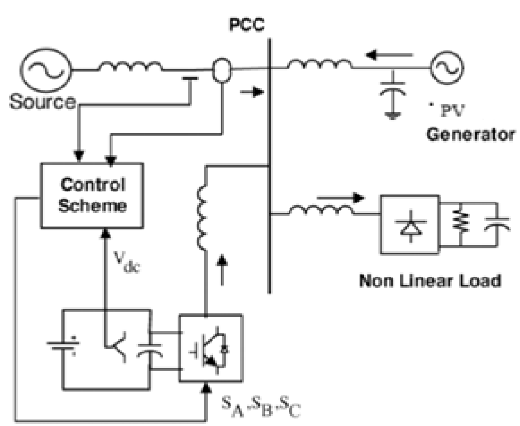

Fig.2: System operational scheme in grid system

- STATCOM is a three-phase voltage source inverter that has capacitance on its DC-link connection and is connected to point of
- common coupling. The STATCOM injects current of variable magnitude and frequency component at the bus of common coupling.
- The shunt connected STATCOM with battery energy storage system; Non-linear load and induction generator are altogether
- connected at PCC (point of common coupling) in the grid system. The STATCOM output is varied according to the controlled
- strategy, so as to maintain the power quality norms in the grid system. The current control approach is included in the control
- scheme that defines the function of the STATCOM in the power system. Using an Insulated Gate Bipolar Transistor (IGBT) by a
- STATCOM, it is expected to support reactive power input to the generator and nonlinear load on the grid system.

IV. CONTROL SCHEME

- The control method is based on the injection of current into the network using a "Bang-Bang controller" which is works on
- hysteresis current-control method. This controller is also acknowledged as the 2-states controller. Using this technique, the
- controller maintains an oscillating control system between the boundaries of the hysteresis region and receives the proper switches
- for STATCOM operation. The control system diagram is shown in Figure 3 for the switching signal to STATCOM.

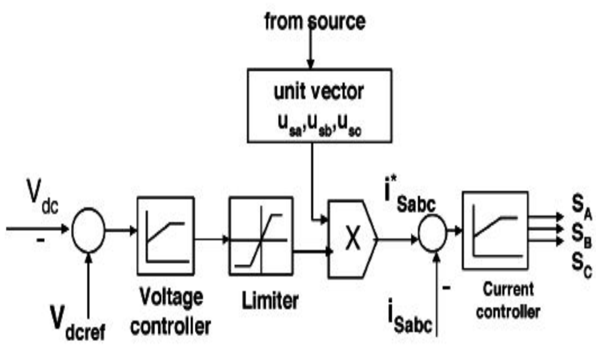

Fig.3: Control system scheme

A. Grid Synchronization

In 3-phase balanced system, at the sampling frequency the RMS voltage source amplitude is calculated with the help of source phase voltage (Vsa , Vsb,Vsc) and is expressed, as sample template Vsm , sampled peak voltage, as in (1).

$$V_{sm} = \left\{ \frac{2}{3} \left(V_{sa}^2 + V_{sb}^2 + V_{sc}^2 \right) \right\}^{\frac{1}{2}} \quad \dots (1)$$

The unit vectors (in-phase) are obtained from AC source-phase voltage and the RMS value of the unit vectors usa, usb , usc shown in (2).

$$u_{sa} = \frac{V_{sa}}{V_{sm}}, \quad u_{sb} = \frac{V_{sb}}{V_{sm}}, \quad u_{sc} = \frac{V_{sc}}{V_{sm}} \quad \dots (2)$$

The in-phase generated reference currents are obtained using in-phase unit voltage template as, in (3).

$$i^*_{sa} = I.u_{sa}, i^*_{sb} = I.u_{sb}, i^*_{sc} = I.u_{sc} \quad \dots (3)$$

Where I is proportional to magnitude of filtered source voltage for respective phases. This assures that the source current is controlled to be sinusoidal. The unit vectors implement the significant function in the grid connection for the synchronization for STATCOM. This method is simple, robust and favorable as compared with other methods.

B. Bang-Bang Current Controller

The Bang-Bang controller operates by comparing the generated current with the reference current, and the resulting error signal is used to control the switching of the STATCOM IGBT. This control signal is derived through a hysteresis current controller, which is widely used due to its simplicity, fast dynamic response, stability, and ability to operate without tracking errors. Additionally, it effectively handles rapid current variations and is robust against load fluctuations.

In the hysteresis current control (HCC) technique, the error between the actual and reference current is maintained within a predefined hysteresis band, defined by upper and lower limits. When the error exceeds either boundary, the controller immediately switches the IGBT to bring the current back within the allowable range. This continuous switching action ensures that the output current closely follows the reference current.

The generated switching pulses are then applied to the Voltage Source Inverter (VSI), which produces the desired compensating current. The switching function for phase 'a' is expressed through specific equations, where the hysteresis band (HB) determines the permissible deviation range. This method ensures efficient current regulation and improved performance of the STATCOM system.

$$i_{sa} < (i_{sa}^{*} - HB) \rightarrow S_A = 0$$
$$i_{sa} > (i_{sa}^{*} - HB) \rightarrow S_A = 1 \quad \dots (7)$$

Similarly, the switching function can be derived for phases 'b' and 'c' respectively.

V. RESULTS ANALYSIS

1) Simulations And Results Grid With STATCOM

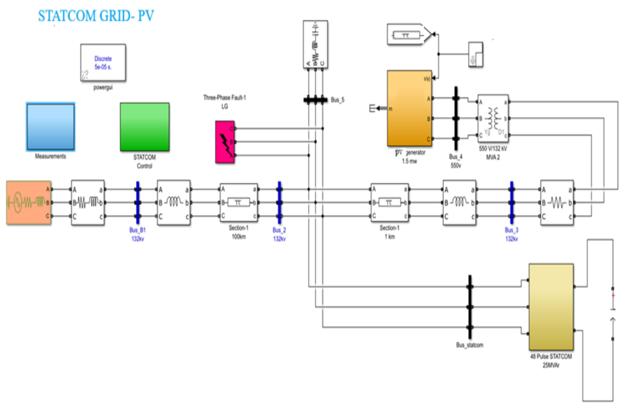

Fig.4: SIMULINK model of the proposed scheme with STATCOM

In the simulation setup described above, we established a comprehensive model to assess the performance of a Static Synchronous Compensator (STATCOM) in mitigating disturbances in a power grid. The simulation environment consisted of several key components interconnected to replicate real-world conditions.

Firstly, incorporated a Three-Phase AC source to serve as the primary power supply for the simulation. This source was connected to a 100km grid line, representing the backbone of the power distribution network. Additionally, we introduced a solar energy PV connected to a 1km grid line to emulate renewable energy integration into the grid. This addition reflects the increasing trend of incorporating Solar power into traditional power grids.

Furthermore, we introduced an RLC Load with a fault condition at the end of the grid line. This simulated disturbance allowed us to assess the grid's response to unexpected events, such as faults or fluctuations in load demand. By incorporating this fault condition, we could evaluate the effectiveness of the STATCOM in maintaining grid stability under adverse conditions.

The STATCOM itself was modeled with four transformers and eight universal bridges, reflecting its typical configuration in practical applications. These components enabled us to simulate the operation of the STATCOM in injecting compensation power into the grid as needed to stabilize voltage and improve power quality.

Central to the simulation setup was the STATCOM controller, responsible for regulating the operation of the STATCOM. This controller was programmed to inject compensation power into the grid at specific intervals whenever disturbances occurred.

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By precisely controlling the STATCOM's operation, we could evaluate its effectiveness in mitigating grid disturbances and improving overall system performance.

To assess the impact of the STATCOM, we conducted simulations under two conditions: one with the STATCOM active (With STATCOM grid) and another without the STATCOM (Without STATCOM grid). By comparing the results obtained under these two conditions, we could quantify the benefits of integrating the STATCOM into the grid.

To analyze the simulation results, we utilized various scopes to visualize and compare key parameters such as voltage, current, and power flow. These scopes provided valuable insights into how the grid responded to different operating conditions and the effectiveness of the STATCOM in stabilizing the system.

Overall, the simulation setup allowed us to comprehensively evaluate the performance of the STATCOM in mitigating disturbances and improving power quality in a grid environment. By simulating realistic scenarios and comparing results, we could gain valuable insights into the potential benefits of integrating STATCOM technology into power distribution networks.

2) Voltage Source Current Control—Inverter Operation:

The three-phase injected current from STATCOM into the grid eliminates the non-linear load and distortion generated by the pv generator. The IGBT-based three-phase inverter is connected to the grid via a transformer. The generation of signals switching from the reference current is simulated in the hysteresis band of 0.08. The narrow hysteresis band switching option in the system improves the current quality. Control signal of the switching frequency in its operating band 0.08.

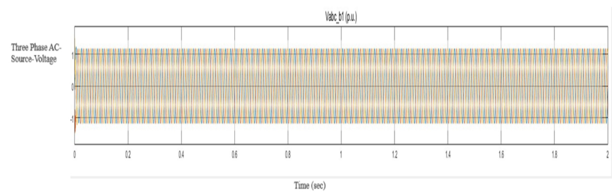

Fig.5: Three Phase AC-Source-Voltage in (p.u) with STATCOM

With the inclusion of a Static Synchronous Compensator (STATCOM), the Three Phase AC-Source-Voltage, measured in per unit (p.u.), demonstrates improved stability and voltage regulation. STATCOM helps mitigate voltage fluctuations and ensures consistent voltage levels within the system, enhancing the reliability of the power supply.

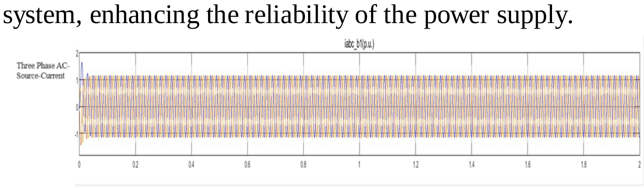

Fig.6: Three Phase AC-Source-Current in (p.u) with Statcom

Incorporating a Static Synchronous Compensator (STATCOM) into the system leads to improved stability and regulation of Three Phase AC-Source-Current, measured in per unit (p.u.). The STATCOM effectively regulates the current flow, reducing fluctuations and ensuring a more consistent current profile throughout the system. This results in enhanced reliability and performance of the power distribution network.

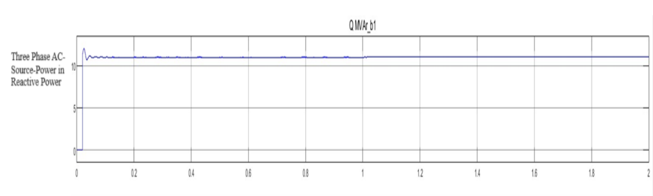

Fig.7: Three Phase AC-Source-Power in Reactive Power (Quality) in mega volt (MV) with Statcom

With the implementation of a Static Synchronous Compensator (STATCOM), the Three Phase AC-Source-Power experiences significant improvements in Reactive Power (Quality), measured in mega volt-ampere reactive (MVAr). The STATCOM effectively manages reactive power flow, mitigating voltage fluctuations and enhancing power quality across the system. This leads to a more stable and reliable power supply, minimizing disruptions and improving overall grid performance.

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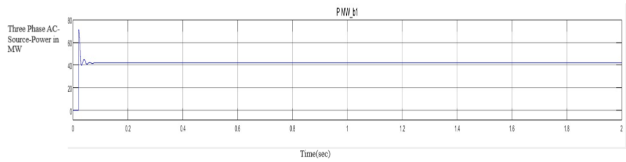

Fig.8: Three Phase AC-Source-Power in Mega Watt (MW) with Statcom

With the integration of a Static Synchronous Compensator (STATCOM), the Three Phase AC-Source-Power demonstrates enhanced stability and control, resulting in improved Mega Watt (MW) power delivery. The STATCOM regulates power flow, optimizing system performance and minimizing losses. This leads to more efficient operation and increased reliability of the power grid.

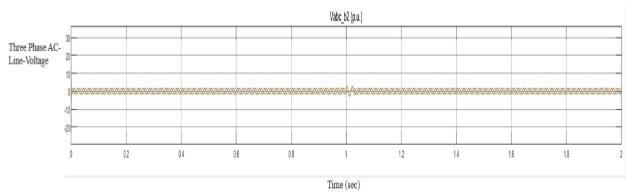

Fig.9: Three Phase AC-Line-Voltage (Vabc) in (p.u)

The Three Phase AC-Line-Voltage (Vabc) in per unit (p.u) represents the voltage levels across the three phases of the power line. Expressed in per unit, it standardizes voltage values relative to a base value, facilitating comparison across different systems. This measurement is crucial for assessing the voltage stability and quality of the three-phase AC power transmission.

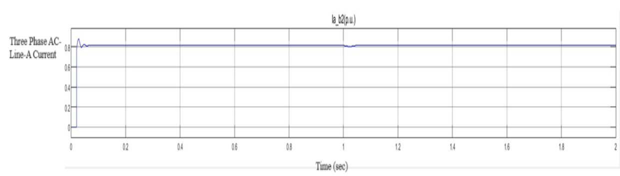

Fig.10: Three Phase AC-Line-A Current (Ia) in (p.u) with STATCOM

The Three Phase AC-Line-A Current (Ia) in per unit (p.u) with STATCOM represents the current flowing through one phase of the three-phase AC power line. Expressed in per unit, it standardizes current values relative to a base value, facilitating comparison across different systems. The inclusion of STATCOM helps regulate and stabilize the current flow, enhancing the overall performance and reliability of the power transmission system.

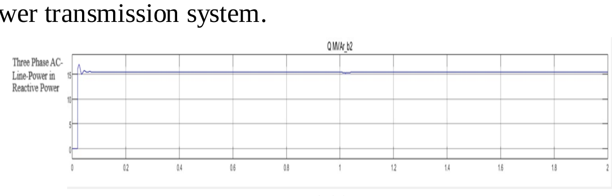

Fig.11: Three Phase AC-Line-Power in Reactive Power (Quality) in mega volt (MV)

The Three Phase AC-Line-Power in Reactive Power (Quality) in megavolt-ampere (MVAr) measures the reactive power flow in the three-phase AC power line. It indicates the portion of power that oscillates between the source and load without performing useful work, affecting system voltage and stability. Monitoring and managing reactive power with devices like capacitors or STATCOMs improve power factor and system efficiency, minimizing losses and enhancing voltage regulation.

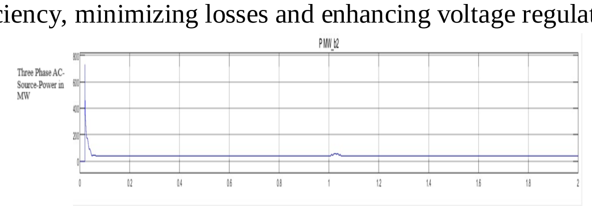

Fig.12: Three Phase AC-Source-Power in Mega Watt (MW)

The Three Phase AC-Source-Power in megawatts (MW) represents the total active power supplied by the three-phase AC source. It signifies the actual power delivered to the load, contributing to electrical work and system operation. Accurate measurement and control of this power parameter are crucial for maintaining grid stability and meeting demand requirements. Additionally, optimizing power generation and distribution processes can enhance overall system efficiency and reliability.

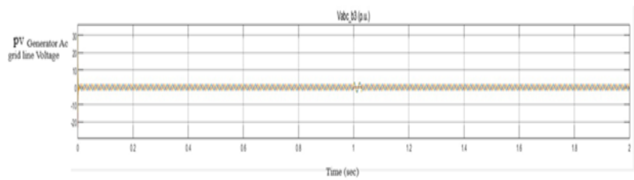

Fig.13: PV Generator Ac grid line Voltage in (P.u) with STATCOM

The PV Generator AC grid line Voltage, expressed in per unit (P.u) with STATCOM, denotes the voltage magnitude at the connection point to the grid. With the STATCOM's assistance, voltage regulation is improved, ensuring stable and reliable operation of the grid. This controlled voltage level facilitates efficient power transmission and distribution, enhancing the overall performance and reliability of the solar energy system.

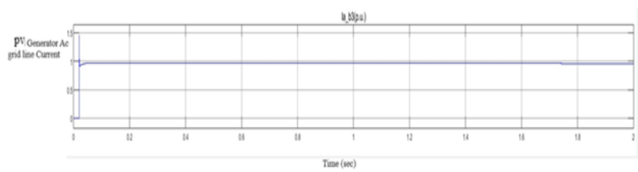

Fig.14: PV Generator Ac grid line Current in (P.u) with Statcom

The pv Generator AC grid line Current, measured in per unit (P.u) with Statcom, represents the magnitude of current flowing through the grid connection. With the inclusion of Statcom, current fluctuations are mitigated, leading to smoother and more stable grid operation. This controlled current flow helps optimize power transmission and distribution, contributing to improved efficiency and reliability of the solar energy system.

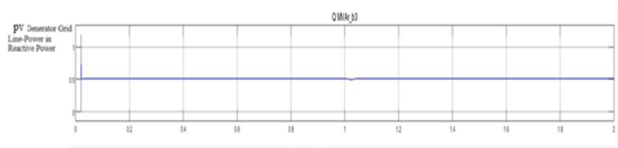

Fig.15: PV Generator Grid Line-Power in Reactive Power (Quality) in mega volt (MV)

The PV Generator Grid Line-Power, measured in mega volts (MV) and representing reactive power quality, denotes the ability of the PV generator to maintain voltage stability and regulate power flow. With enhanced reactive power control, the grid experiences reduced voltage fluctuations and improved power factor, resulting in better system efficiency and reliability. This optimization ensures smoother operation and minimizes grid disturbances, contributing to the overall stability of the power network.

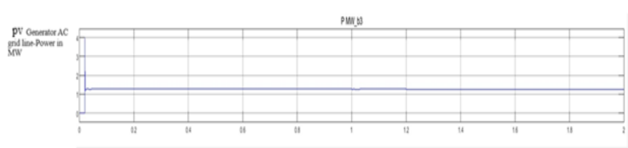

Fig.16: PV Generator AC grid line-Power in Mega Watt (MW) with Statcom

With the inclusion of Statcom, the PV Generator AC grid line power in Mega Watts (MW) is efficiently regulated, ensuring optimal power flow and stability within the grid.

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Statcom enables precise control over reactive power, enhancing the system's ability to manage fluctuations and maintain voltage levels. This results in improved grid performance, reduced losses, and enhanced overall efficiency, facilitating reliable electricity supply from the PV generator to the grid.

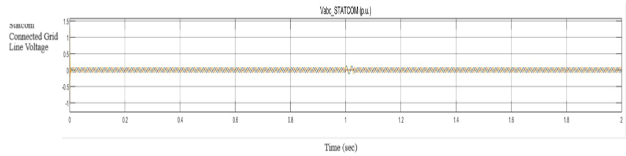

Fig.17: Statcom Connected Grid Line Voltage in p.u

The Statcom-connected grid line voltage in per unit (p.u) demonstrates enhanced stability and control compared to its counterpart without Statcom. With Statcom, voltage fluctuations are minimized, ensuring consistent and reliable power delivery throughout the grid. This improved voltage regulation optimizes grid performance, mitigates system disturbances, and enhances the overall quality and reliability of the electrical supply.

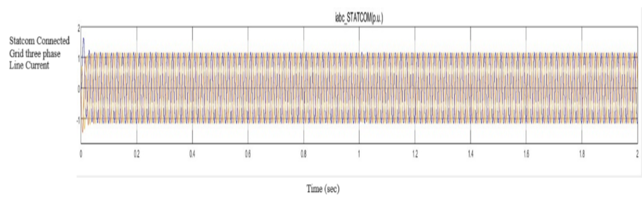

Fig.18: Statcom Connected Grid three phase Line Current in p.u

In the presence of Statcom, the three-phase line current in per unit (p.u) exhibits smoother and more controlled behavior compared to its absence. Statcom effectively regulates current flow, reducing fluctuations and ensuring balanced operation across the grid. This improved current stability enhances the overall performance and reliability of the electrical system, contributing to better power quality and system efficiency.

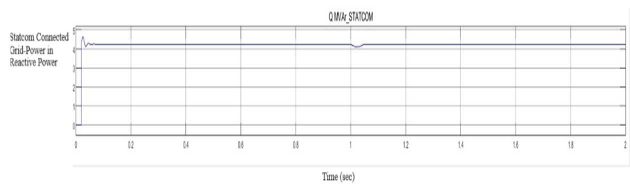

Fig.19: Statcom Connected Grid-Power in Reactive Power (Quality) in mega volt (MV)

With Statcom integration, the grid's reactive power quality in mega volt-amperes (MVAr) experiences significant enhancement. Statcom actively regulates reactive power flow, mitigating voltage fluctuations and improving system stability. This optimized reactive power management leads to smoother grid operation, minimizing power losses and ensuring reliable performance even under varying load conditions.

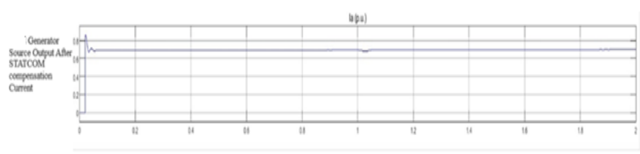

Fig.20: PV Generator Source Output After STATCOM compensation Current in p.u

After compensation by the STATCOM, the current output from the PV generator is expressed in per unit (p.u.). The STATCOM effectively regulates the current flow, ensuring stable operation and minimizing fluctuations in the output. This leads to improved grid stability and enhanced performance of the PV generator system.

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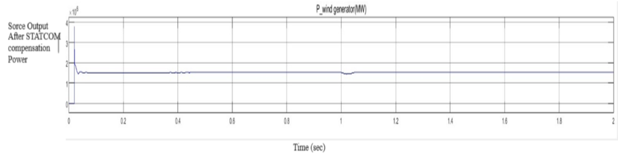

Fig.21: PV Generator Source Output After STATCOM compensation Power in MW

Following compensation by the STATCOM, the power output from the PV generator is measured in megawatts (MW). The STATCOM's intervention optimizes power delivery, mitigating fluctuations and enhancing grid stability. This results in improved efficiency and reliability of the PV generator system, ensuring consistent power supply to the grid.

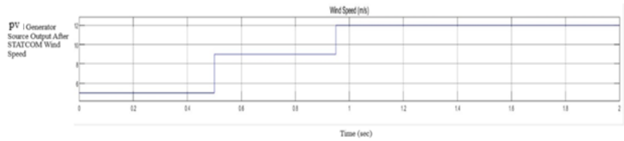

Fig.22: PV Generator Source Output After STATCOM

After the intervention of the STATCOM, The STATCOM helps regulate the PV generator's operation, ensuring that it operates within optimal speed ranges for efficient power generation. This results in improved stability and performance of the solar energy system, enhancing its overall effectiveness in converting solar energy into electrical power.

The analysis of the figures presented above reveals significant improvements in power quality resulting from the integration of a Static Synchronous Compensator (STATCOM) into the grid system. Initially, the presence of disturbances, particularly evident at the load end due to a fault, posed challenges to stable power transmission. However, with the introduction of compensation by the STATCOM through successful injection, these disturbances were effectively mitigated.

The impact of the STATCOM's intervention extended across the entire grid, encompassing both the power sources and the grid lines themselves. As a result, power quality throughout the system experienced a notable enhancement, leading to a more stable flow of power. This improvement is crucial for ensuring the reliability and efficiency of the grid, as disruptions caused by disturbances can compromise the performance of connected devices and disrupt essential services.

By comparing the outcomes of the models with and without the STATCOM, a clear distinction emerges regarding the power quality of the grid. In the absence of the STATCOM, disturbances were prevalent at various points along the grid, including the termination points of the power sources and the load. This scenario reflects the typical challenges encountered in grids lacking adequate compensation mechanisms, where disturbances can lead to voltage fluctuations, frequency variations, and other power quality issues.

Conversely, in the model incorporating the STATCOM, a significant improvement in power quality was observed throughout the grid, spanning from the Three-Phase AC Grid to the PV Generator and the load. The STATCOM's ability to remove disturbances and stabilize the grid resulted in smoother power flow and enhanced reliability.

The effectiveness of the STATCOM in improving power quality underscores its utility as a Flexible Alternating Current Transmission System (FACTS) device, particularly in high-voltage grid applications. Its capability to mitigate disturbances and provide voltage support contributes to the overall resilience and stability of the electrical infrastructure.

The integration of a STATCOM represents a substantial advancement in power system engineering, offering tangible benefits in terms of improved power quality and grid stability. By addressing disturbances and enhancing voltage support, the STATCOM plays a crucial role in optimizing power transmission and ensuring the reliability of electrical networks. As such, it stands as a valuable asset in the realm of high-voltage grid supply, contributing to the seamless operation and performance of modern power systems.

VI. CONCLUSION

This project aims to create an Internet of Things-driven induction motor parameter tracking system. The created system will be capable of performing tasks such as starting and halting the motor, as well as keeping track of characteristics such as temperature, speed, voltage, or current. The values that have been recorded for these parameters are efficiently transmitted to the interface's LCD display. Long-term monitoring of basic parameters for induction motors can be achieved using a variety of ways.

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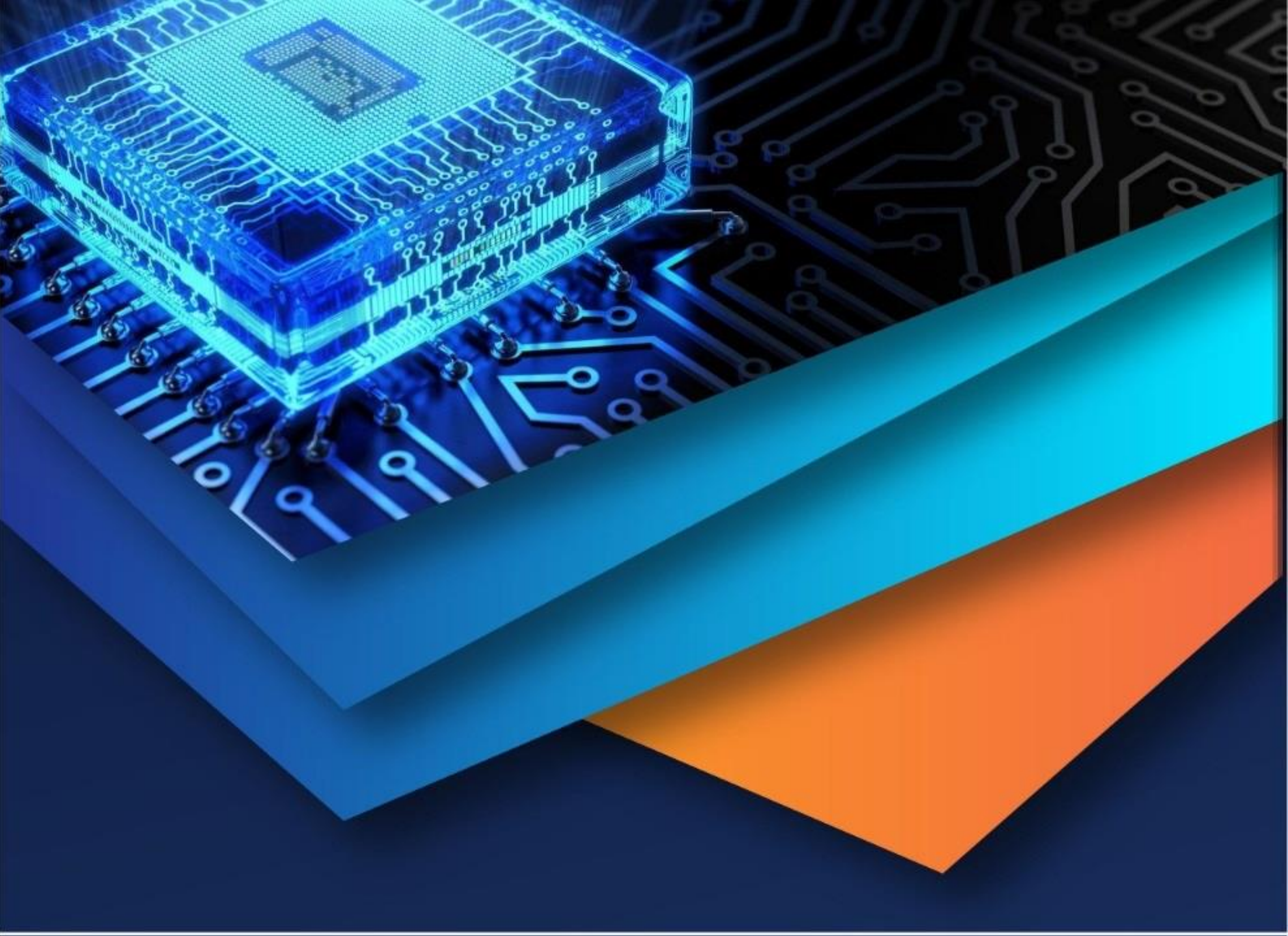

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