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Smart Grid Integration of PV Systems Using a Single Stage Grid Tied Inverter

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ABSTRACT:-

Conventional electrical power generation based on coal-fired plants and fossil fuels introduces carbon emissions, which cause air pollution. To tackle this problem, renewable energy is employed as an alternative mode of power generation. Renewable energy resources such as solar, wind, and hydro are pollution-free, easily erectable, and limitless, so they represent reliable alternatives to conventional energy sources, e.g., oil and natural gas. Among them, photovoltaic, or PV systems are leading this revolution by utilizing the available power of the sun and transforming it from DC to AC power. Grid connected PV systems are often mounted on building roofs, facades, or open spaces where partial shading frequently occurs. The increasing need for renewable energy sources has made it more and more important to integrate photovoltaic (PV) systems into the electrical grid. The grid-connected inverter, which transforms DC power produced by PV panels into grid-compatible AC power, is a crucial part of this integration. The design and control of a single-stage PV grid-connected inverter are approached creatively in this work, focusing on enhancing efficiency, reliability, and grid compliance. A control strategy is developed that allows the inverter to dynamically adjust to changing grid conditions and solar irradiance levels.

Key Words:- Grid Connected PV Systems, d-q Axis Theory, Inverter, LCL Harmonic Filter, MPPT (P & O), and Phase Locked Loop (PLL).

1. INTRODUCTION:-

1.1 Objective:-

The increase of world energy demand due to the modern industrial society and population growth is motivating a lot of investments in alternative energy solutions in order to improve energy efficiency and power quality issues. The use of photovoltaic (PV) energy is considered to be a primary resource because there are several countries located in tropical and temperate regions where the direct isolation density may reach up to 1000W per sq-m.

The primary objective of this project is to efficiently integrate solar power generated by photovoltaic (PV) panels into the existing electricity grid and promote the adoption of renewable energy. This project aims to ensure that the solar panels operate at their maximum power output under varying environmental conditions. This project also aims to synchronize the output power of the solar inverters with the utility grid, regulating voltage and frequency to meet grid requirements and minimize disruptions.

1.2 Description:-

In this project we can see the power conversion from DC (PV panels) to AC (Grid/Utility). With MATLAB/Simulink, a single-stage PV grid-connected inverter system is modeled and simulated. The PV array's maximum power is extracted using a P&O MPPT algorithm that generates a reference current (Iref) and processes it in the dq-reference frame. In order to provide error signals (Ed, Eq) that are controlled by PI controllers to produce reference voltages (Va, Vb, and Vc) for SPWM generation, this current is compared to the real grid current.

A Phase Locked Loop (PLL) ensures synchronization with the grid, and an LCL filter is used at the inverter output to reduce harmonics and improve waveform quality. The system achieves efficient power injection, grid compliance, and dynamic performance under varying solar conditions.

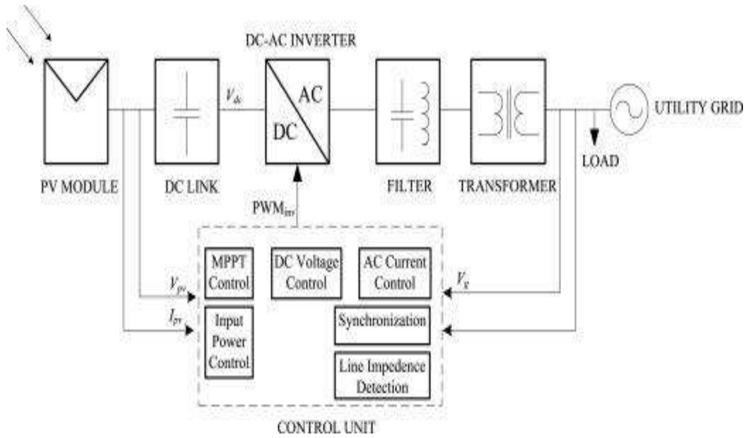

Figure-1: Single Stage Grid Connected PV Block Scheme

1.3 Focus Of The Project:-

Recently, energy generated from clean, efficient and environmentally friendly sources has become one of the major challenges for engineers and scientists. The thorough modeling of the entire system is covered in this work. A DC/AC inverter transforms the DC output voltage of the solar modules into an AC system and connects the PV array to the utility grid. A PI control circuit is used to regulate the inverter's DC input, which needs to remain constant. To guarantee a clean current injection to the grid, an LCL filter has been added. The proposed model of the entire components and control system are all simulated in Matlab/Simulink Software. Two different cases are simulated; steady and transient states. All simulation results have verified the validity of models and effectiveness of control methods.

Additionally, Solar Grid places a premium on reliability and stability, employing measures to mitigate potential grid disturbances and fluctuations associated with renewable energy sources. A robust monitoring and control system forms the backbone of the project, facilitating real-time performance tracking, data analysis, and remote management to optimize system efficiency and reliability.

In tandem, rigorous safety protocols and compliance with industry standards underscore Solar Grid's commitment to personnel safety, equipment integrity, and grid security.

2. PV GENERATOR MODEL:-

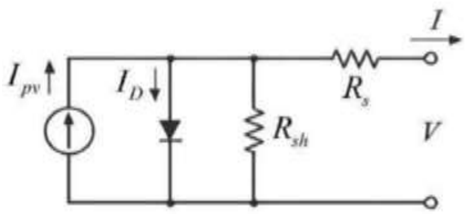

Figure-2: Equivalent Circuit of Solar Cell

Photovoltaic generators are not strictly fixed current or voltage sources; however, they can be modeled as current generators with dependent voltage sources..The solar cell does not function when it is dark. It doesn't generate any voltage or current. A p-n semiconductor junction is necessary for a solar panel cell. A current (DC current) is produced when exposed to light.The sun irradiation has a linear effect on the generated current. The following formulas can be used to set the solar cell circuit's I-V characteristics. The formula ID = IO [exp (q(V + I RS)/KT)) gives the current flowing through the diode. While, the solar cell output current:

$I = IL - ID - Ish$

$I = IL - IO\ [\exp (q(V + I\ Rs)/KT)) - 1] - (V + IRs)/ Rsh)$

Where:

I : Solar cell current (A)

IL: Light generated current (A) [Short circuit value assuming no series/ shunt resistance]

IO : Diode saturation current (A) q : Electron charge (1.6×10-19 C)

K : Boltzman constant (1.38×10-23 J/K)

T : Cell temperature in Kelvin (K)

V : solar cell output voltage (V)

Rs : Solar cell series resistance (Ω)

Rsh : Solar cell shunt resistance (Ω)

2.1 P-V Characteristics

P-V Characteristics is curve plotted between Power and Voltage of a cell or module or array. The point at which maximum power is obtained is called maximum power point and the plot is approximately linearly increasing up to MPP.

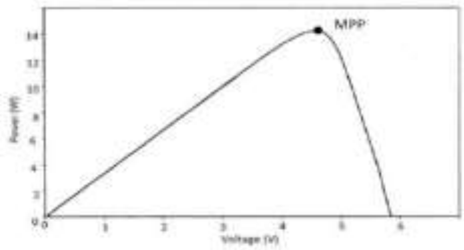

Figure-3: P-V Characteristics of PV Cell

2.2 I-V Characteristics

I-V Characteristics is curve plotted between Current and Voltage of a cell or module or array. The plot is straight line up to MPP. The open circuit voltage and short circuit current are shown by the maximum values on the x- and y-axes, respectively. The maximum power is determined by the combination of Voc and Isc.

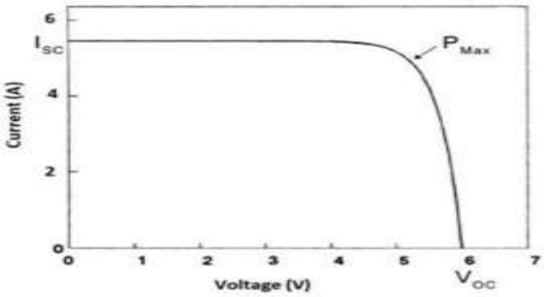

Figure-4: I-V Characteristics of PV Cell

3. D-Q AXIS THEORY:-

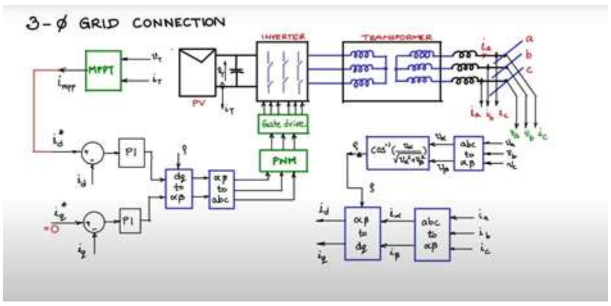

Figure-5: 3-phase grid integration using dq axis theory

Through the conversion of AC quantities into DC-like components in a rotating reference frame, the dq-axis (Park) transformation is utilized in this study to simplify the control of three-phase PV inverter output. A Phase-Locked Loop (PLL) is used to align grid voltage with the d-axis, enabling decoupled control of active and reactive power. The q-axis current reference (Iq) is set to zero in order to align inverter current with grid voltage and achieve unity power factor, ensuring that only genuine power is injected into the grid. To optimize power extraction from the PV array, the MPPT algorithm determines the d-axis current reference (Idref).

Actual dq currents are compared with their references, and the resulting errors are processed through PI controllers to generate voltage commands (Ed & Eq). These are transformed back to abc-frame reference voltages (Va, Vb, Vc) for PWM generation, controlling the inverter to deliver synchronized real power to the grid

4. INVERTER:-

Nearly every necessity in homes, businesses, and industries uses an alternating current (AC) power source. The inability to store AC for later use is its main drawback, though.Thus, AC is transformed into DC, which is subsequently stored in batteries. In order to power the AC-based appliances, DC is now transformed back into AC whenever AC is required. Therefore, an inverter is a device that transforms DC into AC. DC is converted to variable AC using an inverter. This fluctuation may occur in the voltage's amplitude, frequency, phase difference, or number of phases.

One of three wave output types is produced by power inverters. Modified Sine Wave, or Square Wave Modified Square Wave The True Sine Wave, or Pure Sine Wave Three distinct power output characteristics are represented by the three distinct wave signals. Most gadgets cannot run efficiently with the irregular power distribution caused by square wave inverters. Square wave inverters were the first types of inverters made and are obsolete. Modified square wave (modified sine wave) inverters deliver power that is consistent and efficient enough to run most devices fine. Some sensitive equipment requires a sine wave, like certain medical equipment and variable speed or rechargeable tools

The DC-AC converter's two primary purposes are

1. Produce AC output current effectively while keeping it in sync with the AC grid voltage.
2. Equilibrate the PV array's average power delivery to the grid.

4.1 Voltage source inverter (VSI):-

An apparatus that transforms a unidirectional voltage waveform into a bidirectional one—that is, a converter that changes its voltage from DC to AC—is called a voltage source inverter, or VSI. A perfect voltage source inverter maintains a steady voltage throughout the procedure. A DC voltage source, a transistor for switching, and one sizable DC link capacitor are often included in a VSI. Batteries, dynamos, solar cells, and transistors such as IGBTs, BJTs, MOSFETs, and GTOs can all be utilized as DC voltage sources. Two topologies of VSI are single-phase and three-phase inverters, with each phase further subdivided into half-bridge and full-bridge inverters.

4.2 Current source inverter (CSI):

Respectively, CSI the DC source appears as a constant current input and the voltage is changing with the load. The protection filter is normally a capacitance in parallel with the DC source.Also self-commutated inverters produce very good sine wave outputs when PWM technique and low pass filters are used.

Solar panels absorb energy from the sun's rays, and the energy is transferred to the semiconductor, creating an electric field that generates voltage and current. The voltage remains relatively constant, but the current can vary based on the amount of light. To increase solar power capacity, multiple solar panels can be connected in series, raising the system's voltage. When a grid-connected inverter or charge controller needs 24 volts or more, series connections are utilized. Connect the positive terminal of one panel to the subsequent panel's negative terminal to wire the panels in series. To sum up, utilizing solar energy for residential purposes is an effective and sustainable method of utilizing the sun's energy and enhancing our dependence on renewable energy sources.

5. MPPT (Maximum Power Point Tracking):

A solar cell's efficiency is poor. Numerous procedures must be followed in order to properly match the source and load with the ultimate goal of increasing efficiency. Maximum Power Point Tracking (MPPT) is one such tactic. The goal of this process is to extract as much power as possible from a variable source. The I-V bend in photovoltaic systems is non-direct, which makes it challenging to use to power a specific array. This is accomplished with the aid of a converter whose duty cycle is varied using an MPPT algorithm.

The amount of insulation and the operating temperature have a significant impact on the maximum power that a PV panel can produce. As a result, constant monitoring of the maximum power point is required. A PV system's performance fluctuates practically constantly due to weather and load variations. To guarantee that the photovoltaic arrays provide the most power possible, a dynamic tracking system is essential. They employ the Perturb and Observe (P&O) approach. This method has few measured parameters and a straightforward feedback structure. This method involves periodically perturbing the module voltage and comparing the resulting output power to that at the preceding perturbing cycle. This algorithm introduces a small perturbation into the system.

The solar module's power fluctuates as a result of this disturbance. The disturbance continues in the same direction if the power rises as a result of it. The disturbance then reverses once the peak power is reached, when the power at the MPP is zero and then drops. The algorithm oscillates around the peak power point once the stable condition is reached. The perturbation size must stay extremely tiny in order to keep the power variation modest. The method is sophisticated enough to establish a reference voltage for the module that matches its peak voltage. The module's operational point is then moved to that specific voltage level by a PI controller.

6. PHASE LOCKED LOOP (PLL):-

A three-phase grid-connected solar inverter's Phase-Locked Loop (PLL) system is a control mechanism that synchronizes the inverter's output with the voltage and frequency of the grid. The grid voltage is continuously monitored by the PLL system in order to determine its phase angle. Usually, this is accomplished by comparing the grid voltage's phase with an internally generated reference signal. The PLL system measures the grid voltage's frequency in addition to phase detection. The PLL system creates an error signal based on any phase mismatch that exists between the reference signal and the grid voltage.

The output voltage of the inverter is then phase-aligned with the grid using this error signal. In a similar manner, the PLL system produces an error signal to modify the frequency of the inverter's output in the event that there is a frequency discrepancy between the grid and the reference signal. The active and reactive currents of the inverter are kept in sync with the grid voltage by the PLL system. Figure 6 Recently, grid-tied photovoltaic systems have been synchronized using traditional Phase Locked Loop System (PLL) approaches. An excellent PLL can provide quick and precise synchronization information because of its high degree of immunity and sensitivity to disturbances, harmonics, unbalances, sags/swells, notches, and other types of distortions in the input signal.

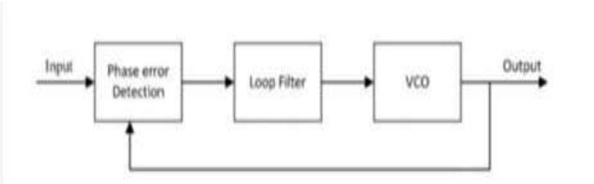

Figure--6 Conventional Phase Locked Loop System

The three main components of a typical phase-locked loop, as illustrated in Figure 6, are a voltage-controlled oscillator (VCO), a loop filter, and a phase (error) detection unit (PD).The phase difference between the input and output signals is measured by the phase detector. The DC component of the phase error is then extracted by passing the resulting phase error through a loop filter.

The resulting DC component is then amplified and sent to the VCO, which is made up of a PI controller that creates the output signal's frequency. The output signal's phase angle is then extracted from the PLL loop and used to create the grid current reference signal. Following this, the output signal passes through an integrator.

7. MATLAB-SIMULINK ENVIRONMENT:-

A PV solar cell array connected to a 50 Hz, 400V (rms) grid via a DC/AC inverter is illustrated in the system model in Figure. The PV system's 600 V is applied to a dc to ac converter signal. The PV array at the start of the system has its output voltage and current continuously checked. The maximum power point, which dynamically supplies a reference current (Iref) for optimal power extraction under changing irradiance conditions, is tracked using an MPPT algorithm based on the Perturb and Observe (P&O) technique. In the dq-reference frame, this reference current is processed and contrasted with the real current that was injected into the grid.

To keep the system stable and synchronized, PI controllers are used to control the generated error signals (Ed and Eq). Inverse Park and Clarke transformations are then used to convert these dq-axis voltages into three-phase reference voltages (Va, Vb, and Vc). The three-phase voltage source inverter (VSI) is controlled by SPWM pulses generated from these reference signals.

In order to ensure correct alignment and power flow, a Phase Locked Loop (PLL) is utilized to track the grid voltage phase angle (ωt) and synchronize the inverter output with the grid. To reduce switching harmonics and enhance the quality of current injected into the grid, an LCL filter is applied at the inverter's output.

7.1 PV ARRAY SYSTEM:-

The subsystem block from the Simulink library browser was used to generate the model of the PV panel as a constant dc source in Figure 7, which incorporated all of the PV panel's functionalities. Temperature and irradiance are the model's two inputs. The block's output provides the voltage and current. The PV model's parameters are displayed in the table below.

Parameters	**Values**
Solar irradiance Gref	1000 W/m^2
Cell temperature Tref	25 ^{0}C
Imp	7.35A
Vmp	29V
Pmp	213.15W
Isc	7.84A
Voc	36.3V

Table-1 PV CELL PARAMETERS

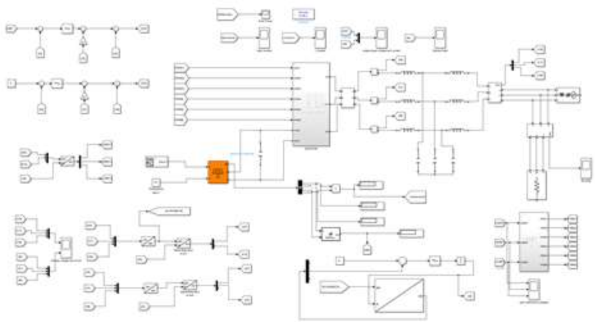

Figure-7 Simulink model of the Grid Connected PV system

7.2 INVERTER SYSTEM:-

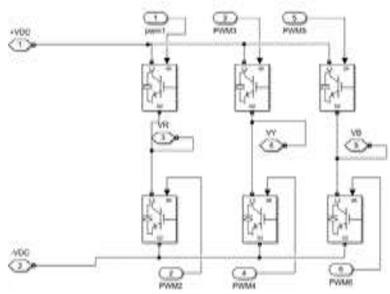

Figure-8 Simulink model of the 3-phase Inverter

The MATLAB model of a three-phase inverter with IGBTs acting as switches and the SPWM Subsystem providing the triggering pulses for each IGBT is displayed in figure 8 above.

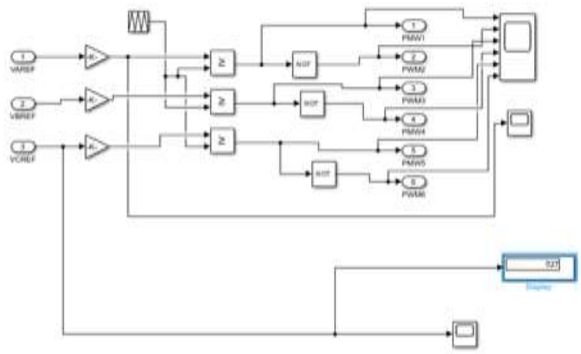

Figure-9 Simulink model of the SPWM Subsystem

7.3 DQ TRANSFORMATION SYSTEM:-

The Figure-10 below represents the transformation of three-phase voltage and current signals from the abc reference frame to the dq0 reference frame, which is essential for implementing vector control in grid-connected inverter systems. The three-phase voltages (VR, VY, VB) and currents (IR, IY, IB) are first converted to the αβ0 frame using Clarke Transformation. The resulting αβ components, along with the grid angle (**ωt**) obtained from the Phase Locked Loop (PLL), are then fed into the Park Transformation to generate the corresponding dq components.

The upper section of the diagram shows the transformation of voltage signals to obtain Vd and Vq, which are used in control logic to regulate inverter output voltage in the synchronous reference frame.

The lower section performs a similar transformation on current signals to produce Id and Iq, enabling accurate current control and synchronization with grid conditions.

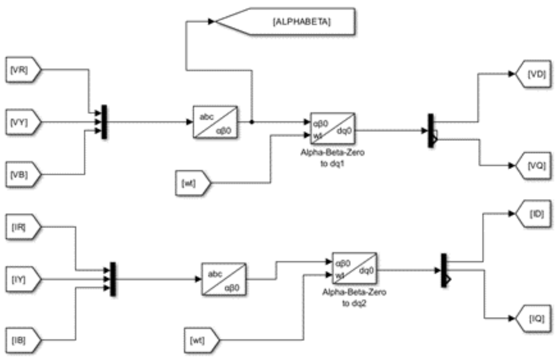

Figure-10 Simulink model of the DQ Transformation system

7.4 VOLTAGE GENERATION:-

The reference voltage generation block and current control loop utilized in the dq-reference frame for grid integration are depicted in the figures below. To control the active power flow, the reference current (Iref), which is derived from the MPPT algorithm, is compared to the d-axis current (Id). In order to maintain reactive power at zero and guarantee unity power factor operation, the q-axis current (Iq) is compared to zero.

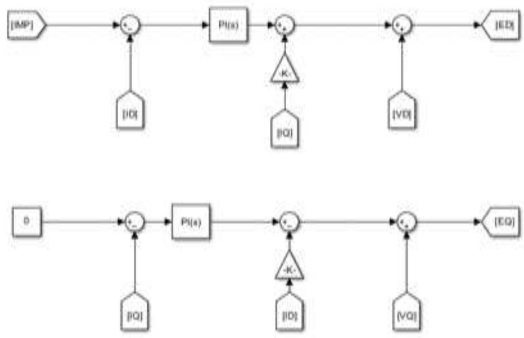

Figure-11 Simulink model of the current control loop

The resulting current errors are processed through PI controllers, generating intermediate control signals (Ed and Eq). These signals are further decoupled using feedforward compensation terms involving the cross-coupling of dq currents (Iq, Id) and dq voltages (Vd, Vq), improving dynamic performance.

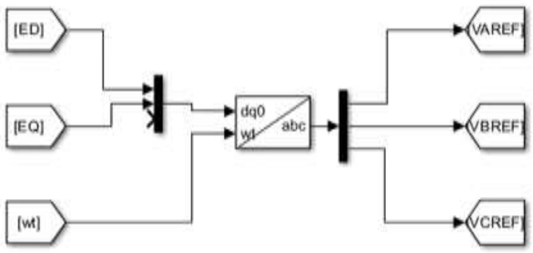

Figure-12 Simulink model of the reference voltage generation

These Ed and Eq signals, along with the phase angle (ωt) from the PLL, are then transformed back to the abc frame using the inverse Park transformation. This results in the generation of three-phase reference voltages (VaREF, VbREF, VcREF), which are used for PWM generation to control the three-phase inverter.

7.5 LCL FILTER DESIGN:-

The inclusion of an LCL filter is crucial for achieving these requirements while maintaining high power quality. LCL filter connected to grid via inverter to reduce harmonics in current. The electrical grid's stability is increased by reducing harmonic interference and smoothing the output current. By lowering Total Harmonic Distortion (THD), the filter improves overall power quality, which benefits other electrical equipment connected to the same system and increases power system stability and efficiency.

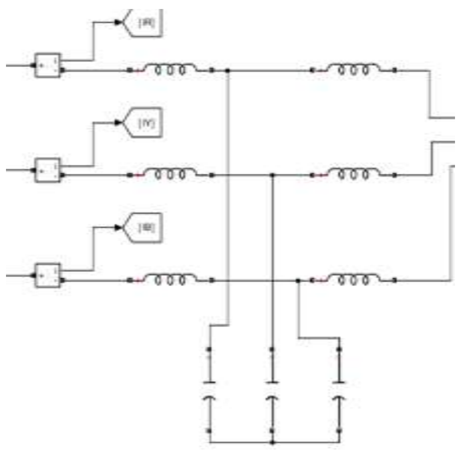

Figure-13 Simulink model of the LCL Filter circuit

8. RESULTS AND SIMULATION:-

The simulation time was set for 5 seconds. A resistive load connected in series with an inductive load and a 400 V AC RMS were used to replicate the grid in accordance with requirements. The maximum power point was successfully tracked and extracted from the photovoltaic system by the MPPT algorithm. The system successfully completes the maximum power point tracking in spite of variations, according to simulation results.

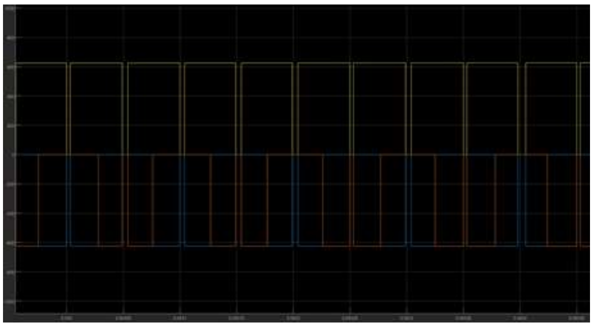

Figure-14 3-phase voltage waveforms across the inverter

Plots of the grid's active and reactive power, grid voltage and current, and inverter voltage simulation results are also shown. Figure 14: Waveforms of three-phase voltage over the inverter To ensure that the PV system injects the most active electricity into the grid, the grid voltage and current are in phase.The reactive power feeding to the grid is set to zero by making IQ equal to zero. The RMS value of grid voltage is 400 V.

Figure-15 Grid voltage and current waveforms

To evaluate the dynamic performance of the proposed PV system, the solar irradiance was varied in steps from 500 W/m² to 700 W/m², and then to 1000 W/m², each after an interval of 0.5 seconds during the simulation. The active electricity supplied into the grid and the PV output current both climb in tandem with this gradual increase in irradiance..

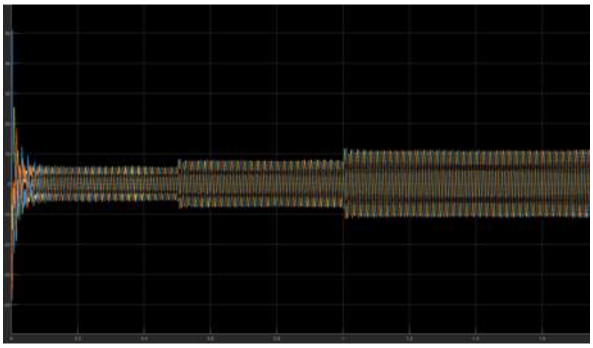

Figure-16 Current injected from the PV system

Figure 16 illustrates how the current injected from the PV system rises in proportion to the irradiance delivered to the PV array.

Figure-17 Power injected from the PV system into the Grid

In an analogous way, as the PV system's exposure to irradiance rises, so does the electricity it injects into the grid. In order to ensure optimal power extraction, the MPPT algorithm (P&O) that has been implemented successfully follows the new maximum power point at every irradiance level.

9. FUTURE SCOPE:-

Investigating ways to further improve the power quality provided by the inverter—with an emphasis on lowering harmonic distortion, minimizing voltage fluctuations, and boosting grid stability during transient conditions—is necessary to advance the project or expand the scope of work in the future

Exploring advanced control strategies such as predictive models or fuzzy logic algorithms for maximum power point tracking to optimize the performance of the inverter under varying operating conditions and grid disturbances. Develop advanced monitoring and diagnostic capabilities for the inverter system to enable real-time performance assessment, fault detection, and predictive maintenance and to identify potential issues proactively.

Improvements to this project can be made by reducing the harmonics during synchronization with the grid using other PLL methods. The algorithm for PLL may be applied to obtain less harmonic oscillation during steady state and transient conditions. A hardware model for the simulation can be developed using DSPACE to validate system performance in real-time conditions. Additionally, IoT-based real-time monitoring can be implemented by creating a robust data logging mechanism to store historical data and analyze the power transferred to the grid as well as the energy stored in the battery.

10. CONCLUSION:-

This paper's simulation, "SMART GRID INTEGRATION OF PV SYSTEMS USING SINGLE STAGE GRID TIED INVERTER," is carried out in MATLAB Simulink with a 4.9 kW grid-integrated photovoltaic array. Using PLL, the angular frequency (row), to which all reference signals are formed, is created using Vr, Vy, and Vb. In order to give correction signals (ed, eq) that are utilized to generate the Va, Vb, and Vc references in order to produce PWM pulses to the inverter, a current control loop is also constructed. To lessen the ripples in the current waveform, an LCL filter is employed. In conclusion, injecting maximum power at different irradiation levels is the main objective. There are three different maximum power injections into the grid: 2472 W at 500 W/m² irradiation at 25°C, 3466 W at 700 W/m² irradiation at 25°C, and 4802 W at 1000 W/m² irradiation at 25°C.

A variety of factors must be considered and optimized while building a PV grid-connected system in order to generate the most power possible. Applying the maximum power point tracking technique to a precise PV model can boost the system's efficiency. MATLAB-SIMULINK is used to simulate the P&O MPPT technique and the PV grid that is connected to it. Simulated in this paper, the MPPT approach can concurrently enhance the PV system's dynamic and steady state performance. The system successfully completes the maximum power point tracking, according to simulation results. Moreover, this study shows that the proposed control scheme offers a simple way to study the performance for utility interface applications.

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