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Phase Locked Loop-based Synchronization of Solar PV System with Single-Phase Grid for Integrated Load Supply

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Abstract: The integration of solar photovoltaic (PV) systems into existing electrical grids has garnered considerable attention in recent years, primarily due to its potential to enhance the utilization of renewable energy sources and mitigate greenhouse gas emissions. Incorporating solar PV systems into single-phase grids for power supply necessitates the use of efficient synchronization techniques to ensure optimal power transfer and dependable operation. Synchronizing solar PV systems with the grid offers various advantages, such as improved power quality, increased grid stability, and optimized energy utilization. The proposed concept utilizes a synchronization technique based on a Phase Locked Loop (PLL), which guarantees that the frequency and phase of the solar PV system align with those of the grid, facilitating their seamless integration. The PLL circuit extracts the fundamental frequency and phase angle from the grid voltage waveform, and then compares them with the solar PV system's output. By generating a control signal through phase and frequency adjustments, the solar PV system achieves effective synchronization with the grid, which enables efficient power transfer. A simulation model is created using MATLAB/Simulink, taking into account a single-phase grid and a solar PV system equipped with grid synchronization. The simulation results clearly illustrate the successful synchronization of the solar PV system with the grid, with minimal deviations in phase and frequency. Moreover, the integrated system can efficiently supply power to a load, ensuring uninterrupted electrical power delivery.

Keywords: *Solar PV system, Grid-Solar PV Integration, Phase Locked Loop (PLL), T/4 PLL based Synchronization, Synchronization.*

1. Introduction:

In recent years, there has been a notable increase in the adoption of solar photovoltaic (PV) systems as a sustainable and renewable energy source. These systems hold the potential to mitigate greenhouse gas emissions and generate clean electricity. The integration of solar PV systems with the existing electrical grid is pivotal to harness their benefits and ensure efficient power supply.

Solar irradiation is subject to fluctuations throughout the day and varying weather conditions. The Maximum Power Point Transfer (MPPT) algorithm's primary objective is to continually monitor and adjust the operating parameters of the PV system to maximize power extraction from the solar panels, irrespective of changing irradiation levels. Through dynamic adjustments, such as modifying the duty cycle of the DC-DC boost converter [4], the MPPT algorithm ensures that the PV system consistently operates at its optimal power point, thus enhancing energy conversion efficiency and overall system performance.

Precise detection of the grid voltage's phase and frequency is indispensable for achieving high power quality and synchronizing the inverter with the grid. Phase-Locked Loops (PLLs) are commonly employed for this purpose, serving dual functions: grid synchronization and load compensation. [8] The PLL acts as a control mechanism that generates a reference signal synchronized with the grid's voltage and frequency, playing a crucial role in enabling stable and efficient power transfer between the solar PV system and the grid.

Drawing from a literature review, several solar PV grid integration techniques have been identified and are summarized as follows:

- A solar PV system equipped with a Fuzzy Logic-based MPPT algorithm (specifically, Incremental

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Conductance), an inverter utilizing an appropriate PWM switching strategy, and grid synchronization. This approach aims to maximize PV system power output, synchronize it with the grid, and ensure high-quality power injection without disturbances.[1]

- Utilization of a single-switch-based high-gain boost converter employing Sliding Mode Control to optimize PV power extraction. This is complemented by a full bridge voltage source converter, which allows high voltage conversion ratios and minimizes voltage stresses on power devices. The Voltage Source Converter facilitates power delivery to the single-phase utility grid while providing harmonic suppression and DC offset rejection.[2]
- A single-phase grid-connected PV system integrated with a nonlinear load, utilizing Frequency Locked Loop control and a voltage source converter (VSC). This approach offers benefits such as harmonic reduction, synchronization, fast dynamic response, and enhanced power quality.[3]
- Employing grid-linked converter controllers and Second Order Generalized Integrator Phase Locked Loops to meet grid connection requirements. These control mechanisms ensure frequency and phase angle alignment between the solar system output and the single-phase grid-connected system, even under continuous operating loads.[5]
- Grid-integrated photovoltaic systems utilize Phase Locked Loops to extract amplitude, frequency, and phase angle from distorted load currents to control the PV-grid-interfaced voltage source converter. The voltage source converter manages active and reactive powers, especially in the presence of grid voltage imbalances and distortions. The system aims to maximize power extraction from the PV-grid system while enhancing power quality.[6]
- A single-phase two-stage grid-connected PV system employs an MPPT controller based on Artificial Bee Colony optimization in a DC-DC boost converter. An inverter and Phase Locked Loop are utilized to achieve synchronization with the grid, even under partially shaded conditions.[7]

These solar PV grid integration techniques provide the foundation for this study, which seeks to maximize solar PV power output under varying environmental conditions and synchronize it with the grid's voltage and frequency for seamless integration and power transfer between the two systems.

2. Methodology:

This study primarily focuses on the implementation of a Solar PV system to optimize power generation while achieving seamless synchronization with the grid. Figure 1 illustrates the block diagram depicting the implementation of the MPPT scheme and grid synchronization using the PLL technique.

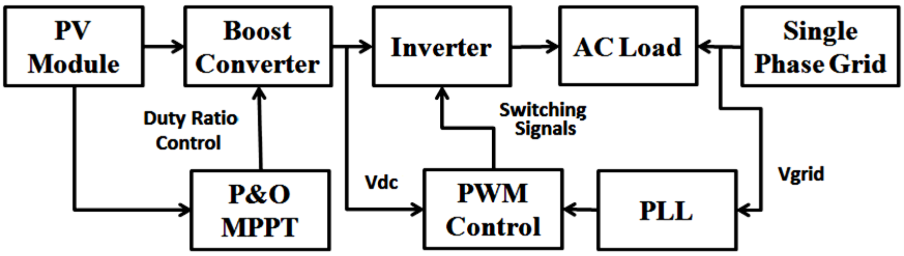

Fig 1: Block Diagram for Synchronization of Solar PV System with Single-Phase Grid

The key components within the proposed system are briefly elucidated as follows:

2.1. Perturb and Observe MPPT:

The Perturb and Observe (P&O) algorithm functions by perturbing the operating point of the PV system, adjusting the duty cycle of the DC-DC converter, and observing the resulting power changes to ascertain the direction of the maximum power point (MPP).

Step 1: Set the initial operating point (voltage and current) of the PV system.

Step 2: Define the perturbation step size (ΔV) for voltage adjustment.

Step 3: Measure PV array voltage (V) and current (I) and compute instantaneous power (P = V * I).

Step 4: Adjust the operating voltage up or down by the perturbation step size (ΔV).

Step 5: Measure the new power value (Pnew) at the perturbed operating point.

Step 6: Compare the new power value (Pnew) with the previous power value (P) from step 3.

Step 6a: If Pnew > P, the system has moved closer to the MPP.

Step 6b: If Pnew < P, the system has moved away from the MPP.
Step 6c: If Pnew = P, the system is already at or very close to the MPP.
Step 7: Adjust the operating voltage based on the determination in step 6.
Step 7a: If Pnew > P, increase the operating voltage (ΔV) further in the same direction.
Step 7b: If Pnew < P, decrease the operating voltage (ΔV) in the opposite direction.
Step 7c: If Pnew = P, no adjustment is needed.
Step 8: Repeat steps 3-7.
The P&O MPPT algorithm offers a straightforward and effective approach to maximize power output by continually tracking the MPP.

2.2. Phase Locked Loop:

The Phase-Locked Loop (PLL) is a feedback control system that compares the phase difference between the reference and feedback signals. It employs this information to control an oscillator, generating an output signal synchronized with the reference signal. The Enhanced Phase-Locked Loop (EPLL) improves upon the conventional PLL by addressing its main drawback, which is the presence of double-frequency ripple in the output signal.

Phase Detector: This compares the phase of the reference signal (input) with the feedback signal (output) from the controlled system, producing an error signal representing the phase difference between the two signals. The error signal is then fed into the Proportional Resonance Controller (PRC).

Proportional Resonance Controller (PRC): The PRC filters the error signal, providing appropriate control signals to the Voltage-Controlled Oscillator (VCO). It ensures proper damping of oscillations and controls the dynamic response of the EPLL.

Voltage-Controlled Oscillator (VCO): The VCO generates an output signal with a frequency proportional to the control signal received from the PRC. The VCO's output signal serves as the synchronized output signal of the EPLL. The EPLL functions within a closed-loop feedback system, continuously adjusting the VCO frequency to minimize the phase difference between the reference and feedback signals.

This mechanism can be employed to control an inverter in a grid-connected system. The EPLL is responsible for synchronizing the inverter's output with the grid voltage, ensuring a stable and dependable power injection.

2.3. PWM Switching Control for Inverter:

In inverters, a Pulse Width Modulation (PWM) signal is widely used to convert DC power into AC power. The PWM signal governs the switching of power semiconductor devices within the inverter circuit, generating a high-quality AC waveform. It does so by comparing the reference signal with the carrier signal to produce a modulating signal. This modulating signal represents the instantaneous amplitude or duty cycle of the PWM signal, which, in turn, drives the power semiconductor devices in the inverter. By adjusting the duty cycle of the PWM signal, the inverter can regulate the output voltage and frequency to match grid or load requirements. The PWM technique enables precise control over the inverter's output, facilitating efficient power conversion from DC to AC.

3. MATLAB/Simulink Implementation of Solar PV System Synchronization with Single-Phase Grid:

The proposed approach has been implemented in MATLAB/Simulink for a solar PV system integrated with a single-phase grid and synchronized using Enhanced Phase-Locked Loop (EPLL) techniques.

The simulation involves various blocks, each of which is described as follows:

a) The Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm is utilized to generate gate pulses for controlling the boost converter switch. This algorithm leverages the voltage and current data from the PV panel to determine the optimal operating point for the system. Please refer to Figure 2 for the MATLAB/Simulink implementation of the Duty Ratio Controller for the Boost Converter based on P&O MPPT.

b) The Enhanced Phase-Locked Loop (EPLL) algorithm is employed to extract the grid phase angle by means of a phase detector. A Proportional Resonance (PR) controller is employed to achieve a high-gain output. A comparison is made between the reference DC voltage (typically 400 V) and the voltage produced by the boost converter, resulting in an error signal. This error signal is instrumental in converting the DC voltage into AC voltage with the requisite phase angle. By comparing the error signal with the inverter output, the desired output for the inverter is determined. A voltage-controlled oscillator, controlled by a Pulse Width Modulation generator, is responsible for generating gate pulses for the inverter. This ensures that the AC voltage generated by the inverter is aligned with the desired waveform and remains synchronized with the grid.

Please refer to Figure 3 for the MATLAB/Simulink Implementation of the EPLL for controlling the Inverter output.

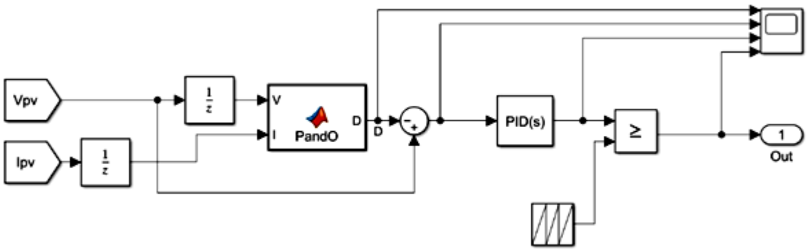

Fig 2: MATLAB/Simulink Implementation of P&O MPPT based Duty Ratio Controller for Boost Converter

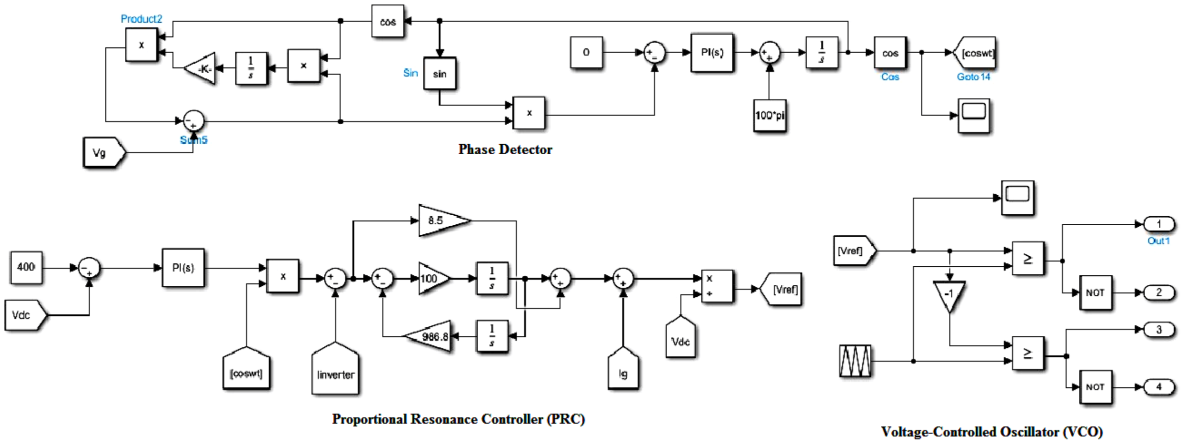

Fig 3: MATLAB/Simulink Implementation of Enhanced Phase Locked Loop

c) The complete solar PV system comprises various components, including PV panels, P&O MPPT, a boost converter, Enhanced PLL, an inverter, LC filter, load, and the grid. For an overview of the MATLAB/Simulink Implementation of the Solar PV System synchronized with a Single-Phase Grid using Enhanced Phase-Locked Loop, please see Figure 4.

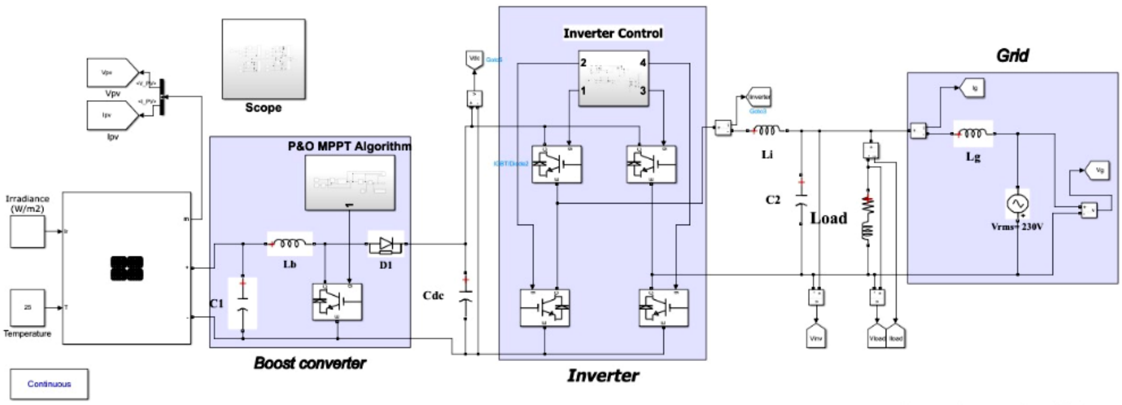

Fig 4: MATLAB/Simulink Implementation for Synchronization of Solar PV System with Single-Phase Grid

4. Results and Discussion:

The study involved an assessment of the performance and suitability of synchronizing a solar PV system with a single-phase grid, carried out using MATLAB/Simulink. The output waveforms were recorded and analyzed utilizing the Scope tool. Figure 5(a) displays the Grid Voltage and Current waveform, Figure 5(b) represents the Inverter Voltage and Current waveform, and Figure 5(c) illustrates the Load Voltage and Current waveform. These waveforms depict the behaviour of the interconnected components within the system. They offer valuable insights for assessing the performance and compatibility of the PV system in synchronization with the single-phase grid.

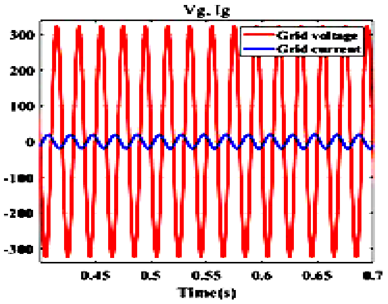

Fig 5(a): Waveform of Grid voltage and current

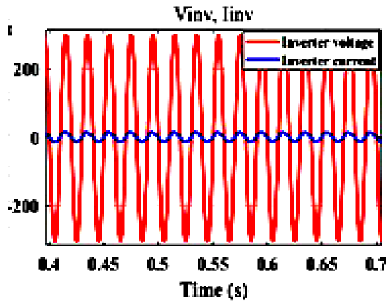

Fig 5(b): Waveform of Inverter voltage and current

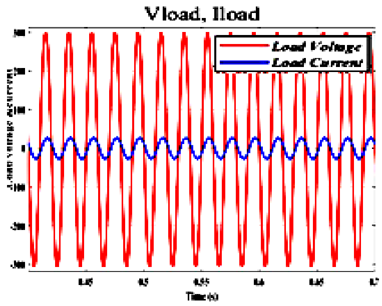

Fig 5(c): Waveform of Load voltage and current

Figure 6 presents the output waveforms (Active, Reactive, Voltage, and Current) at the Load side. The graph shapes indicate that the waveforms exhibit a purely sinusoidal nature. This demonstrates that the Load can be effectively powered using both the grid and the PV system.

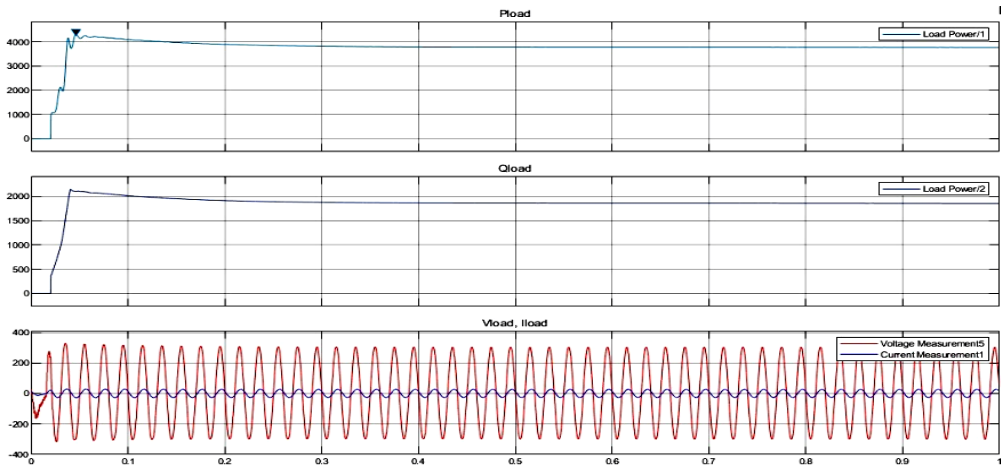

Fig 6: Output Waveforms at Load Side

In Table 1, numerical values for voltage waveforms on the Load, Inverter, and Grid sides are provided. These values were determined using the peak finder and signal statistics feature within the Scope tool.

Table 1: Voltage Waveform Parameters

Parameters	Load side	Inverter side	Grid side
Maximum Voltage	329.3V at 0.035 sec	329.3V at 0.035 sec	325V at 0.015 sec
Peak to Peak Value	649.4V	649.4V	650V
Rise Time	5.575 msec	5.575msec	5.819msec
Overshoot (+ve)	1.293%	1.293%	0.505%
Slew Rate	85.784 (/msec)	85.784(/msec)	88.466 (/msec)

In Figure 7, Total Harmonic Distortion (THD) obtained from FFT window analysis for Voltage Waveform at the Load side is depicted. The THD value stands at 1.25% when applying the Enhanced

Phase-Locked Loop (EPLL) technique at the Load side. A lower THD value signifies a reduced level of harmonic content in the voltage waveforms. The EPLL technique proves to be effective in ensuring a cleaner and less distorted power output.

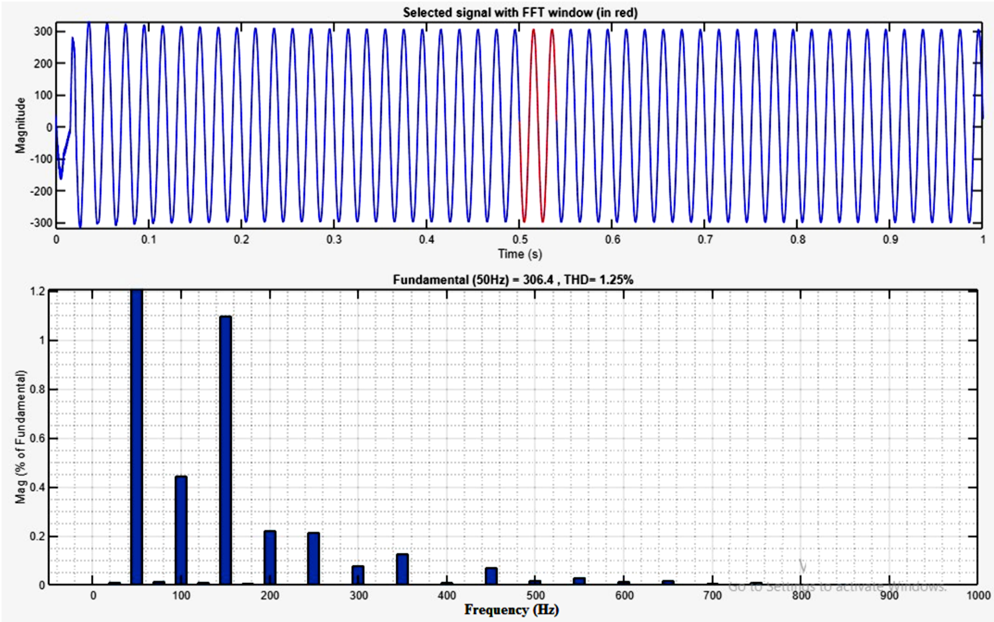

Fig 7: THD Analysis using FFT Window for Load Voltage Waveform

5.Conclusion:

The suggested approach for achieving synchronization between a Solar PV System and a Single-Phase Grid, incorporating elements such as MPPT, boost converter control, Enhanced Phase-Locked Loop technique, and Inverter Control, was effectively replicated in a MATLAB/Simulink simulation. The MPPT algorithm proved adept at tracing and optimizing the solar PV system's power output, and the boost converter, with its duty ratio control, ensured efficient power transmission to the inverter. The EPLL technique accurately discerned the phase difference between the grid and inverter sides, facilitating precise control of the inverter's switching devices. Consequently, the inverter delivered voltage that seamlessly synchronized with the grid for the load. The use of the EPLL technique greatly enhanced synchronization accuracy, leading to improved overall performance. Notably, the Total Harmonic Distortion (THD) in the system witnessed a reduction, resulting in a cleaner and less distorted power output. Opportunities for future work encompass the exploration of advanced MPPT techniques, the development of enhanced control strategies to further enhance performance, the integration of energy storage systems, the design of standalone grid capabilities, the practical implementation of the proposed system, and an evaluation of its techno-economic feasibility.

References:

[1] Sheshraj Burande, Abhishek Nawale and Dimpal Zade, 'Modeling and Simulation of Solar System with MPPT Based Inverter and Grid Synchronization', International Research Journal of Engineering and Technology, Volume: 10 Issue: 05, May 2023, pp. 614-619.

[2] Pemendra Kumar Pardhi, Shailendra Kumar Sharma and Ambrish Chandra, 'Grid-integrated single phase solar PV system employed with single switch high gain boost converter', Electric Power Systems Research, Volume 213, December 2022. https://doi.org/10.1016/j.epsr.2022.108231

[3] Lalit Kumar and Sukhbir Singh, 'Power Quality Improvement of Grid Connected Solar PV System', International Journal of Advanced Research in Science, Communication and Technology, Volume 2, Issue 2, July 2022, pp. 840-847. doi: 10.48175/568 840

[4] Sourabh Kumar, Rejo Roy, Albert John Varghese and Satyadharma Bharti, 'Grid Integration of PV System Using Effective Synchronizing Method', Advances and Applications in Mathematical Sciences, Volume 21, Issue 9, July 2022, pp. 5365-5372.

[5] A.J. Varghese, R. Roy and S. R. Awasthi, 'Intelligent Control Of Small VAWT Based WECS for Low Wind Speed Regions Using Advanced Hill Climb Search MPPT and BELBIC Controller', IEEE International Power and Renewable Energy Conference, 2021, pp. 1-5. doi: 10.1109/IPRECON52453.2021.9640873.

[6] Kanwar Pal, Shailendra Kumar, Bhim Singh and Tara C. Kandpal, Improved phase-locked loop-based control for grid-integrated PV system', IET Renewable Power Generation, Volume 14, Issue 5, 2020, pp. 705-712. doi: 10.1049/iet-rpg.2019.0361"

[7] Deepthi Pilakkat and S. Kanthalakshmi, 'Single phase PV system operating under Partially Shaded Conditions with ABC-PO as MPPT algorithm for grid connected applications', Energy Reports, 2020, pp. 1910–1921. https://doi.org/10.1016/j.egyr.2020.07.019

[8] Hemant Saxena, Alka Singh & J. N. Rai, 'Design and analysis of different PLLs as load compensation techniques in 1-Ø grid-tied PV system', International Journal of Electronics, April 2019, pp. 1-28. doi: 10.1080/00207217.2019.1600745

[9] Chinmayee K.S, 'Synchronization of Photovoltaic Systems in Single-Phase Grid-Connected Under Grid Faults', International Journal of Advance Research, Ideas and Innovations in Technology, Volume 3, Issue 5, 2017, pp. 294-301.

[10] Sheeba, T. B. ., Hemanth, S. V. ., Devaraj, V. ., Arularasan, A. N. ., & Gopianand, M. . (2023). Digital Hash Data Encryption for IoT Financial Transactions using Blockchain Security in the Cloud. International Journal on Recent and Innovation Trends in Computing and Communication, 11(4s), 129–134. https://doi.org/10.17762/ijritcc.v11i4s.6316

[11] Dr. M. Varadharaj. (2019). Density Based Traffic Control System with Smart Sensing Of Emergency Vehicles. International Journal of New Practices in Management and Engineering, 8(02), 01 - 07. https://doi.org/10.17762/ijnpme.v8i02.75

[12] Raghavendra, S., Dhabliya, D., Mondal, D., Omarov, B., Sankaran, K.S., Dhablia, A., Chaudhury, S., Shabaz, M. Retracted: Development of intrusion detection system using machine learning for the analytics of Internet of Things enabled enterprises (2023) IET Communications, 17 (13), pp. 1619-1625.