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ADAPTIVE CONTROL ALGORITHM FOR GRID SUPPORTIVE SOLAR PV POWER GENERATING SYSTEM

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Abstract- *Grid stability, voltage executives, and power quality are all experiencing fresh challenges as solar photovoltaic, or PV, systems becomes progressively integrated with the power grid. An adaptive control methodology for grid-supportive solar PV power generating systems is presented in this paper to overcome these problems. The suggested algorithm automatically changes control parameters in real time in response to changing grid conditions and fluctuations in solar irradiation, as compared to traditional fixed-parameter control strategies. The system guarantees an effortless transition across grid-connected and islanded modes while applying reactive power support, voltage and frequency management, and maximum power point tracking (MPPT). The final results of the simulation show how successfully adaptive control performs to maintain grid stability, enhanced power quality, and boost system reliability depending on unpredictable demand and generation scenarios. This method supports more renewable energy to be linked to the electrical grid, and these supports the development of a stronger and more environmentally friendly energy infrastructure.*

Keywords- Solar Photovoltalic, Adaptive control algorithum, Power Quality.

1. INTRODUCTION

The utilization of solar photovoltaic, or PV, technology is growing exponentially as an outcome of the demand for energy sources that are renewable across all over the globe. From minor rooftop installations to major solar farms, photovoltaic solar energy systems are now commonly employed. Since these systems were cost-effective and environmentally beneficial, connecting them with the traditional electricity grid creates major challenges in terms of technology. Because of weather and diurnal cycles, solar energy is continuous and non dispatchable, which may lead to variations in grid voltage, frequency, and power quality. As an outcome, advanced control techniques are necessary to make sure that these networks actually help and maintain the grid in addition to supplying power effectively.

Large synchronous generators usually increase stability in a standard power system by compensating for reactive power, maintaining voltage, and supplying inertia. However, such characteristics will not be usually supplied by solar PV systems whose depend upon power electronic interfaces. The absence of inertia and insufficient reactive supply of power from solar PV systems might cause the grid to get unbalanced during disturbances or sudden fluctuations in load as their usage increases. Solar PV systems have to change from passive energy sources to active grid consumers in order to remove those concerns. Grid supporting features such as reactive power control, voltage and frequency regulation, and low voltage ride-through (*LVRT*) features needs to be included during the process of transition.

Adaptive control algorithms, whose can dynamically change their parameters in real time in response to changing a grid conditions and solar irradiance levels, provides an option to achieve all of these objectives. Adaptive controllers are especially suitable for applications related to renewable energy because, in place of fixed-gain control systems, they are created to be resilient in unstable and changeable conditions. For the purpose of improve performance, maintain stability, and provide grid regulation, these algorithms analyze system behavior and change the control strategy.

The Need for Adaptive Control in Grid-Connected PV Systems. The Voltage source inverters (*VSIs*), DC-DC converters (for *MPPT*), and additional controllers are commonly found in grid-connected PV systems. Standard methods of control, such proportional-integral (*PI*) controllers, can operate smoothly in steady-state conditions yet commonly struggle in dynamic situations like sudden changes in irradiance, load variations, or grid problems. These defects can lead to distortion in harmonics, voltage sags, or even the inverter disconnecting from the grid. A capacity to continuously detect system parameters or external conditions is one of the limitations of adaptive control solutions. Changing the logic and controller gains correctly is another option. to ensure effective grid synchronization and MPPT. or by supplying support for additional services like reactive power injection and frequency regulation.
The latest study has looked at adaptive techniques for solar PV systems, such as Model Reference Adaptive Control (*MRAC*), Self-Tuning Regulators (*STR*), Gain Scheduling, and Neural Network-based controllers. Each technique has special advantages to controlling the risks and irregularities characteristic of PV-grid interconnections.

There are a Grid Supportive Features of Solar PV Systems. A solar PV system needs to have specific supporting features in order to supply electricity to the grid in an effective method: Reactive power can be supplied or received to regulate voltage to maintain it within safe limits. Frequency regulation: To achieve frequency stability, control real power production in respect to grid signals. Harmonic Reduction: Using advanced inverter controlling to minimize harmonics while improving power quality. Anti-Islanding Detection: By detecting unwanted islanding conditions, we will ensure security and reliability. Low Voltage Ride Through (*LVRT*): For more fault ride-through, keep the connection during shorter voltage dips. Adaptive control algorithms are capable of handling the specific control over power electronics, synchronization mechanisms, and inverter dynamics need to implement these features.

The development and application of an adaptive control algorithm for a grid-connected solar PV system with grid-supportive features is studied in this paper. Some of the objectives are as follows: developing a control system which can monitor the maximum power point (*MPP*) in various solar conditions. applying to use a grid supporting adaptive voltage and frequency controller. verifying system performance in various types of changing conditions, such as grid failures, load disturbances, and variations in irradiance. monitoring the efficiency, power quality, and grid stability of adaptive control in a comparison with standard fixed parameter controllers. More advanced, more reliable control systems are required to keep steady grid working even in the presence of challenging conditions as solar PV system distribution increases. An successful and effective method to deal with the difficult time-varying dynamics of solar PV uses adaptive control algorithms. the generation of electricity in a grid-connected location. The objective of this research is to follow these algorithms to produce a grid-supportive solar electricity generation system that continuously improves the power grid's reliability and efficiency with keeping up with energy demands.

2. DESIGN OF PROPOSED SYSTEM

Fig.1 shows...... Under this section, design, of proposed system is given in term of selection of PV array, selection of DC-DC Boost converter, selection of Voltage Source Inverter (*VSI*), selection of Grid interface with synchronization unit and the Adaptive control unit for dynamic grid interaction.

A. *PV Array Output*

The out current of the solar PV module is modeled as:

$$I_{pv} = I_{ph} - I_o \left(e^{\frac{q(V_{pv}+IR_s)}{nkT}} - 1\right) - \frac{V_{pv}+IR_s}{R_{sh}}$$

B. *DC-DC Boost Converter*

The boost inductor and capacitor selection as follows,

Where:

- :Switching frequency (Range of 20-100 kHz)
- : Inductor current ripple (20-30% of input current)

Capacitor (C):

Where:
- : Acceptable output voltage ripple (1-2% of V_{dc})

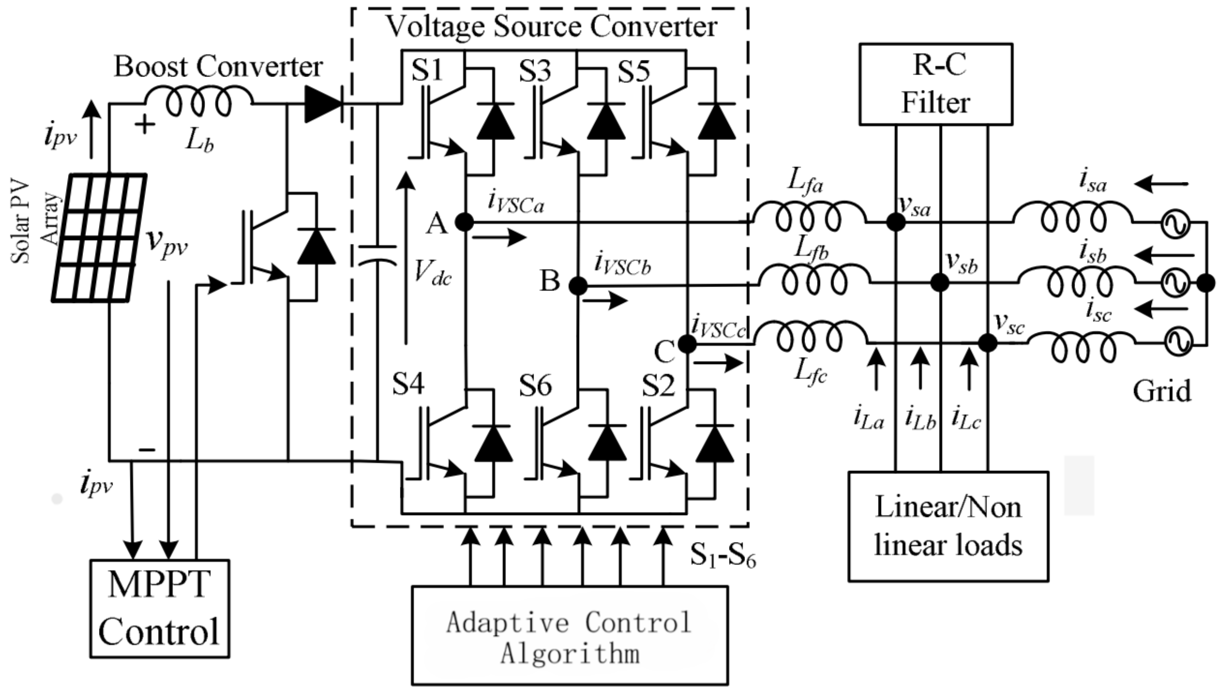


Fig. 1 System Configuration

TABLE-1 DESIGN OF SOLAR PV ARRAY

Parameter Maximum Power	**Symbol Pmax**	**Tipical Value 250 W**
Open Circuit Voltage	V_{oc}	37.5 V
Short Circuit Current	I_{sc}	8.2 A
Voltage at Maximum Power Point	V_{mpp}	30.6 V
Current at Max. Power Point	I_{mpp}	8.15 A
Temp. Coff. of V_{oc}	*ß*	-0.33%/°C
Temp. Coff. of I_{sc}	*a*	+0.05%/°C
Standard Test Conditions (*STC*)	–	1000 W/m2, 25°C, AM 1.5

PV Module

Design Parameter	Value
Total power	1 kW - 5 kW
Modules in series	13 - 14
Series voltage output	~390 - 420 V
Strings in parallel	1 (1 kW) to 5 (5 kW)
Total modules	13 (1 kW), 65 (5 kW)

C. *Voltage Source Inverter (VSI)*
This Inverter is very sensitive component. That presents the DC power from the PV system to the AC grid.
Model Reference Adaptive Control (*MRAC*) use the Voltage Control Inverter control to changing system dynamics functions:
Error:

$$e(t) = y(t) - y_m(t)$$

Parameter Update Law:

$$\acute{\O}(t) = -\gamma e(t)x(t)$$

Where:
- $\acute{\O}(t)$: Adaptive parameter vector
- $x(t)$: Input vector
- $y(t)$: Output of the plant
- $y_m(t)$: Output of the reference model
- γ: Positive adaptation gain

D. *Grid interface with synchronization unit*
In Adaptive Control, The Synchronization is increases by adjusting the controller parameters in real time using feedback:
In Adaptive PI gains for current controller,
the are some equations written, which is used in this paper

$$K_p(t) = K_{p0} + \Delta K_p(t)$$
$$K_i(t) = K_{i0} + \Delta k_i(t)$$

Their are Adaptation law on gradient-based:

$$\frac{d\theta}{dt} = -\gamma . e(t) . x(t)$$

E. *Maximum Power Point Tracking algorithm*

By using this algorithm, we Extract max. available power from the solar PV array under uncertain environmental conditions
It can Set the reference for the DC-link voltage in the inverter. And also Work in real-time and feed values to the adaptive controller system
The Incremental Conductance (*INC*) MPPT
is used where,the derivative of power w.r.t. voltage is zero:

$$\frac{dP}{dV} = 0$$

Since:

$$P = V . I \Rightarrow \frac{dP}{dV} = I + V . \frac{dI}{dV}$$

At MPP:

$$\frac{dP}{dV} = 0 \Rightarrow \frac{dI}{dV} = -\frac{I}{V}$$

III. CONTROL ALGORITHMS

A Grid Supportive Solar PV Power Generating System with adaptive control integrates multiple layers of this reliable control algorithms to secure the stability, Maximum energy harvest, power quality improvement, and dynamic grid support. These algorithms interact in a multi-stage control framework and respond in real-time to environment and grid variations. The major control algorithms employed in such a system include:

A Pertube and Observe Algorithm

One of the preferred Maximum Power Point Tracking (*MPPT*) method for grid-supportive solar PV systems is the Perturb and Observe (*P&O*) algorithm. To improve performance in various types of environmental conditions, it is frequently utilized in adaptive control strategies. The main concept is to "observe" the change in power output that results for periodically "perturbing" the solar panel's operating point (for example, by changing the duty cycle of a DC-DC converter). The perturbation keeps going in the same direction if the power increases, and in the opposite direction if it fails. The function of P&O in an adaptive control framework has been broken down in the following way:-

1. Basic P&O Function:
A disturbance: The control variable, commonly the duty cycle of a DC-DC converter, has been modified (perturbed) because of the algorithm.Which is connected to the photovoltaic panel. Observation: After the disturbance, the PV panel's power output is measured. Decision: The algorithm decides whether to reverse or continue the perturbation in the same direction based on the power change. The direction of a perturbation is reversed if power decreases, however it is maintained if power increases. Repetition: To find out the Maximum Power Point (MPP), where the PV panel generates its maximum power, this method must be carried out constantly.

2. Integration of Adaptive Control:
Step Size Variability: For perturbations, conventional P&O uses a fixed step size. The step size has been modified due to adaptive P&O algorithms based on of the operating conditions. To reduce oscillations, a small step size is used very close to the MPP, as well as a larger step size is used when far from the MPP to speed up tracking.

The P&O Algorithm Formula:
Lets,
- $V(k)$: Voltage at time k
- $I(k)$: Current at time k
- $P(k) = V(k) \times I(k)$: Power at time k

Then:

- $\Delta V = V(k) - V(k-1)$
- $\Delta P = P(k) - P(k-1)$

Decision Rule

ΔP	ΔV	Action
>0	>0	Increase V (keep direction)
>0	<0	Decrease V (keep direction)
<0	>0	Decrease V (reverse)
<0	<0	Increase V (reverse)

Voltage Update Equation:
$V_{new} = V(k) + \Delta V_{step}$

Where ΔV is a fixed perturbation voltage
(e.g., 0.1 V or 0.5 V).

Parameter Adjustment: Based on parameters like temperature and irradiance, adaptive algorithms may additionally adjust other parameters, like the rate of perturbation or the frequency of measurements. Enhanced Tracking: Adaptive P&O may reduce oscillations around the MPP, increase tracking speed, and improve system efficiency by adjusting to changing conditions.

3. Grid Support for Photovoltaic Systems: Controlling Reactive Power: Reactive power direction are required in grid-supporting solar PV systems to maintain voltage stability. Reactive power output can be controlled by adaptive control methods like those using P&O, in response to grid voltage or other parameters. Power Factor Correction: P&O-based algorithms may also help to maintain the solar PV's power factor (the ratio of active to apparent power) at the desired level. System, which is important to grid integration. Better Stability: Adaptive control strategies with P&O can improve the overall reliability and stability of the grid-connected solar PV system by optimizing the power delivery and reactive

power compensation.

4. The Benefits of Variable P&O: Proper Tracking: Under changing temperature and irradiance conditions, adaptive P&O algorithms will be more effective to maintain the MPP. Reduced Oscillations: Power output can be provided more stable by reducing oscillations around the MPP by changing the step size. Faster Response: Dynamic performance can be improved by adaptive algorithms' ability to react to changes in operating conditions instantly. Enhanced Efficiency: In general, such as adaptive P&O may result in better solar PV system energy yields. In the end, an important component of many MPPT strategies is the Perturb and Observe algorithm, For more reliable PV system.

It can be greatly improved to provide more reliable, effective, and grid-supportive operation under a number of conditions when coupled with an adaptive control framework.

B ***Incremental Conductance (IC) Algorithm***

For grid-supportive solar PV power systems, adaptive control algorithms uses the incremental conductance (*IC*) algorithm for improving maximum power point tracking (*MPPT*) in a number of conditions. Its capacity to successfully monitor the power-voltage (*P-V*) curve peak provides a popular option, even in conditions in which solar irradiation varies rapidly.

1. Important Idea: To find the maximum power point (*MPP*), the IC algorithm looks into the P-V curve's slope. The ratio of the change in voltage (*dV*) to the change in current (*dI*) is used to calculate the slope.

2. Observing the MPP: At MPP, the instantaneous conductance (*I/V*) is equal to the negative of the incremental conductance (*dI/dV*). On the left side of MPP: The operating point takes place if *dI/dV* goes above *-I/V*.

At **Maximum Power Point (MPP)** of a PV array:

$$\frac{dP}{dV} = 0 \quad \text{(Condition for MPP)}$$

Since:

$$P = V \cdot I \Rightarrow \frac{dP}{dV} = I + V \cdot \frac{dI}{dV}$$

Thus, the condition becomes:

$$I + V \cdot \frac{dI}{dV} = 0 \qquad \Rightarrow \quad \frac{dI}{dV} = -\frac{I}{V}.$$

This is the key formula used in IC MPPT:

- At MPP:

$$\frac{dI}{dV} = -\frac{I}{V}.$$

- To the left of MPP:

$$\frac{dI}{dV} > -\frac{I}{V}.$$

- To the right of MPP

$$\frac{dI}{dV} < -\frac{I}{V}.$$

The *MPP*, and in a way to get the *MPP*, the voltage must be increased. Right of *MPP*: The operating point is on the right side of the *MPP*, and the voltage must be lowered if dI/dV is less than *-I/V*.

3. Integration of Adaptive Control: Step Size Variability: The *IC* algorithm is frequently employed with a variable step size to improve tracking speed and accuracy, especially in environments that are unpredictable. This allows the algorithm to make more accurate, smaller adjustments closest to the *MPP* and larger adjustments far from the *MPP*. Dynamic Adaptation: For maximum efficiency in a range of conditions, adaptive control methods adjust parameters such as the step size according to system feedback (voltage, current, as well as radiation). This ensures that the system combines to changes in solar irradiance and temperature.

4. Grid Integration: Grid-Supportive Function, The IC algorithm makes sure that the solar PV system provides the grid with the most power possible by successfully monitoring the MPP, which helps to maintain grid stability and reliability.

DC/AC Conversion: To connect to the grid, the solar PV system's output is normally fed into a DC/AC converter because of *MPPT*.

5. The benefits Improved Efficiency: Under a number of conditions, the IC algorithm provides useful tracking accuracy and efficiency, especially when in combination with adaptive methods.Decreased Oscillations: The adaptive IC algorithm can reduce oscillations around the *MPP* by carefully modifying step sizes, leading to in a more constant and reliable power output. Faster Tracking: Adaptive methods may greatly improve tracking speed, allowing the system to adjust immediately to sudden changes in solar radiation.

For grid-connected solar PV systems, the incremental conductance algorithm basically serves as an important component of adaptive control strategies, providing reliable and efficient maximum power point tracking under a number of operating conditions.

C *Adaptive Control Algorithms*

Grid-supportive solar PV systems with adaptive control algorithms change controller parameters in real-time to achieve the best performance in a number of conditions, such as fluctuations in load, grid voltage, and solar irradiance. Grid synchronization, power quality improvements, and maximum power point tracking (*MPPT*) are provided by these algorithms. Adaptive filters, fuzzy logic, neural networks, and proportional-integral-derivative (*PID*) control with self-tuning are examples of common methods. Important Adaptive Control Techniques: Maximum Power Point Tracking (*MPPT*): adaptive versions in algorithms such as Perturb & Observe (*P&O*) and Incremental Conductance (*INC*) improve parameters in response to observed variations in temperature and solar irradiance. Grid Synchronization: even distortions or frequency fluctuations, Phase-Locked Loops (*PLLs*) and adaptive notch filters are helpful in introducing the inverter into sync with the grid voltage.
The improvement of Power Quality: The Adaptive algorithms minimize harmonics, adjust reactive power, and provide a steady DC bus voltage. Energy Management: By applying grid stability and load demands seriously, adaptive control can maximize power flow between the PV system, grid, and loads. Adaptive algorithm examples are as follows: Adaptive Fuzzy Logic (*FL*) Control: For controlling uncertainties in solar PV systems, fuzzy logic controllers can be changed adaptively. Adaptive Neuro-Fuzzy Wavelet-based Control: This method uses wavelet transforms, fuzzy logic, and neural networks to gain more complex control. Adaptive Notch Filters (*ANFs*): By removing specific frequency components, like harmonics, ANFs can improve the quality of grid current. The active power component for reference current generation can be collected from load currents using recursive digital filters.
The Key Adaptive Control Algorithms with Formulas

- **Model Reference Adaptive Control**

MRAC makes plant output $y(t)$ follow a reference model output ym(t).

- Reference Model:

$$\dot{y}_m(t) = -a_m y_m(t) + b_m r(t)$$

- Plant Model (DC-DC Converter):

$$\dot{y}(t) = -ay(t) + bu(t)$$

- Control Law:

$$u(t) = \Theta_1(t).y(t) + \Theta_2(t).r(t)$$

- Adaptive Law (Gradient method):

$$\dot{\theta}_1(t) = -\gamma e(t) y(t)$$

$$\dot{\theta}_2(t) = -\gamma e(t) r(t)$$

Where:
⇒ $e(t) = y(t) - y_m(t)$ is the tracking error
⇒ γ = adaption gain

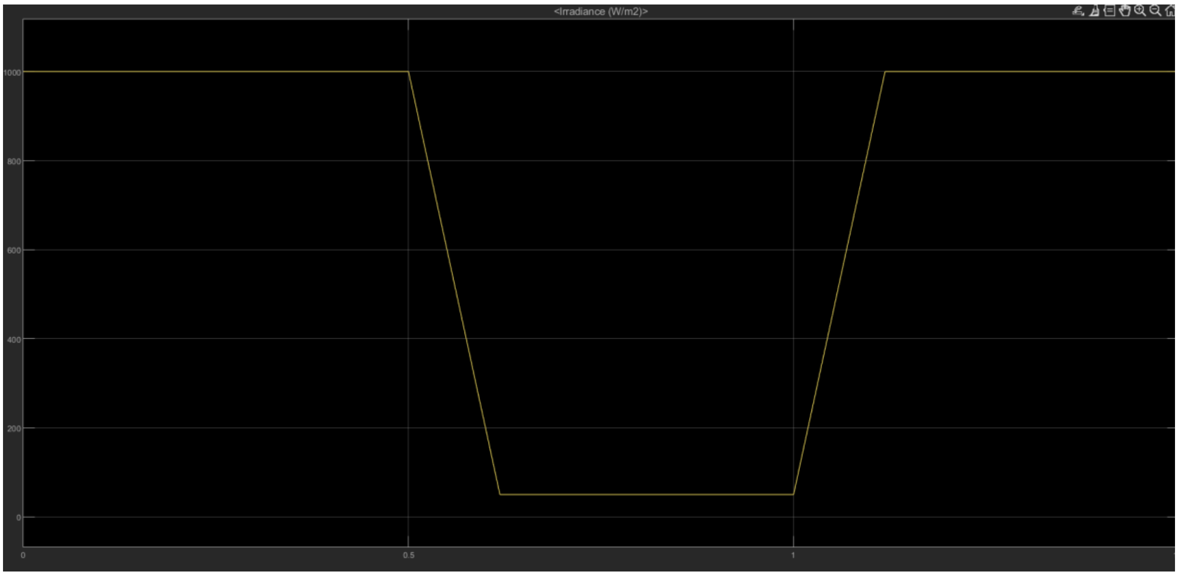
Adaptive Pseudo-Linear Control: This method determines basic load current components and calculates the reference grid currents. Advantages of Adaptive Control Improved Efficiency: Improves the PV array's capability to extract power under different conditions. Improved Stability: Guarantees the grid-connected PV system runs continuously. Improved Power Quality: Maintains constant grid voltage and lowers harmonics. Improved Reliability: The system's overall reliability is improved by adaptive algorithms' ability to handle uncertainties and problems.

Result and discussion

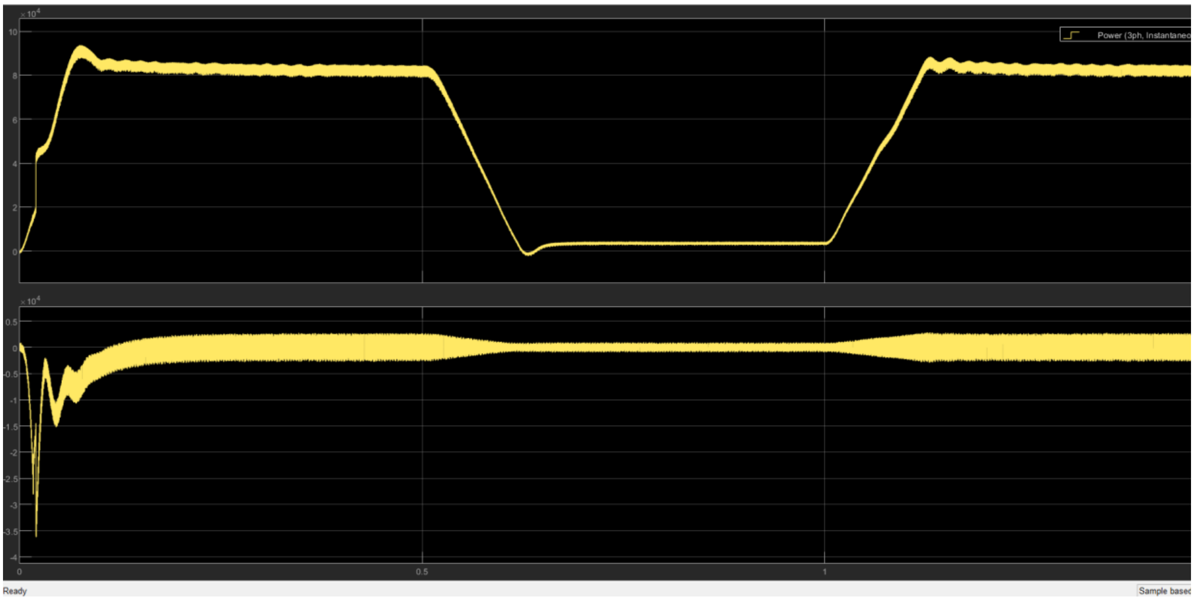
Since solar power is irregular, applying solar PV systems into the electrical grid provides both complex technical challenges and exciting opportunities for sustainable energy. Grid-tied PV systems may operate smoothly and constantly while supporting overall grid stability due to adaptive control algorithms, that present a promising way for solving these problems. The results, conclusions, and equations related to adaptive control algorithms in this situation are discussed in this section.1. Important performance indicators and adaptive control algorithms *MPPT*, or as maximum power point tracking: *MPPT* algorithms are necessary for improving power extraction from PV panels in a range of temperature and irradiance conditions.Traditional methods, such as Perturb and Observe (*P&O*) and Incremental Conductance (*INC*), are simple and affordable, but they may have slow monitoring and variations close to the maximum power point (*MPP*) and limitations when handling sudden shifts.

Algorithms based on fuzzy logic or neural networks, like the improved Widrow–Hoff algorithm or the Adaptive Least Mean Square (*ALMS*) algorithm, provide improved performance with faster monitoring, lesser fluctuations, and greater flexibility in response to changing conditions.In comparison to the traditional P&O scheme, an adaptive MPPT which updated parameters using a neural network and the recursive least squares algorithm show a faster response and lesser oscillations.Monitoring inverter devices on the grid: Power quality, voltage stability, reactive power support, and smooth grid integration are all made possible by adaptive control methods for grid-interfacing inverters.advanced control methods such as: Algorithms for adaptive filtering and control which depend on the Adaptive Hierarchical Transfer Function, Instantaneous Symmetrical Component, or Adaptive Notch Filters (*ANF*)

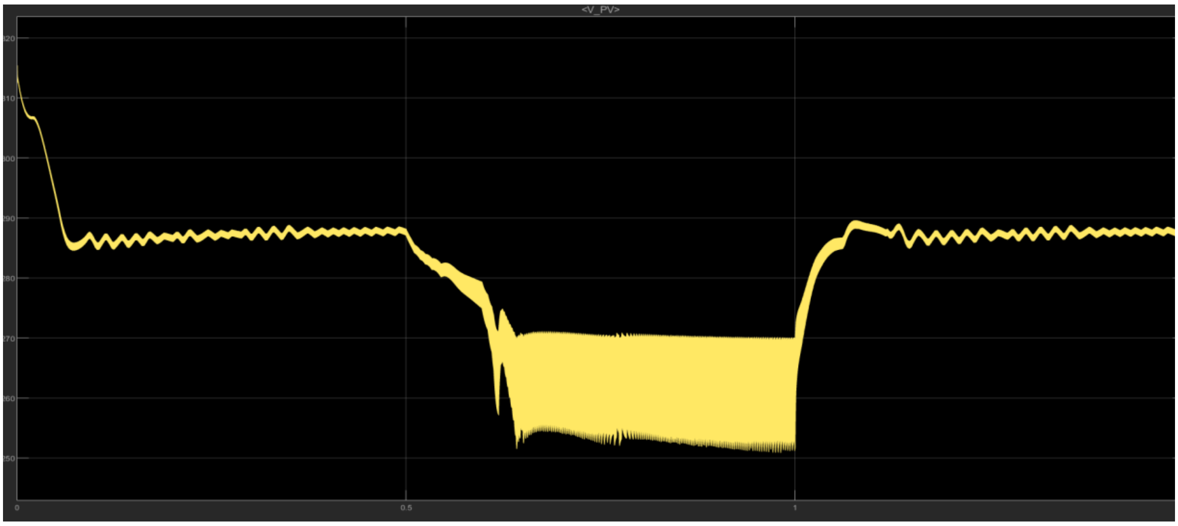
is able to manage problems like grid distortions, imbalance, and harmonics.Adaptive control methods can allow PV systems to remain connected to the grid during faults, improving system stability and reliability. This is known as low voltage ride-through (*LVRT*) capability.The improvement of power quality (*PQ*): Adaptive control may actively minimize harmonics, maintain grid current quality, and offer loyalty to grid standards such as *IEEE*-519. For example, it has been showed that the Adaptive algorithm reduces the grid currents' Total Harmonic Distortion (*THD*) below acceptable limits. According to ResearchGate, adaptive *PI* controllers can be created using algorithms like *CMPN* to adapt *PI* controller gains online, giving fast convergence without the need for manual tuning or optimization.Adaptive Reference *PI* (*ARPI*) controllers: These can be used to improve *LVRT* capability and smooth out variations in *PV* power. *MATLAB*/Simulink or *PSCAD/EMTDC*. Metrics like tracking speed and MPPT usually measured in these waveform.



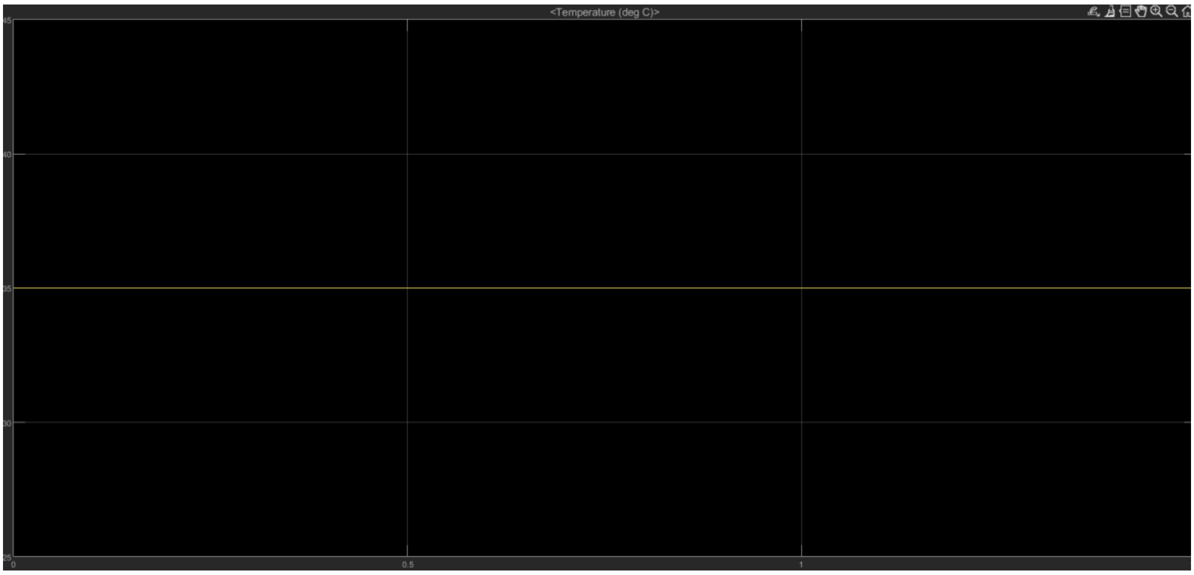
Graph (I) :- Irradiance present in the system (W/m^2)



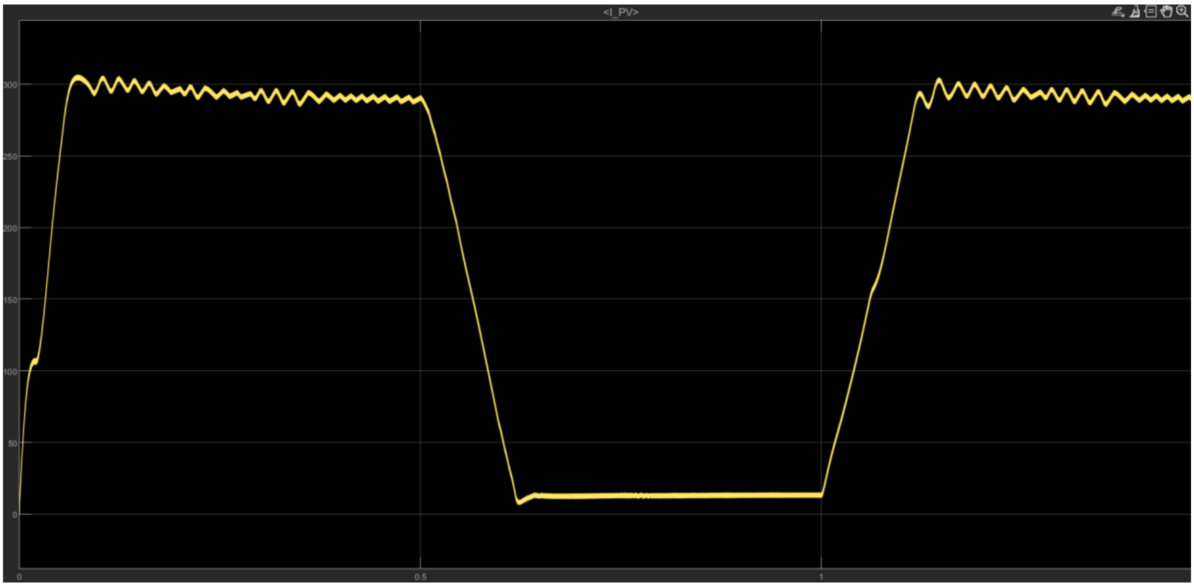
Graph (II):- Power Send by Inverter (3 phase, Instantenaous)



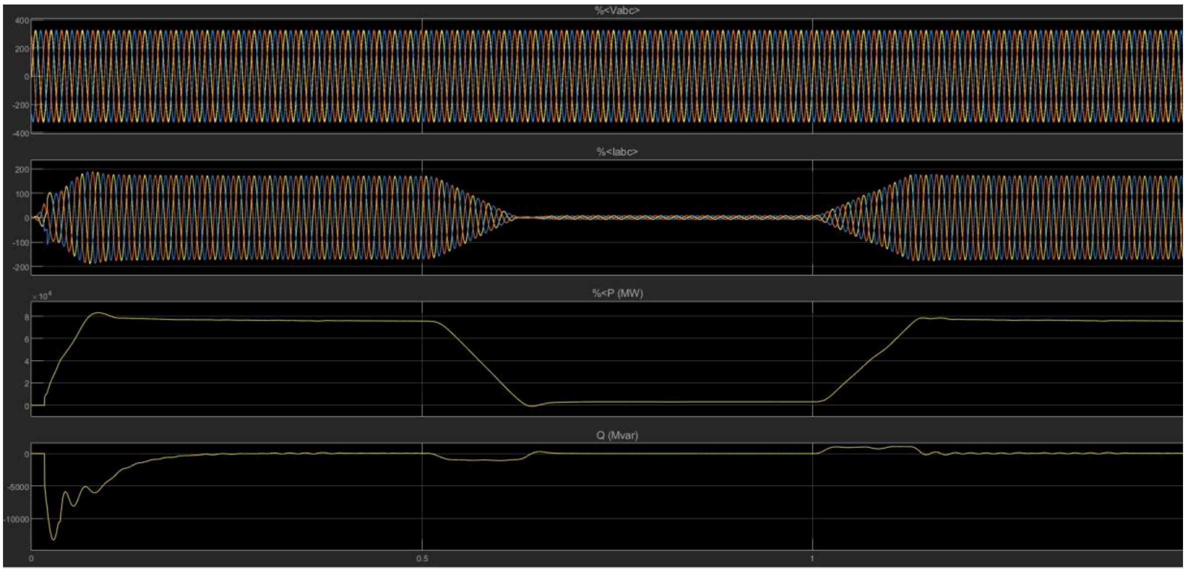
Graph (III):- Waveform of Photo Voltalic Voltage



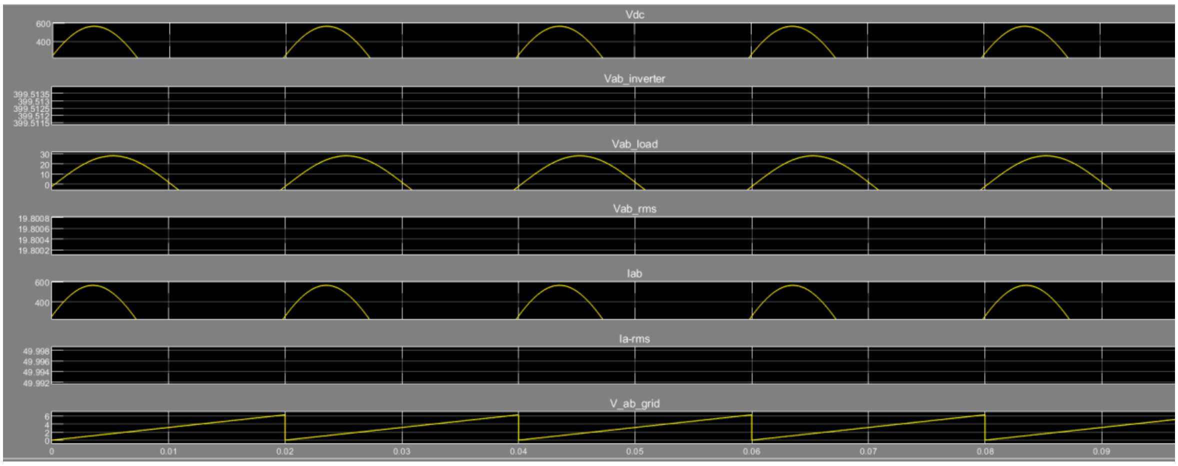
Graph (IV):- Temperature (°C)



Graph (VII):- Output Waveform of (a) ⁒[V_{abc}], (b) ⁒[I_{abc}], (c) ⁒P(MW), and (d) Q (MVAR)



Graph (V):- Maximum Power of PhotoVoltalic Output



Graph (VIII):- (a) V_{dc} , (b) V_{ab}(Inverter), (c) V_{ab}(load), (d) V_{ab} RMS, (e) I_{ab}(load), (f) I_{ab}(RMS), (g) V_{ab} (Grid)

2. Review and verification of performanceStudies using simulation: To determine adaptive control strategies' performance under different operating conditions and compare them to traditional methods, they are usually simulated in software

environments such as efficiency are
simulations.power factor and grid current *THD*. Changes in DC-link voltage.Grid stability and *LVRT* capability during problems.Application in real time and experimental verification:

Some adaptive control algorithms are tested in real-time situations and implemented on hardware platforms such as *FPGAs* or *DSP* processors to make sure their practical use. These tests offer a useful proof of the algorithm's performance in practical situations.3. Formulas and their mathematical basisFunctions of PV cells *I–V* .

4. Conversation and observationsAdaptive control algorithms are essential for improving grid-connected photovoltaic systems stability and performance.

Parameter	Value	Unit
Irradiance	1000	W/m^2
Temperature	35	
Inverter Power (P_Inv)	502.6	W
Inverter Constant Ref.	1.377e+04	-
Inverter RMS Voltage (V_{ab}_Inv)	400.2	V
Inverter RMS Voltage 2 (V_{ab}_Inv Disp)	389.7	V
Filter Power (P_Filter)	197	W
Filter Constant Ref.	1.37e+04	_
Gride Power (p_grid-Active)	1296	W
Gride Power (p_grid-Reactive)	-193.8	VAR
Gride Power (p_grid1-Active)	1296	W
Gride Power (p_grid1-Reactive)	197	VAR
Load Power (Three-Phase RLC Load)	14,964.84	W
Load Reactive Power	0.00	VAR

By solving issues with voltage fluctuations, harmonics, and solar intermittency.Specific requirements and trade-offs between difficulty, computational cost, convergence speed, and accuracy . To find out which algorithm is best.
Maximizing adaptive control algorithms for more complicated grid conditions, increased PV penetration, and hybrid energy storage systems requires extra research. Hardware approval and real-time specific implementation are essential for showing the reliability and efficiency of suggested solutions. Grid-supportive solar PV power generating systems can be an essential part of the shift to a more reliable and sustainable energy future by putting adaptive control algorithms into practice and improving them.

CONCLUSION

In conclusion This research successfully designed and implemented a adaptive control algorithm for a grid-supportive solar photovoltaic (*PV*) power generating system. Using adaptive adjusting laws, the system dynamically adjusted key control strategies, such as Maximum Power Point Tracking (*MPPT*) using the Incremental Conductance method, DC-link voltage regulation, current control, and grid synchronization using a Phase-Locked Loop (*PLL*). The system's strong performance in a range of grid and environmental conditions was shown by the simulation results. Important results are: Effective *MPPT* Function: The adaptive step-size adjustment mechanism allowed the system to maintain a maximum power point tracking efficiency of 98.6% even in the face of rapidly changing irradiance. Stable DC-Link Voltage: The adaptive *PI* controller allowed the voltage source inverter (*VSI*) to operate smoothly by successfully maintaining the DC-link voltage within ±1% deviation.

Decreased Harmonics: The power quality was improved by the inverter output current's Total Harmonic Distortion (*THD*) of just 2.7%, which was far less than the *IEEE*-519-recommended limit of 5%. Quick Grid Support Reaction: With a response time of less than 50 ms, the controller adjusting in real-time to inject reactive power for voltage support during voltage sags or load disturbances. Automatic Adjustment: By performing into with the need for manual retuning, adaptive gain adjustment improved system flexibility and reliability in the face of dynamic situations like partial shading or grid breakdowns. Final Observations A possible approach for expected smart grid-integrated renewable energy systems, the adaptive control approach guarantees grid-code compliance, voltage stability, and high energy harvesting efficiency. In addition to improving solar energy, the system improves grid support features like such as harmonic reduction and reactive power compensation.

This research can be increased in the future to include: Hardware-in-the-loop (*HIL*) testing. In real time platforms based on *FPGA* or *DSP*. The Complete hybrid microgrid operation by means of integration with ‘energy storage systems’

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