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Power Quality Enhancement in Grid-Connected Solar PV Systems Using Adaptive Control and Multilevel Inverter Topologies Under Dynamic Grid Conditions

Abstract: - This paper introduces a control strategy that uses an integrator-based positive sequence estimator to improve the power quality of a grid-connected double-stage solar PV system. The control extracts positive sequence components from distorted and unbalanced grid voltages to calculate unit templates and grid reference currents during grid anomalies like distortion, unbalance, sag/swell, and DC offset. A feedforward term is introduced to the photovoltaic array to ensure rapid transient response, and the DC-link voltage is adaptively regulated to reduce the voltage source converter (VSC) losses during weak grid conditions. The paper compares the performance of two-level and three-level inverters in this system configuration, highlighting the differences in power quality improvement, harmonic reduction, and system efficiency under various grid disturbances and intermittent solar conditions. Simulation results, performed in MATLAB, validate the superior performance of the three-level inverter in terms of lower total harmonic distortion (THD) in grid currents, in compliance with IEEE standard 519, while demonstrating the satisfactory response of both inverter types during challenging grid conditions like intermittent solar irradiation, DC offset, voltage distortions, unbalance, and voltage sag/swell.

Keywords: Solar PV system, Power quality improvement, Grid-connected, Positive sequence estimator, Two-level inverter, Three-level inverter, Voltage source converter (VSC), Harmonic distortion, Weak grid

I. INTRODUCTION

The growing global energy demand and environmental concerns have led to a major shift toward renewable energy sources, with solar photovoltaic (PV) systems playing a key role in this energy transition. Solar energy is abundant, renewable, and environmentally friendly, making it one of the promising sources of clean energy. Grid-connected PV systems are rapidly becoming a key element of modern power networks, contributing to sustainable energy generation while reducing greenhouse gas emissions [1]. However, integrating PV systems into the grid presents several challenges, particularly in terms of maintaining power quality and ensuring stable operation under grid disturbances, voltage fluctuations, and variations in solar irradiance. These challenges are exacerbated in weak grid conditions, where the grid impedance is high, making the system more liable to voltage distortions, unbalance, and other anomalies.

One of the major challenges in grid-connected PV systems is the degradation of power quality due to disturbances like voltage sags, swells, unbalance, and harmonic distortion. These issues can impact the performance of the power system, resulting in higher losses, lower efficiency, and potential damage to sensitive equipment. Additionally, grid-connected inverters, which connect the PV system to the grid, are essential for ensuring the overall performance and stability of the system. The inverter control strategy must ensure that the power injected into the grid is of high quality, with minimal harmonic distortion, even under fluctuating conditions. To achieve this, advanced control algorithms and inverter topologies are required to increase the power quality and maintain system stability.

Power quality is a main aspect of grid-connected PV systems, as poor power quality can lead to several issues, including increased harmonic distortion, voltage fluctuations, and system instability. Harmonics are a significant concern, as they can cause overheating of equipment, increased losses in the power system, and malfunction of sensitive devices. The total harmonic distortion (THD) of grid currents must be minimized to ensure compliance with international standards, such as IEEE 519, which sets the allowable limits for harmonics in power systems. In the context of weak grids, where the system impedance is higher, maintaining power quality becomes even more challenging, as the system is more vulnerable to voltage sags, swells, and unbalance [3].

Inverter-based PV systems are particularly susceptible to power quality issues, as the inverter must induce the DC power made by the PV array to AC power that can be injected into the grid. The performance of the inverter is linked to the quality of the power it delivers to the grid [4]. Therefore, an effective inverter control strategy is key

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to ensure that the grid-connected PV system operates well and maintains power quality under various grid conditions. Inverters are a crucial component of grid-connected PV systems, as they perform the essential task of converting the DC power from the PV array into AC power that is compatible with the grid [5]. The performance of the inverter, particularly its ability to handle grid disturbances and maintain power quality, is a key factor in determining the overall efficacy and stability of the PV system. In this context, the two-level and three-level inverter topologies are commonly used in grid-tied PV systems, each with its own set of advantages and limitations [6].

The two-level inverter is a conventional inverter topology that operates by switching the DC voltage between two levels, typically the positive and negative sides of the DC-link voltage. This simple topology is widely used in small to medium-scale PV systems due to its relatively low cost, ease of implementation, and straightforward control. However, the two-level inverter suffers from certain limitations, particularly in terms of power quality. The output voltage waveform of a two-level inverter contains significant harmonic content, which can lead to higher THD in the grid currents. This issue becomes more pronounced in weak grid conditions, where the higher grid impedance amplifies the effects of voltage distortions and unbalance [7].

To mitigate the harmonic distortion in two-level inverters, various modulation methods such as pulse width modulation (PWM) are employed. However, these techniques can only reduce harmonics to a assured limit and may not be enough to meet stringent power quality standards in all grid conditions [8]. Moreover, two-level inverters are less efficient at handling high power levels, as they require larger filter components to smooth the output waveform, resulting in increased system losses [9]. The three-level inverter, also known as a multilevel inverter, offers an improved alternative to the two-level topology. In a three-level inverter, the output voltage can take on three distinct levels: positive, zero, and negative. This allows for a more refined output waveform with lower harmonic content, reducing the need for large filter components and improving the overall power quality. The three-level inverter is particularly advantageous in high-power applications, where its ability to produce smoother voltage waveforms leads to lower THD in the grid currents and higher system efficiency [10].

In addition to its superior power quality performance, the three-level inverter also has a lower switching frequency compared to the two-level inverter, which lowers the switching losses and betters the efficacy of the system [11]. This makes the three-level inverter as choice for large-scale grid-tied PV systems, where high power levels and stringent power quality requirements are critical. However, the three-level inverter is more complex and expensive to implement, as it requires additional components such as capacitors and switching devices.

In [12] discussed adaptive control strategies to get power quality in grid-connected PV systems. The authors propose a control mechanism that adapts to varying solar irradiation and grid disturbances, achieving a reduction in total harmonic distortion (THD) and voltage unbalance. This study lays the groundwork for exploring various control strategies, such as integrator-based positive sequence estimators (PSE), that are central to this research. In [13], focused on the harmonic distortion issues in PV systems using two-level inverters and suggests the use of harmonic filters to reduce THD. The findings highlight the limitations of two-level inverters in maintaining power quality, especially under weak grid conditions. This research is relevant for comparing the harmonic performance of two-level inverters with three-level inverters in later studies. In [14] provided a direct comparison between two-level and three-level inverters in terms of efficiency, power quality, and THD reduction. It concludes that while two-level inverters are simpler and cheaper to implement, three-level inverters offer significant advantages in reducing THD and improving power quality, particularly in high-power applications. This comparison forms a foundation for the current study's focus on inverter topologies.

In [15], introduced advanced control algorithms for multilevel inverters, including three-level and higher-level topologies. The paper highlights the benefits of multilevel inverters in achieving better harmonic performance and increased efficiency under varying grid conditions. This study supports the argument for using three-level inverters in grid-tied PV systems with weak grids. In [16], authors analyzed the effects of weak grid conditions on the performance of solar PV systems, focusing on power quality disputes as voltage unbalance, sag, swell, and harmonic distortion. The authors propose various control techniques to mitigate these issues, emphasizing the need for robust inverter control strategies. This research is closely related to the current study's aim to enhance power quality using an integrator-based PSE control strategy.

In [17], proposed the benefit of a three-level inverter to get the power quality in grid-tied PV systems. Their research shows that three-level inverters provide better voltage regulation, lower THD, and higher efficiency compared to two-level inverters, particularly in weak grid conditions. This study is integral to understanding the benefits of three-level inverters, which are further explored in the current paper. In [18], focused on the use of integrator-based control techniques to better power condition in grid-tied PV systems. The authors demonstrate the efficacy of these control strategies in mitigating grid disturbances like voltage sag, swell, and harmonic distortion. This study directly supports the use of an integrator-based PSE control strategy in the current research to enhance power quality under weak grid conditions. In [19], addressed the challenges associated with using two-level inverters in grid-tied PV systems, particularly in weak grid conditions. The authors propose control strategies to mitigate the power quality issues caused by harmonic distortion and grid voltage anomalies. In [20], focused on reducing THD in grid-connected PV systems using three-level inverters. The authors compare the performance of three-level inverters with two-level inverters, demonstrating that three-level inverters achieve significantly lower THD and improved power quality. In [21], authors proposed an adaptive control strategy for PV systems operating under weak grid conditions. The authors focus on maintaining power quality and system stability during grid disturbances, using a control method that adapts to grid voltage fluctuations and harmonics.

This paper focuses on improving the power quality of a grid-tied PV system under weak grid conditions by an integrator-based positive sequence estimator (PSE) control strategy. The PSE control is designed to get the PSC from distorted and unbalanced grid voltages, enabling the system to generate accurate reference currents and unit templates for efficient power injection into the grid. This control approach ensures stable operation and improved power quality even during grid anomalies such as voltage distortions, DC offset, sag, swell, and unbalance. Additionally, the paper compares the performance of two-level and three-level inverters in this context, highlighting their respective advantages and disadvantages in terms of harmonic reduction, efficiency, and response to grid disturbances. By combining the PSE control with advanced inverter topologies, such as the three-level inverter, the proposed system achieves significant improvements in power quality, with lower THD and enhanced system stability. The contrast between the two-level and three-level inverters in this context highlights the benefits of the three-level inverter in terms of harmonic reduction, efficiency, and response to grid disturbances.

II. PV GENERATED SYSTEM INTEGRATED TO WEAK GRID

Figure 1 provides a detailed illustration of the fundamental structure of a three-phase grid-connected double-stage solar PV system. This type of system is used to integrate solar power to the electrical grid, ensuring efficient power conversion and maintaining grid stability. The system is comprised of various components, each playing a dynamic role in the process of generating and transferring energy by the solar PV array to the weak utility grid.

The PV array is the primary source of renewable energy in the system. It consists of multiple solar panels that convert sunlight into direct current (DC) electricity. The PV array is designed to operate at varying levels of solar irradiance and temperature, directly affecting its power output. The goal of the system is to maximize the extraction of this solar energy and convert it into alternating current (AC) power for grid use. The DC-DC boost converter plays a critical role in extracting maximum power from the solar PV array. It steps up the DC voltage generated by the PV array to a higher level that matches the DC-link voltage for optimal power conversion. The boost converter operates in conjunction with a Maximum Power Point Tracking (MPPT) algorithm to ensure that the PV array consistently operates at its maximum power point (MPP), irrespective of changes in environmental situations like irradiance and temperature.

To maximize the energy collected from the PV array, a Perturb and Observe (P&O) MPPT algorithm is used. This algorithm is one of the most common methods for enhancing the output of solar PV systems. It operates by periodically adjusting the operating voltage of the PV array and observing the resulting change in power output. If the power increases, the adjustment continues in the same direction; if the power decreases, the adjustment is reversed. This iterative process enables the system to continuously track the MPP of the PV array, ensuring that it operates at the highest efficacy even under changing environmental conditions.

The P&O MPPT algorithm ensures that the boost converter maintains the optimal voltage input from the PV array, dynamically adjusting to real-time changes in irradiance and temperature. This facility to track the MPP under fluctuating conditions is crucial for ensuring the efficacy of the solar PV system, especially in locations where sunlight intensity can vary throughout the day. The DC-link capacitor is positioned between the DC-DC boost converter and the VSC. Its primary function is to keep a stable DC voltage level at the input of the VSC. The capacitor acts as an energy storage section, smoothing the power flow from the PV array and DC-DC converter to the VSC. This helps in reducing fluctuations in the DC-link voltage caused by varies in solar power generation, ensuring consistent and stable operation of the VSC.

The solidity of the DC-link voltage is essential for the proper functioning of the VSC, and the capacitor serves as an intermediate energy buffer between the power conversion stages. The VSC is liable for converting the DC power supplied by the PV array to three-phase AC power, which is then fed into the utility grid. The VSC operates with pulse-width modulation (PWM) control to generate sinusoidal waveforms that are synchronized with the grid voltage. It makes sure that the power sent to the grid is of high quality, with minimal harmonic distortion. Additionally, the VSC is designed to use at unity power factor (UPF), meaning that it supplies active power to the grid without introducing reactive power or voltage imbalances.

The VSC is also responsible for controlling the current added to the grid. It operates in a grid-following mode, ensuring that the generated AC current is in phase by the grid voltage, thus maximizing the efficiency of power transfer. The AC inductors are placed between the VSC and the grid to smooth the AC current waveforms generated by the VSC. These inductors help to filter out high frequency switching harmonics that are generated during the conversion process. By smoothing the output current, the inductors ensure that the power sent to the grid is of high quality, meeting grid codes and standards. To further reduce high frequency switching ripples that originate from the VSC's PWM operation, ripple filters (usually in the form of RC filters) are installed. These filters help to absorb the switching noise and harmonics, improving the total power quality of the system. The use of ripple filters is essential to make sure that the current injected into the grid remains sinusoidal, minimizing any potential disturbances or inefficiencies.

In this system, an adaptive DC-link voltage control mechanism is implemented to set the DC-link voltage. Keeping a constant DC-link voltage is vital for stable and efficient operation, especially during dynamic conditions like fluctuating irradiance, grid voltage variations, and power demand changes. The adaptive DC-link control adjusts the DC-link voltage dynamically in response to variations in grid conditions and solar power generation. For instance, during periods of high solar irradiance, when the PV array generates more power, the DC-link voltage may need to be increased to handle the additional power flow. Conversely, when the grid experiences disturbances such as voltage sag or swell, the DC-link voltage is altered to maintain efficient operation and to minimize power losses in the VSC. By adapting the DC-link voltage to the prevailing conditions, the system can operate more efficiently, reducing the stress on the power electronics and ensuring that the VSC operates within safe limits. This adaptive control helps to optimize the overall performance of the solar PV system, extending the life of the components and improving the efficacy of power transfer to the grid.

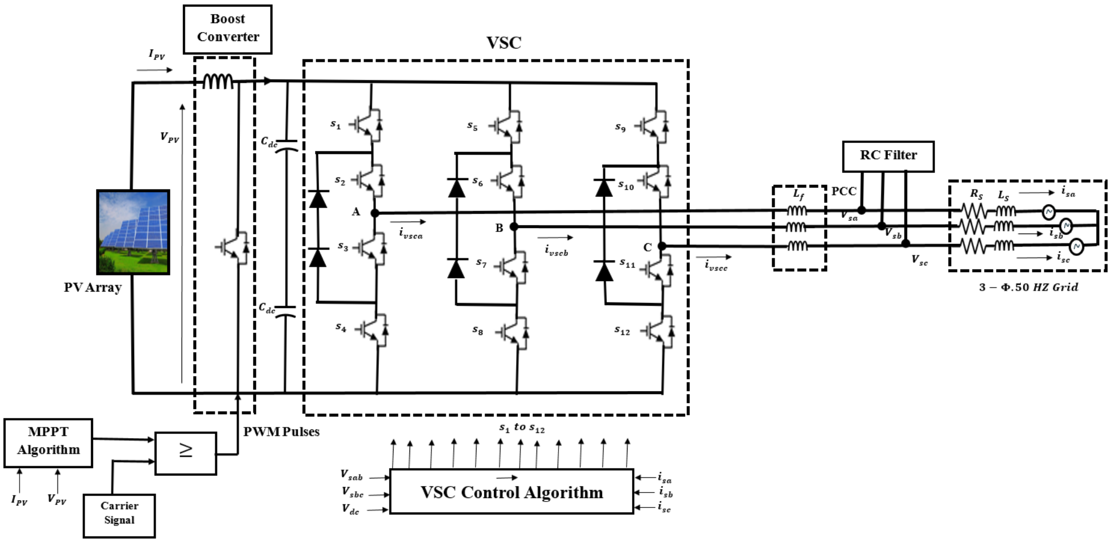

Fig.1. PV generated system integrated to weak grid with three level inverter

III. CONTROL STRATEGY FOR THREE LEVEL VSC

Figure 2 shows the fundamental diagram of an integrator-based positive sequence estimator control. Two control strategies are employed: MPPT control and VSC control. The MPPT control is managed toget maximum power from the PV source. The VSC control algorithm creates gate pulses and enhances power quality in irregular conditions such as intermittent solar irradiations, DC offset, grid voltage distortions, unbalanced voltages at the three-phase point of common coupling (PCC), as well as voltage sags and swells. The VSC control includes the estimate of the loss component (w_{cp}), the PV feed-forward term (w_{pv}), the net active component (w_{sp}), and the grid reference currents (GRC).

A. MPPT Technique

A Perturb and Observe (P&O)-based MPPT algorithm aids maximum power from the PV source during fluctuating solar conditions. It determines the duty cycle for the boost converter, which is estimated by:

$$D = 1 - \frac{V_{pv}}{V_{dc}}$$

Here, V_{dc} represents the DC-link voltage, while I_{pv}, V_{pv}, and P_{pv}refer to the PV array current, voltage, and power, respectively. To create the gate signal for the boost converter, the duty ratio (D), calculated in equation (1), is related with a sawtooth waveform.

B. VSC Control

Figure 2 illustrates the VSC control technique, which includes adaptive DC-link voltage control and grid reference current (GRC) generation. The operation of this scheme is explained below.

C. Unit Templates Estimation

The PCI line voltages (V_{Sab}, V_{Sbc}) are measured and converted into phase voltages (V_{Sa}, $V_{Sb}$and V_{Sc}) . These phase voltages are then changed into the α -β -0 components using Clarke's Transformation (CT), as shown in Figure 3.

$$\begin{bmatrix} V_{S\alpha} \\ V_{S\beta} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{Sa} \\ V_{Sb} \\ V_{Sc} \end{bmatrix}$$

These transformed voltages are fed into an integrator-based positive sequence estimator control to mitigate harmonic content. The integrator-based positive sequence estimator control gets positive sequence components (PSCs) from unstable and partial voltages, ensuring satisfactory system operation under adverse grid conditions, such as voltage sags, swells, unbalances, distortions, and DC offsets. The PSCs are calculated as follows.

Using symmetrical components theory, unbalanced three-phase voltages are converted into balanced components as:

$$\begin{bmatrix} V_{p\alpha\beta} \\ V_{n\alpha\beta} \end{bmatrix} = \begin{bmatrix} j\omega_0 & 0 \\ 0 & -jw_0 \end{bmatrix} \begin{bmatrix} V_{p\alpha\beta} \\ V_{n\alpha\beta} \end{bmatrix} + \begin{bmatrix} \omega_0 \\ \omega_0 \end{bmatrix} \left(v - \left[k_\alpha k_\beta\right] \begin{bmatrix} V_{p\alpha\beta} \\ V_{n\alpha\beta} \end{bmatrix} \right)$$

The above equation becomes

$$\begin{bmatrix} V_{p\alpha\beta} \\ V_{n\alpha\beta} \end{bmatrix} = \frac{\left[k_\alpha k_\beta\right]\omega_0}{s^2 + 2\omega_0\left[k_\alpha k_\beta\right] + \omega_0^2} \begin{bmatrix} s + j\omega_0 \\ s - j\omega_0 \end{bmatrix} \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix}$$

Here, $V_{p\alpha\beta}$ and $V_{n\alpha\beta}$ represent the positive and negative sequence components in the α -β domain, respectively. The constantsk_α and k_β are defined as well, while ω_0 is the rated frequency (calculated as 2·π·50=314 rad/s). These PSCs are then altered into the abc form. The PSCs (V_{pa}, V_{pb}, and V_{pc}) are extracted from this output by inverse CT.

$$\begin{bmatrix} V_{pa} \\ V_{pb} \\ V_{pc} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} \frac{2}{3} & 0 \\ -\frac{1}{3} & \frac{\sqrt{3}}{3} \\ -\frac{1}{3} & \frac{\sqrt{3}}{3} \end{bmatrix} \begin{bmatrix} V_{p\alpha} \\ V_{p\beta} \end{bmatrix}$$

These obtained positive sequence voltages (V_{pa}, V_{pb}, and V_{pc}) are used to assess the in-phase unit templates (UTs) (U_{pa}, U_{pb} , and U_{pc}) as follows:

$$V_t = \sqrt{\frac{2}{3} \times \left(v_{pa}^2 + v_{pb}^2 + v_{pc}^2\right)}$$

where V_t is terminal PCI voltage

$$U_{pa} = \frac{U_{pa}}{V_t}, U_{pb} = \frac{U_{pb}}{V_t}, U_{pc} = \frac{U_{pc}}{V_t} U_{pa}$$

### *D.	PI Controller for DC-Link Voltage*

To estimate ω_{pc} (the loss component of the DC-link), the sensed V_{dc} is subtracted from the source DC-link voltage v_{dc}^*, resulting in an error. This error is then see to a Proportional-Integral (PI) controller. This process can be described using the following equations:

$$\omega_{pc} = \left(k_{pd} + \frac{k_{id}}{s}\right)(V_{dc}^* - V_{dc})$$

where k_{pd} and k_{id} are the PI controller gains.

### *E.	DC-Link Voltage Adaptive Control*

The V_{dc} is adjusted in response to variations in the grid voltages to reduce VSC losses. Consequently, V_{dc} is dependent on the grid voltage. The V_{dc} is influenced by the grid voltage. But the energy caused by a solar PV system stays modest by changes in the source voltage. During certain dynamic conditions, it is possible for the current to over the rating of the VSC. The reference DC-link voltage V_{dc}^* is estimated as follows:

$$V_{dc}^* = \lambda\sqrt{3}V_t$$

where the value of λ >1, typically taken as 1.2.

### *F.	PV Source Component Computation*

Changes in PV irradiation caused disturbances in the system. To reduce these effects, a PV term is added. This PV source term helps the system operate efficiently under changing conditions. It is calculated as follows:

$$\omega_{pv} = \frac{2}{3} \times \frac{P_{pv}}{V_t}$$

### *G.	grid reference currents Estimation:*

To generate the gate signals for the VSC, the grid reference currents are calculated. These grid reference currents are computed as follows:

$$i_{sa}^* = \omega_{sp}.u_{pa}$$

$$i_{sb}^* = \omega_{sp}.u_{pb}$$

$$i_{sc}^* = \omega_{sp}.u_{pc}$$

In this context, ω_{sp} represents the net weight component, defined as:

$$\omega_{sp} = \omega_{cp} - \omega_{pv}$$

The differences between the reference currents i_{sa}^*, i_{sb}^*, i_{sc}^* and the actual currents i_{sa}, i_{sb}, i_{sc} are sent to the hysteresis control for the generation of VSC gate pulses.

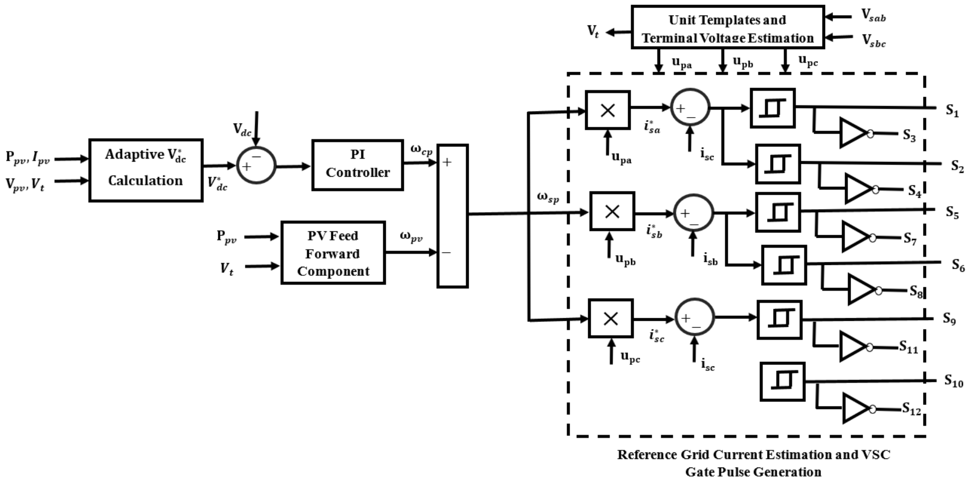

Fig 2.control strategy for three level converter

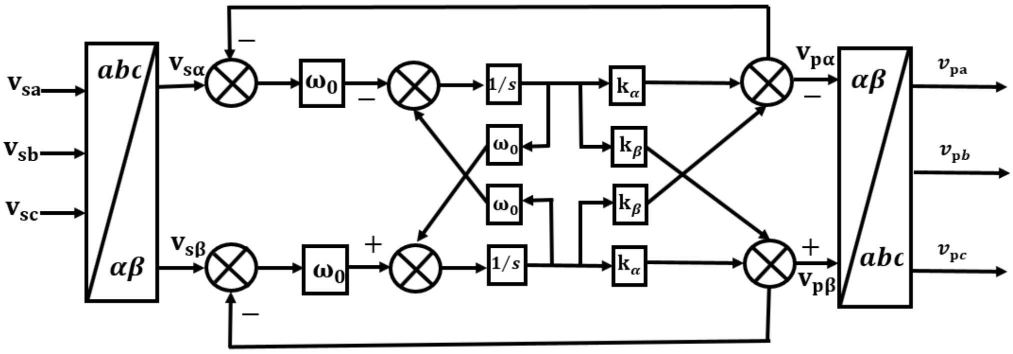

Fig 3. Positive sequence estimator control

IV. SIMULATION RESULTS

In this section, the simulation outcome of a two-stage photovoltaic (PV) system connected to weak grid, incorporating a DC/DC convertor and a three-level inverter, are presented. The system is assessed various dynamic conditions, and the results demonstrate the execution of the control strategy and the inverter configuration. Fig 1 illustrates the schematic of the system, highlighting the integration of the PV array, the DC/DC converter, and the three-level inverter interfacing the grid. Parameters of the system are shown in table 1. The system is tested under several operating scenarios, including irradiance variation, grid voltage swell, grid voltage sag, and a comparative analysis between two-level and three-level inverters. The key parameters analysed include grid voltage, grid current, VSC current, PV array current, and the weight component of the positive sequence. These variables provide insight into the system's stability, power quality, and transient response under dynamic conditions.

Table 1. System Parameters

Parameters	**Value**
PV Array	
Power Rating	31 kW
Maximum Power (W)	203.902
Cells per module (Ncell)	60

Open circuit voltage Voc (V)	33.17
Short-circuit current Isc (A)	8.08
Voltage at maximum power point Vmp (V)	26.9
Current at maximum power point Imp (A)	7.58
Temperature coefficient of Voc (%/deg.C)	-0.36099
Temperature coefficient of Isc (%/deg.C)	0.102
Shunt resistance Rsh (ohms)	315.6349
Series resistance Rs (ohms)	0.29005
Parallel strings	6
Series-connected modules per string	26
Boost Converter	
Inductor L_{dc} (mH)	2
Capacitor C_{dc} (μF)	100
Voltage Source Converter	
Interfacing Inductor L_f (mH)	50
RC R_f (Ω)	0.2
RC C_f (μF)	100
Grid Voltage and Frequency, (V) and (Hz)	415, 50

A. Case 1: Irradiance Variation

In this scenario, the system’s behaviour is analysed to changes in solar irradiance, which directly affects the output power of the PV array. The solar irradiance variation is a common occurrence in real-world PV systems due to environmental factors like cloud cover, shading, or time-of-day changes. As the irradiance decreases, the amount of energy captured by the PV modules diminishes, impacting the overall system power generation. The system is expected to maintain its performance, particularly with respect to power quality, grid interaction, and MPPT operation during such variations.

Figure 4 presents the waveforms of the grid voltage and the current under irradiance variation. At a high level of solar insolation, the PV system generates maximum power, resulting in a higher grid current as more power is fed into the grid. As the irradiance decreases, there is a noticeable reduction in the grid current, which directly corresponds to the drop in the power being supplied by the PV array.

Despite the reduction in grid current, the grid voltage remains stable and sinusoidal, as the control system, particularly the integrator-based positive sequence estimator (PSE), ensures that the inverter maintains a proper balance between the grid current and voltage. The PSE control continues to get the positive sequence components of the grid voltage, ensuring that the grid current remains in phase and harmonically pure, even as the power made by the PV array diminishes. This is crucial for maintaining grid stability and adhering to power quality standards, such as the IEEE 519.

Figure 5 provides detailed waveforms of the VSC current, PV array current, and the weight component of the positive sequence. These waveforms reflect the internal dynamics of the grid-connected PV system as it responds to irradiance changes. As irradiance decreases, the output current of the PV array also decreases because less solar energy is available for conversion into electrical power. This reduction related to the decrease in insolation. The PV array is operating under maximum power point tracking (MPPT) conditions, entirely using the perturb and observe

(P&O) MPPT algorithm, which dynamically adjusts the operating point of the PV array to always ensure maximum power extraction. As a result, even as the irradiance drops, the PV array continues to direct at its most efficient point, although the total power generated is lower.

The VSC current decreases when the power output from the PV array drops. The VSC converts the DC power from the PV array into AC power to be sent to the grid. As the PV array generates less power due to reduced irradiance, the VSC reduces its current output correspondingly. However, the VSC control keeps the quality of the current waveform, ensuring that it stays sinusoidal and synchronized by the grid voltage. The three-level inverter, with its superior switching capabilities, helps in maintaining smoother transitions and lower harmonic distortion in the VSC current, even during such dynamic variations.

The weight component reflects the positive sequence components extracted by the integrator-based PSE control. The PSE continuously monitors the grid voltage to isolate the positive sequence component, ensuring that the grid current remains balanced, regardless of grid disturbances or fluctuations in PV power output. In this case, as the irradiance decreases, the weight component adjusts dynamically, indicating that the PSE control is accurately tracking the grid voltage's positive sequence and keeping the system synchronized with the grid.

Even as the solar irradiance decreases, the system maintains MPPT operation through the P&O algorithm. The P&O MPPT controller adjusts the managing voltage of the PV array to ensure that it remains to operate at its maximum power point, extracting as much energy as possible from the available sunlight. When the irradiance decreases, the MPPT algorithm compensates by slightly reducing the operating voltage, ensuring the PV array remains at its peak efficiency. As a result, even though less power is available, the system operates optimally, ensuring efficient energy extraction under changing irradiance conditions.

Due to the reduction in available solar energy, the overall power given by the PV array to the grid decreases. This reduction in power is reflected in the grid current, which decreases proportionally. However, the system ensures that the grid voltage remains stable and that the power added to the grid is of high quality, with low harmonic distortion and minimal imbalances, due to the integrator-based PSE control and the capabilities of the three-level inverter.

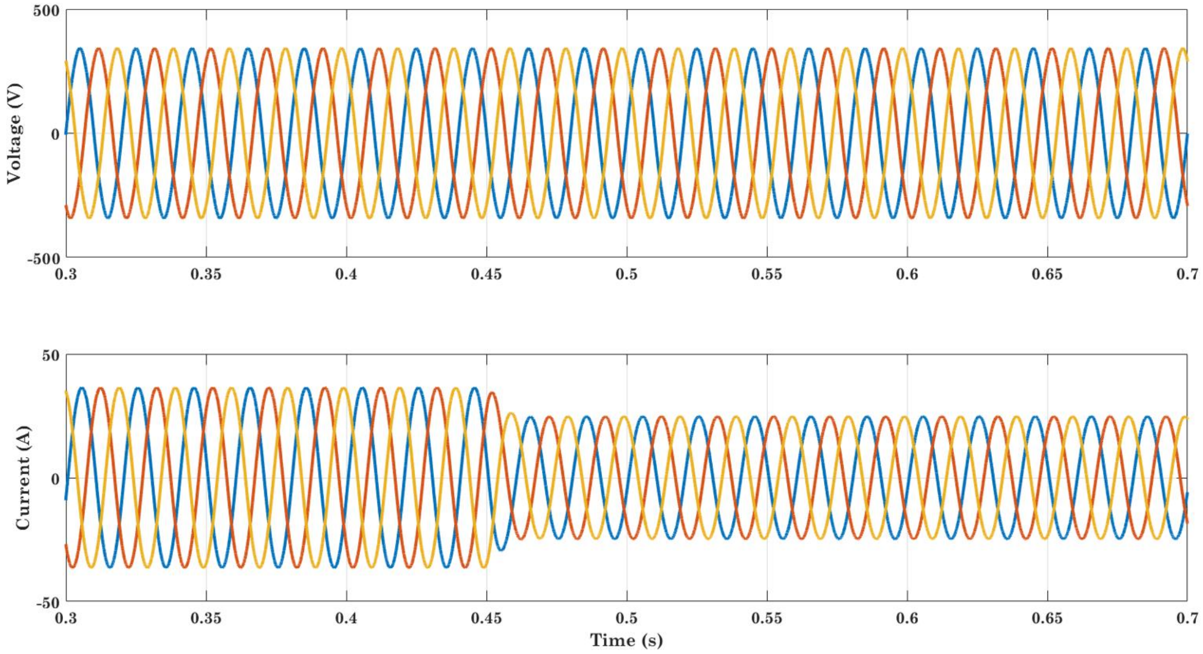

Figure 4: Grid voltage and current

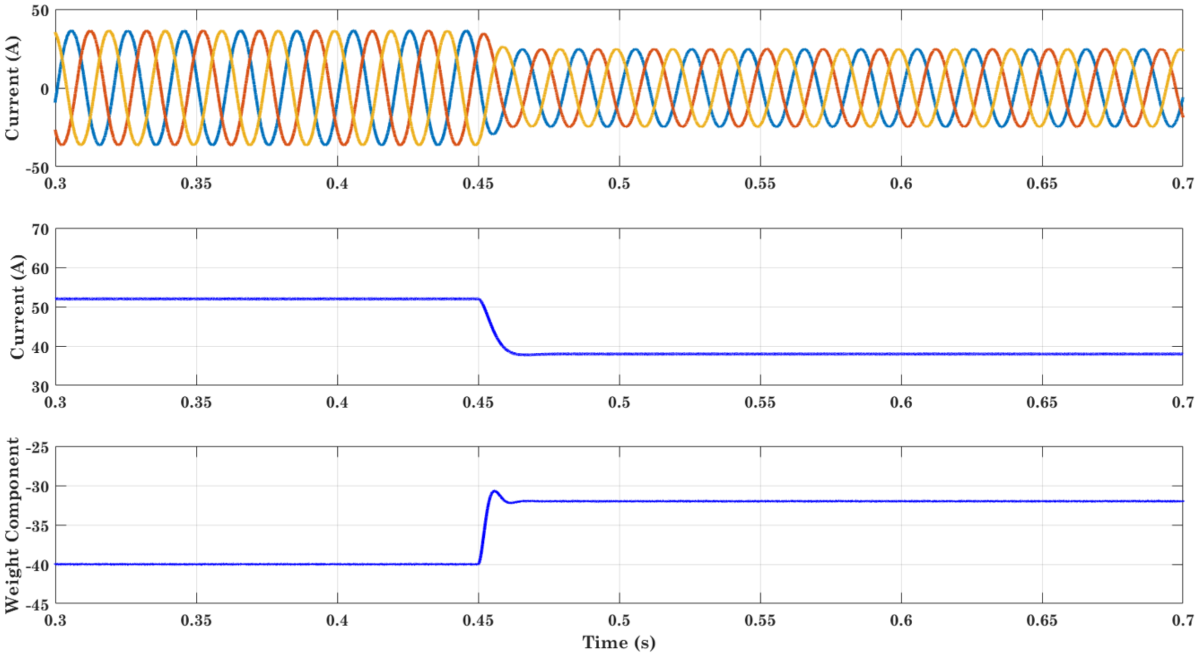

Figure 5. VSC current, PV array current and weight component

B. *Case 2: Grid Voltage Swell*

A voltage swell gets when there is a rapid rise in the grid voltage above its nominal value. This phenomenon is typically caused by a sudden disconnection or removal of a large load from the supply grid, leading to a temporary overvoltage condition. In such scenarios, the performance of grid-tied PV systems can be affected, as the inverter needs to adjust its operation to maintain power quality and prevent any damage to the connected equipment. The system must manage both the voltage swell and the resulting changes in power flow for safe and efficient operation.

Figure 6 shows the waveforms of the grid voltage and current in a voltage swell scenario. In this simulation, a voltage rise of 20% above the nominal grid voltage is introduced to assess the system's execution. The system must dynamically adjust the power added into the grid to ensure stable operation while maintaining the desired power quality.

During a voltage swell, the grid voltage waveform shows a clear 20% increase in magnitude for a certain period. This rise in voltage can negatively impact the connected loads and the VSC if not properly managed. The grid-tied inverter must adapt its control to this overvoltage condition to avoid overloading the procedure. To maintain the constant power supply to the grid, the system decreases the grid current in proportion to the voltage swell. The grid current is inversely proportional to the grid voltage to settle that the total power added into the grid remains unchanged, even as the voltage rises. This adjustment in the grid current is vital for stabilizing the power output and avoiding an raise in the active power supplied, which could overload the grid.

The integrator-based positive sequence estimator (PSE) control ensures that the grid current remains balanced and sinusoidal, even though its magnitude has decreased. The PSE extracts the positive sequence mechanisms by the grid voltage, enabling the inverter to generate a corresponding balanced current that adheres to power quality standards, such as low harmonic distortion (THD), even during abnormal grid conditions like a voltage swell.

Figure 7 illustrates the waveforms of the DC-link voltage and the voltage VSC current in the voltage swell. These two parameters are critical for the process of the grid-connected PV system, as they influence the system’s ability to regulate power flow and maintain stable operation. During a grid voltage swell, the fixed DC-link voltage can lead to a raise in VSC losses. This is because the VSC, which changes the DC power from the PV array into AC power for the grid, must work harder to insist the needed current output while dealing with the increased grid voltage. If the DC-link voltage remains constant, the mismatch in the DC voltage and the higher grid voltage outcome in increased switching and conduction defeats in the VSC.

To mitigate this issue, the system incorporates an adaptive DC-link voltage control. Instead of maintaining a fixed DC voltage, the DC-link voltage is altered dynamically in response to changes in the grid voltage. In the voltage swell, the DC-link voltage is grown in proportion to the grid voltage rise, allowing the VSC to operate more efficiently and reducing the associated losses. This adaptive control strategy helps to optimize the performance of the inverter, preventing excessive heat generation and power loss in the VSC. The adaptive DC-link voltage helps keep the system efficient and stable, even during grid voltage anomalies, and helps prolong the lifespan of the VSC components by dropping stress on the power electronics. The VSC current also adjusts during the voltage swell to reflect the reduced power demand by the PV array. As the grid voltage increases, the current injected by the VSC in the grid is reduced, ensuring that the total power added into the grid remains consistent with the available solar power. This current reduction is achieved through precise control of the switching operations within the three-level inverter, which modulates the VSC current output in response to the changing grid conditions.

The three-level inverter plays a key role in maintaining smooth transitions and reducing the overall harmonic content of the VSC current. By allowing for finer control over the voltage waveform, the three-level inverter reduces switching losses and ensures a higher quality of the injected current, even during abnormal grid conditions like a voltage swell. The integrator-based PSE control further ensures that the VSC current rest balanced, sinusoidal, and synchronized by the grid voltage, minimizing distortions and maintaining compliance with IEEE 519 harmonic standards.

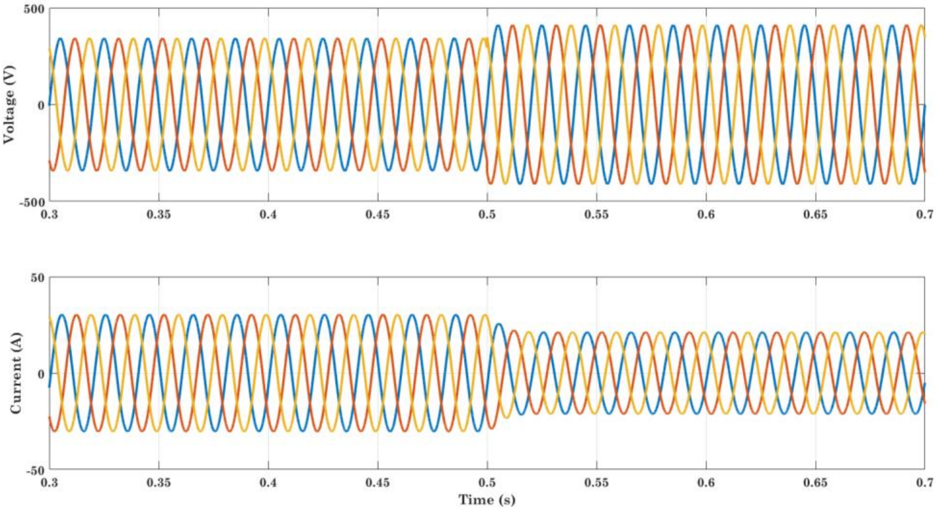

Figure 6. Grid voltage and current

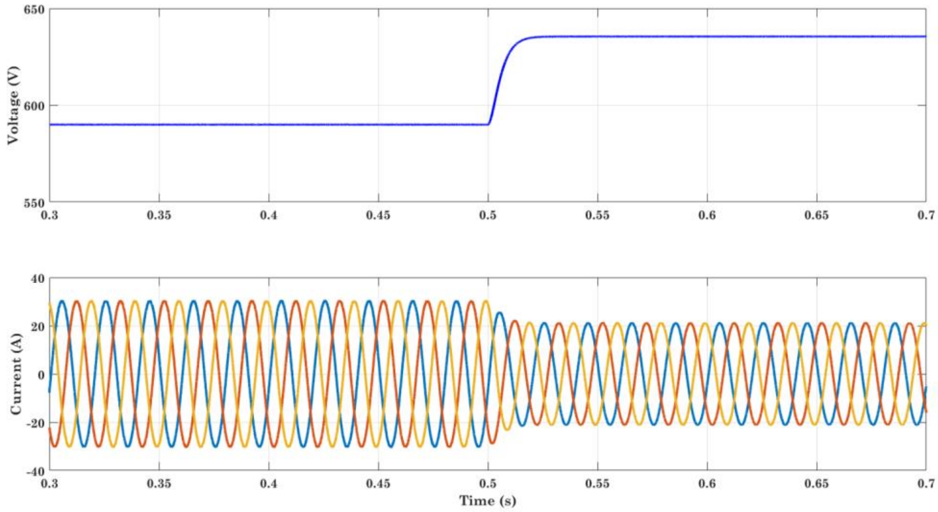

Figure 7. DC link voltage and VSC current

C. Case 3: Grid Voltage Sag

Grid voltage sags, or dips, occur when there is a sudden decrease in voltage in the distribution grid, typically caused by an increase in load demand or grid disturbances such as faults. A voltage dip can significantly affect the operation of grid-connected PV systems, as it can lead to variations in the current supplied to the grid and increased stress on the power electronics. In this scenario, the system's response to a grid voltage dip of 20% is analysed. The impact of this voltage sag on the grid and the system's components is demonstrated in Figures 8 and 9. These figures illustrate key electrical parameters during the voltage dip, including the grid voltage, grid current, DC-link voltage, and VSC current.

Figure 8 shows the behaviour of the grid voltage and grid current in the grid voltage dip. As seen, when the grid voltage drops by 20%, the grid current increases proportionally. This increase in current is due to the system attempting to maintain constant power supply to the grid. Figure 9 shows the DC-link voltage and the current through the VSC during the grid voltage dip. In normal operation, the DC-link voltage is kept stable to ensure the VSC works properly. The VSC converts the DC power from the solar PV array into AC power that is synchronized with the grid. During the voltage sag, while the grid voltage decreases, the DC-link voltage initially remains stable. This stable DC-link voltage allows the VSC to continue operating without interruption. However, maintaining a fixed DC-link voltage under these conditions leads to an increase in switching losses in the VSC.

The increase in grid current during a voltage dip amplifies the switching losses in the VSC, which are directly related to the current flowing through the power switches. As the grid current rises to compensate for the reduced voltage, the VSC must handle higher currents, leading to more frequent switching events and increased energy dissipation in the form of heat. This can degrade the efficacy of the system and shorten the lifetime of the power electronic components. To mitigate this issue, an adaptive DC-link voltage control strategy is employed. Rather than asserting a constant DC-link voltage during grid disturbances, the system adapts the DC-link voltage in response to changes in the grid voltage. When the grid voltage dips, the DC-link voltage is reduced accordingly, which helps to decrease the VSC's switching losses. By flexibly adapting the DC-link voltage to the grid conditions, the system optimizes the performance of the VSC, reducing the heat generated by switching events and prolonging the life of the components. This adaptive control ensures that the system can maintain efficient operation during grid disturbances, minimizing energy losses and maintaining stable power supply to the grid.

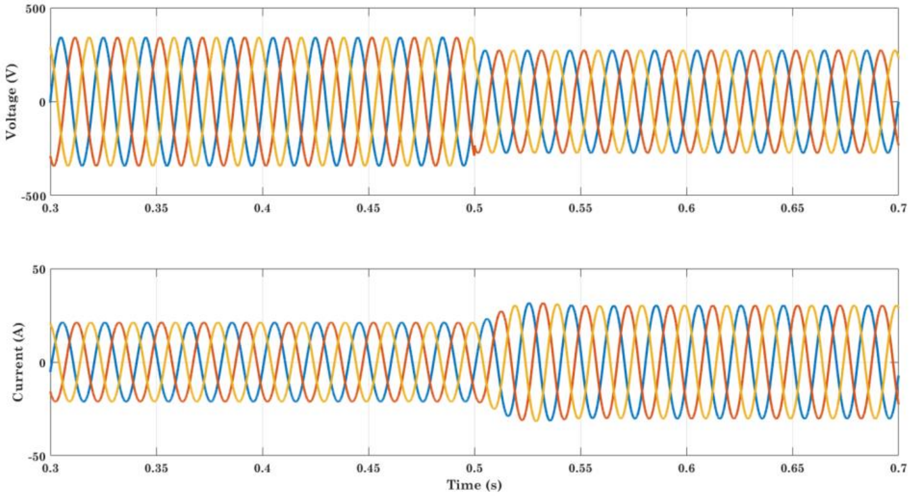

Figure 8. Grid voltage and current

Table 2. THD comparison

	Two Level Inverter			Proposed Three Level Inverter		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Grid Voltage	3.1%	3.05%	3.06%	1.4%	1.39%	1.39%
Grid Current	2.5%	2.5%	2.45%	1.1%	1.1%	1.01%

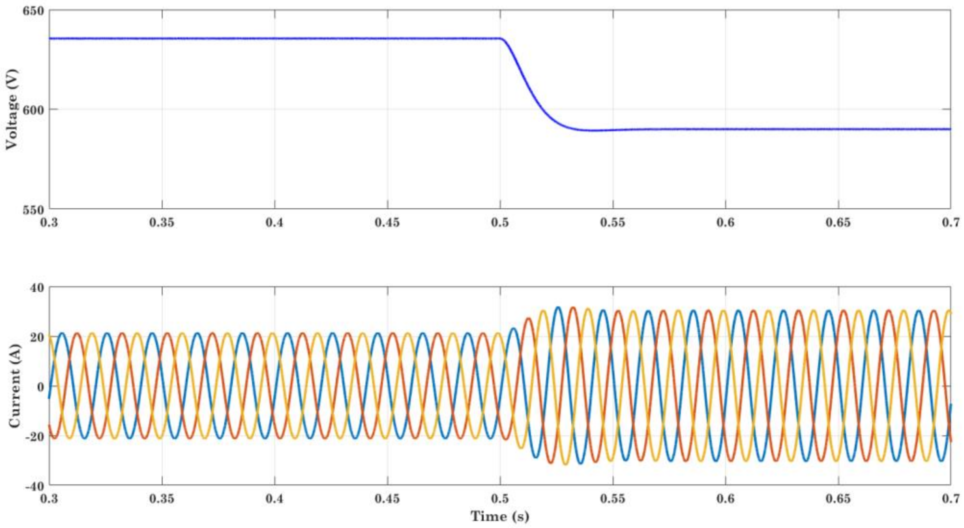

Figure 9. DC link voltage and VSC current

D. *Case 4: comparison with two level inverter*

Table 2 provides a detailed comparison of the system's performance using a standard two-level inverter and the future three-level inverter system, focusing on the Total Harmonic Distortion (THD) in the grid current and voltage. With the two-level inverter, the THD in the grid current is assessed at 2.5%, and the THD in the grid voltage is 3.1%. These relatively high distortion levels indicate inefficiencies in power quality and may lead to undesirable effects on grid performance. In contrast, when the proposed three-level inverter system is implemented, the THD is significantly reduced. The THD in the grid current drops to 1.1%, and in the grid voltage, it reduces to 1.4%. This substantial improvement demonstrates the effectiveness of the proposed system in minimizing harmonic distortions, ensuring smoother and more efficient grid operation. By improving the THD values, the proposed three-level inverter enhances the overall power quality, reduces losses, and ensures compliance with grid standards. The results clearly show that the three-level system outperforms the two-level inverter, making it as choice for making high-quality power delivery.

V. CONCLUSION

This paper presents a comprehensive study on power quality improvement in a grid-connected double-stage solar PV system, using two-level and three-level inverters in various dynamic conditions. The proposed system uses an integrator-based positive sequence estimator to reliably extract positive sequence components of grid voltages and maintain strong performance, even when the grid experiences issues like voltage distortion, unbalance, and sag/swell. The system uses adaptive control strategies for the DC-link voltage to optimize the performance of the VSC, reducing power losses during weak grid conditions. Key dynamic scenarios, including variations in irradiance, grid voltage swell, and voltage sag, were simulated to assess the execution of the system. In the case of irradiance variation, the PV array, controlled by the P&O-based MPPT algorithm, successfully tracked the MPP, while the system responded by adjusting the grid current in accordance with the available solar power. In grid voltage swell and sag, the adaptive DC-link voltage control mitigated VSC switching losses and ensured efficient power delivery to the grid by adjusting the grid current accordingly. Moreover, a comparative analysis of the two-level and three-level inverters demonstrated that the three-level inverter offers superior performance in terms of reduced harmonic distortion, better power quality, and lower switching losses, particularly in grid disturbances. The simulation results validated the intended system's ability to meet the stringent power quality standards outlined by IEEE-519, making it suitable for integration into modern grids facing intermittent solar irradiance and grid disturbances. The integration of advanced control strategies, including the positive sequence estimator, MPPT algorithm, and adaptive DC-link voltage regulation, enables the proposed system to improve the consistency, efficacy, and power quality of solar PV systems connected to weak grids. These findings contribute to the ongoing efforts to improve renewable energy integration into the grid while maintaining stability and accordance with grid codes.

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