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Impact of Inverter Controller-Based Grid-Connected PV System in the Power Quality

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Abstract—**In a Grid-Connected Photovoltaic System (GCPS), the inverters are applied for integration with the power grid. This integration brings some issues at the connection point. Therefore, grid-tied inverter control performs a vital role in feeding the power system with good power quality. This study presents a current-controlled Voltage Source Inverter (VSI) strategy for large-scale GCPS generates 1000 kW rated of power. The methodology and structure of the control system are presented. The power quality issues such as harmonics, voltage fluctuation, voltage unbalance, and power factor are limited at the interfacing point into the required limits as imposed by the standards. This study also discusses the controller design and the simulation results are introduced to show its effectiveness. Furthermore, the values obtained may be used to evaluate the power supply quality of various inverter controllers.**

Index Terms—**Photovoltaic system; Power quality; Voltage source inverter; Inverter control; Grid-connected PV system.**

I. INTRODUCTION

Photovoltaic (PV) technology is presently important and its rapid growth is expected to continue and to play a major role in energy production around the world. Recently, there has been constant rapid growth in the PV renewable energy sector [1]. In this regard, based on the renewable status report in 2019, the annual capacity of solar photovoltaics (PV) generation increased only slightly in 2018, but enough to surpass the 100 GW level for the first time. Cumulative capacity increased approximately 25% to at least 505 GW; this compares to a global total of around 15 GW only a decade earlier. By year's end, with around 100 GW added, solar PV was once again the frontrunner for installed renewable power capacity [2].

In a Grid-Connected PV System (GCPS), typically, the PV interconnection is carried out through the inverter. Therefore, the inverter is considered as an essential part in order to invert the generated dc power from the PV system into ac power to match the grid voltage and frequency. This importance comes since the inverter is needed to fulfill the power conversion and control optimization. Inverter technology is likewise necessary for safe and reliable grid integration and to produce a very good power quality to the utility grid [3], [4]. The PV inverters are categorized into various sorts depending on the topology, the method of connection with the electrical grid, and operation standard. There are several forms of connection to the power grid, but the well-known PV inverter-linked grids are the line-commutated and self-commutated inverters [5]. In the case of line-commutated inverter type, it is typically connected to the utility grid via line or directly to the network. In this case, the conversion of power (from dc to ac) is operated by the electrical line. Therefore, in case of grid failure or disturbances, the PV system will be unable to feed electricity into the lines. A self-commutated inverter has two primary branches that are alternatively attached to the dc voltage source in series [6]. Based on the literature, the self-commutated inverter is the predominant category in PV-grid integration. It is preferred because of its ability to handle the output of ac signals (voltage and current), regulate the power factor, and mitigate the current harmonics distortion [7]. For grid interfacing, self-commutated inverters are divided into Voltage Source Inverters (VSI) and Current Source Inverters (CSI) based on the kind of pulse they are controlling, either voltage or current. VSI control also can be divided into voltage- or current-controlled inverter [8].

It is necessary for any inverter controller connected to the power grid not to degrade the power quality at the Point of Common Coupling (PCC) [9]. Therefore, the consequences of bad quality of inverter controller output injected into the system must be taken into consideration. The current-controlled VSI can generate an excellent quality of power quality [10]. The use of this type of controller in the literature in GCPS has been done in [11] with the Proportional Integral Derivative (PID) technique. The effect of inverter current-controller in power quality issues and the performance using a Proportional Resonant (PR) controller were studied in [12]. In contrast to

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another controller, this type of control is able to track the stationary reference value known as ($\alpha\beta$ frame) in a stationary reference frame and the sinusoidal current reference without phase error. The other popular current-controlled type is the Repetitive Current (RC) controller, which is able to eliminate a steady-state error by periodically monitoring its components. Moreover, the RC controllers are able to monitor fundamental current references and compensate for high order harmonics, as proved by [13]. Nevertheless, the RC controllers are applied only for static operation mode and cause stability problems and bad quality of power due to its slow response [14]. The main two non-linear current controllers of the inverter linked GCPS are hysteresis controller and Dead Beat (DB) controller. Hysteresis control is able to handle the power transfer, but a high voltage fluctuation and harmonics have appeared at the PCC [15]. Another kind is the DB controller that is applied as the control approach in lots of applications as described in detail by [16]. In comparing with linear methods, these controllers have some disadvantages regarding complexity and power quality, especially during dynamics operation.

This research introduces a three-phase VSI power control for a grid-tied PV system using a current-controlled strategy. The control technique depends on the PI-based *dq* controller of power to supply active and reactive power into the utility grid using decoupling control. The paper's goal is to control energy transferring at PCC, to enhance the overall performance of energy produced from PV into the grid, and to ensure good power quality has been injected to the utility grid while improving the voltage quality at the PCC.

II. CURRENT-CONTROLLED VSI-BASED GCPS

The generated PV energy is transformed into the grid through the VSI. The input side controller of the inverter is utilized to maximum power tracking while the output side controller is used to regulate the active and reactive power supplied into the grid. Inverter control methods can be either voltage-controlled or current-controlled. However, current-controlled inverters are more common and frequently used in GCPS compared to voltage-controlled inverters because they achieve a high power factor and mitigate the distortion of harmonic current [11].

In this study, the feed-forward decoupling PI current controller-based synchronous rotating reference frame (*d-q* control) is utilized to control the connection of the proposed PV system into the power grid. The three-phase inverter design is implemented with synchronous rotating frame control (*dq* control) using the decoupling and voltage feed-forward strategies. In order to attain PV system integration, two control loops, including both external and internal, are implemented.

A. Proportional-Integral (PI) or d-q Controller

The PI controllers are commonly related to *dq* control method due to its ability to control the dc variables. The *dq* control is likewise known as an SRF control. In this type of control, grid currents in *abc* natural frame are converted into a *dq* reference frame that rotates synchronously with the grid voltage at the angular speed of ω. The transformation equations are known as Park's transformation [17]. A standard shape of the *dq* control can be seen in Fig. 1. The *dq* representation is regarded as a streamlined way of representing a set of three sinusoidal phase currents and voltages using only two values to effectively regulate grid current and voltage. As a consequence, it is a great simplification of the three-phase system and therefore, it can be controlled using only two values.

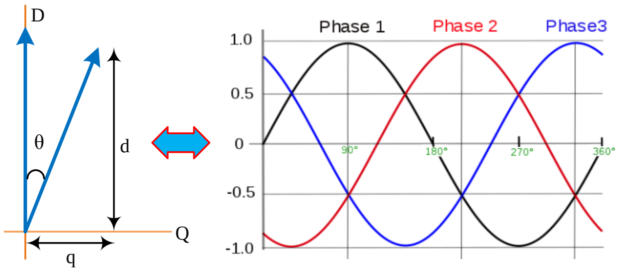

Fig. 1. d-q Coordinates.

The output controller (dc-link voltage controller) is utilized to regulate and produce the active reference current component. On the other hand, depending on the requirement for GCPS at ordinary operation mode, the reference of reactive power is set to zero [18]. In *dq* coordinates system, the PI controller gain is defined through the Transfer Function (TF) showed in the following equation:

$$G_{PI}(s) = K_P + \frac{K_I}{s} \tag{1}$$

where the integral and proportional gain of the PI controller are represented by K_i and K_p, respectively. The *dq* control structure involving decoupling the grid current and grid voltage feed-forward. It is expected that the control's dynamics would be high in the period of grid voltage fluctuations due to the use of grid voltage feed-forward in this structure of the control [19].

B. VSI Inner Control Loop

To facilitate the controller design, in the inner loop control, a feed-forward decoupling control strategy is adopted to decouple the active (I_d) and reactive currents (I_q). The simplification structure of the internal loop control is illustrated in Fig. 2. The instantaneous value of dc-link voltage, current, and grid voltage is obtained in due time through the control system. In the meanwhile, the control pulse width of every bridge arm is measured. For the purpose of synchronization, the current and voltage of the GCPS should have the same frequency and phase, which can be accomplished via the Phase-Locked Loop (PLL). It is important to mention that in order to achieve the PV system's current source integration, the internal loop picks the active reference current produced by the external loop control as the first input. In the meantime, the second input of the internal loop (reactive current) is set to nil. The inverter thus usually works around unit power factor [20].

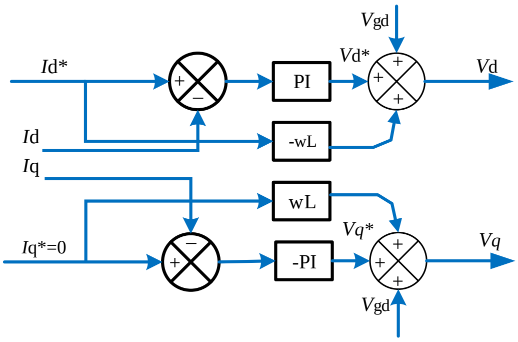

Fig. 2. Inner loop control mode of the inverter.

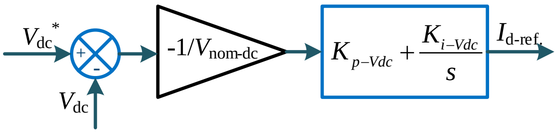

Fig. 3. Outer loop control mode of the inverter.

C. VSI Outer Control Loop

In the VSI system, the outer loop known as dc-link voltage control is useful in stabilizing dc-link voltage (V_{dc}) to its nominal value and provides an active current reference for the internal loop controller. The typical proportional-integral (PI) controller is used to adjust this voltage to maintain the dc-link at its rated value. The streamlined diagram of the external loop displays in Fig. 3.

As the dc-link voltage operates typically at the maximum power point, the output power is supplied to the ac-side. The power delivered to the inverter is calculated based on (2); likewise, the injected power from the VSI to the utility grid is as described (3), as follows:

$$P_{input-inv.} = I_{mpp} \times V_{dc} \tag{2}$$

$$P_{out-inv.} = (I_d \times V_d) + (I_q \times V_q) \tag{3}$$

D. Sinusoidal Pulse Width Modulation

The VSI power converter converts the input dc-voltage to a three-phase ac output voltage. The output ac voltage is created by turning on and off appropriate Insulated Gate Bipolar Transistors (IGBT) within the VSI using PWM signals. The sinusoidal PWM is essentially a carrier-based PWM technique. In this technique, the fundamental sine wave is considered as the modulating signal and the high-frequency triangular wave is the carrier signal.

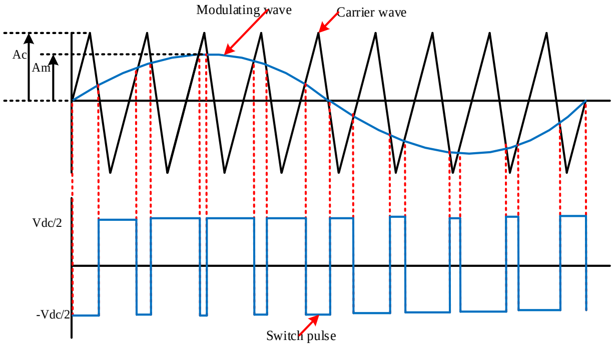

Fig. 4. Principle of sinusoidal PWM control for VSI.

The PWM controller shown in Fig. 4 can compare the magnitude of the modulating wave with the magnitude of triangle carries signal every time and at every point, if the reference signal is higher than the carrier, then the switching pulse would be on (1) and therefore the positive side of dc-link will be connected with the output voltage of inverter leg. If the reference signal is lower than the carrier, then the switching pulse should be off (0) and therefore, the negative side of dc-link will be connected with the output voltage of the inverter leg.

The generated 50 Hz square wave should be converted to a sinusoidal wave that can be connected to the ac power system. Simply, output signals of the PWM are constructed by comparing two control signals, a modulation signal, and a carrier signal. That is referred to as the carrier-based PWM. The high frequency (switching frequency) triangular waveform is the carrier signal, while the modulation signal is the reference sine wave. The output will comply with the shape of the modulation signal in case of its peak is lower than the carrier signal peak. The voltage is therefore encoded into a fixed carrier frequency wave. While the frequency of PWM is continuous, the duties cycle variable from 0% to 100%. The percentage of the on-time period will proportional to the voltage output signal. For example, a 100% duty cycle generates a maximum peak voltage, and a 0% duty cycle produces a 0 output voltage, as illustrated in Fig. 5.

The PWM of the inverter switches (timing of the switches) indicates the modulation of the switching pulses. By using the duty cycle information, the value of the sine wave can be defined. As can be seen in Fig. 5, at the top of the sinewave, the duty cycle is 90-100%, and therefore the sinewave is the maximum, and the sinewave is minimum when the duty cycle is almost zero (the switch almost off). While at π, the duty cycle is almost 50%, so the sinewave is located in the middle. Consequently, the sine wave value is encoded in the duty cycle of this PWM. As a result, the PWM duty cycle is proportional to the reference signal value. The produced wave passes through a filter to produce a pure sine wave as much as possible.

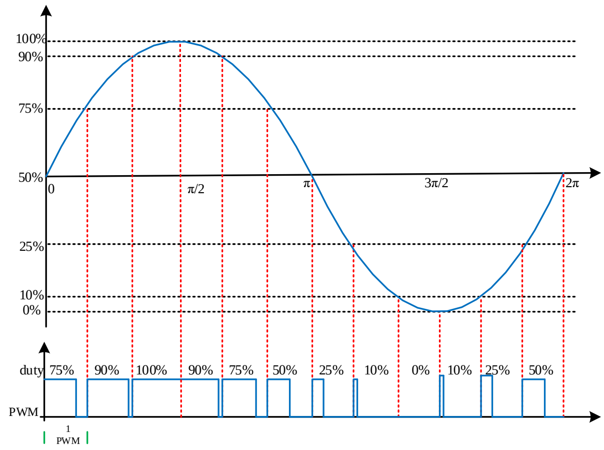

Fig. 5. Sample of sine wave points via corresponding PWM modulated signal.

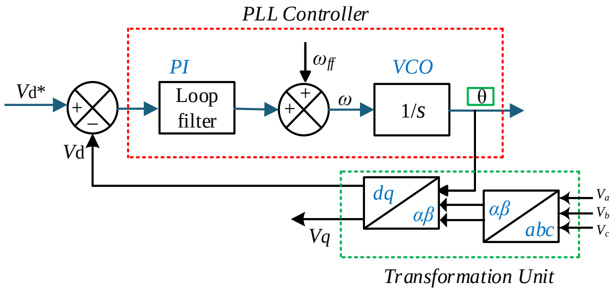

Fig. 6. Structure of the SRF-PLL

E. *The Phase-Locked Loop and Grid Synchronization*

After generating a sine waveform a modulating signal reference using PWM, it is important to match frequency with the grid and lock on like any other generator using grid voltage phase angle synchronization, and this aspect is classified as one of the important issues in PV inverters-grid connection. In this regard, the approach of the phase-locked loop (PLL) is taken into consideration as one of the popular and extensively applied technologies [21].

The SRF-PLL control also named *d-q* control. It is a non-linear closed-loop system with a PI-controller tracking the phase. The input of the SRF-PLL feedback system is the 3-phases voltage of the system and the output is the phase angle. According to the 3-ph PLL structure shown in the block diagram of Fig. 6, it detects the phase angle and creates an error signal by way of comparing the input signal (reference signal) with the output signal. Besides, undesirable harmonics terms in the error signal are removed using the filter loop. The output signal whose frequency oscillates around the system frequency is generated by the voltage-controlled oscillator (VCO) relying on the output of the loop filter. In this approach, the 3-ph voltage vectors in the natural reference frame (*abc*) are transformed to the stationary reference frame ($\alpha\beta$) using Clarke's transformation, after that transferred to *dq* rotating frame (SRF) using Park's transformation [22], as illustrated in Fig. 6.

III. POWER QUALITY IMPACT ON GCPS

For GCPS, the growth of power quality issues that degrade the overall performance of power systems is the harmonic distortion, voltage fluctuation, voltage unbalance, power factor, and frequency. The good power quality to the grid can help the grantee that no adverse energy can populate the power system operation. For this reason, the current-controlled VSI can mitigate this concern according to standard by such a way that permits the PV farm to carry out smoothly as predicted while not inflicting operational problems or protection of the utility grid. Therefore, it is very important to apply strict power quality regulations concerning the penetration of PV generators, which are imposed by either the grid codes [23] or international standard requirements such as the IEEE standards [24] and IEC standards [25]. These standard require the THD to be less than 5%, voltage fluctuations under 6%, and voltage unbalance at steady-state not to exceed 1%, a lagging/leading power factor higher than 0.9, grid operation at nominal frequency should be with a margin of ±1 Hz at a rated inverter output in the PCC.

To fulfill these requirements, the current controlled-VSI mentioned above, which has the ability to control the power follow, regulate the power factor, and reduce current THD is utilized. The three-phase SRF-PLL, which is less sensitive to power quality issues such as harmonics, voltage unbalance, sag, and the swell event also has been used. SPWM technique is used for harmonic reduction in cooperation with the proper RL filter. The filter is also designed in such a way to absorber the switching harmonics and produce a clean sinusoidal wave at PCC [9], [26]. Besides, the PI controller regulator used to regulate d and q current components then produces a unity power factor. The three-level VSI inverter also used due to its ability to reduce the switching frequency and speed up the switching speed, therefore increase production efficiency. As a result, the produced voltage and current is more sinusoidal and have less THD level. The next section will show the effectiveness of the controller via simulation results.

IV. RESULTS AND DISCUSSION

The current-controlled VSI control strategy used for large-scale solar PV with a rated power of 1000 kW interfaced power grid. This simulation considers a PVPP-connected grid and its parameters are given in Appendix A. Simulations were achieved using MATLAB/ Simulink. It is important to mention that the simulation runs at standard test conditions (radiation 1000 W/m^2, temperature 25^{o}C). In this technique, the grid-connected inverter effectively transfers the active power from the PV farm along with good power quality at the interfacing point. Fig. 7 shows the output parameters (voltage, current, and power) of the PV system at the interfacing point. In this design, the distribution system of 11 kV is connected to the large-scale PV system. It can be noticed that the current-controlled VSI has a good ability to transfer a good quality power with minimum losses.

In Fig. 8, it can be seen that the voltage fluctuation at PCC under the 6% limits and therefore matched the required standard at steady-state conditions. Fig. 9 shows the output of the inverter line voltage that regulated to be compatible with the dc-link reference voltage.

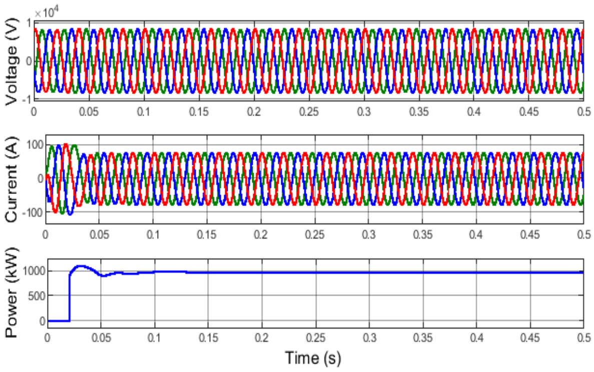

Fig. 7. Output parameters of the PV generators at the connection point.

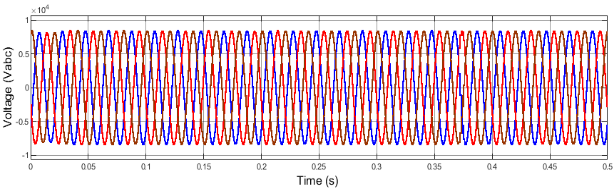

Fig. 8. Output PV system voltage at the PCC.

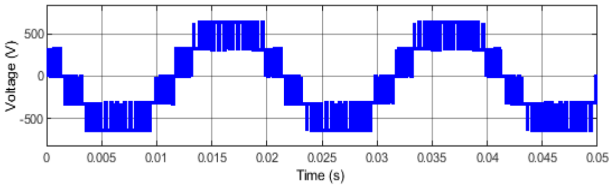

Fig. 9. Inverter output voltage (V_{ab}).

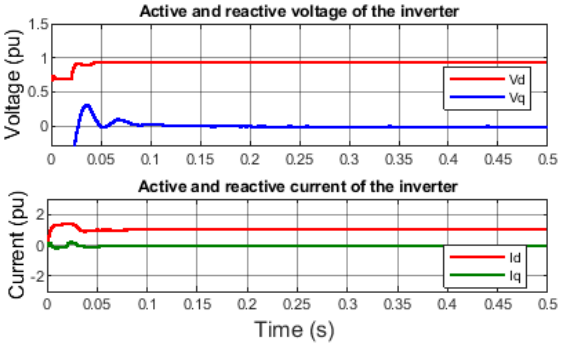

Fig. 10. Active and reactive for current and voltage of (*dq*-control)

Fig. 10 illustrates the d-axis and q-axis of the voltage and current of the VSI decupling control at normal operation. It can be noticed that the current of the q-axis is kept zero, and d-axis current is set at the rated value (1 p.u) because the inverter always operates at almost unity power factor during steady-state operation [14]. The feed-forward decoupling control is applied for smooth fluctuations of the dc-link and to decouple the reactive and active current. The *dq* control transforms the *abc* frame to *dq0* frame rotates in synchronous with the grid voltage.

At PCC, the output of the PV system must have low current THD degrees to guarantee that no negative impacts are induced to other equipment linked to the power grid. With a purpose to calculate the THD, the fast Fourier transform (FFT) tool in Simulink was used to record the THD of the output current waveform with the fundamental frequency at 50 Hz. To reduce the THD, a proper RL filter in the PV inverter had been used and PWM switching frequency is increased. Therefore, the values of RL filter parameters used for calculation of harmonics suppression are 1.25Ω and 0.1 mH, respectively, at switching frequency (f_c) equal to 2000 Hz. The effectiveness of this filtering is shown in Fig. 11 in which the current THD has been reduced to lower values of 1.2%, which is much lower than the value of the 5% limit. The standard requires a voltage unbalance factor (VUF %) not to exceed 1% for the one-minute duration. Fig. 12 illustrates that VUF % at STC is less than 1% within 0.1s and 0.0875% for 0.05 s. It is evident that VUF % is much less than the standard limits.

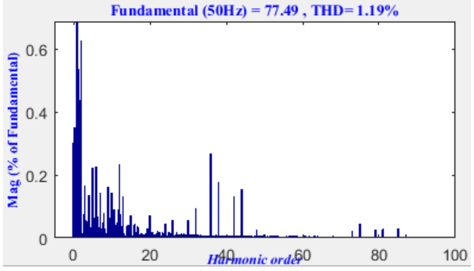

Fig. 11. THD level of the current waveform at PCC

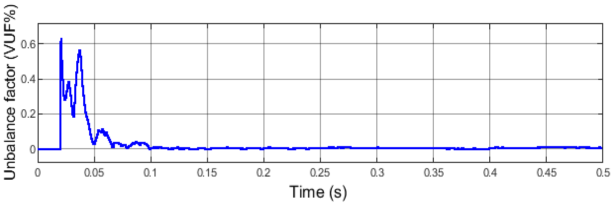

Fig. 12. Voltage unbalance factor of the PVPP-connected grid at STC

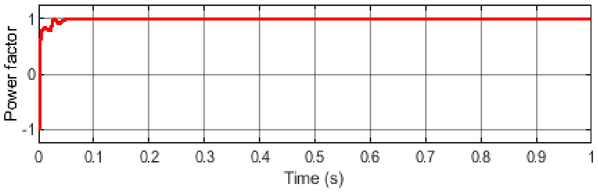

Fig. 13. Power factor of GCPS at the rated inverter output power

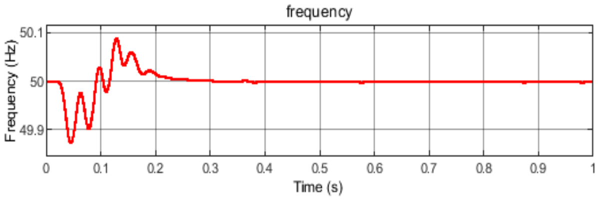

Fig. 14. Behavior of the system frequency

The Power Factor (PF) response of the proposed GCPS is near to unity value, as can be seen in Fig. 13, and this complies with the standard requirements which require leading/lagging PF bigger than 0.9. This unity PF occurs is due to the fact that reactive power equals to zero. In this GCPS system, the power grid operates at a nominal frequency of 50 Hz. During normal operation, GCPs allowable to operate with a margin of ±1 Hz. Fig. 14 shows that the frequency stay oscillates within the required limits.

In comparison with the results in literature, the strategy proposed in this paper shows some merits to meet the compliance requirements. For instance, an active power filter proposed in [27] reduced the current harmonics to 3.46%; however, the our strategy reduces it to 1.19%. Besides, the VUF in this study can be regulated to less than 1%, as comparison, the method proposed in [28] reduced the VUF to 2.85%. The voltage fluctuation of grid-connected PV system was beyond 7% by using the RC inverter controller reported in [13] while it is less than 6% by using our proposed controller. Besides, the power factor and frequency behaviour are enhanced according to the requirements of the standard in our method. In sum, the presented results are compatible with the recent requirements, which is an important indicator of the results' verification. In addition, as compared to existing methods, the proposed strategy effectively enhanced the power quality at the PCC and got an important enhancement with the possible low complexity and cost.

V. CONCLUSION

In this paper, a current-controlled VSI of 1 MW large-scale PV farm connected 11 kV distribution side of the utility grid has been investigated under normal operation mode. The SPWM and SRF-PLL also have been used for better performance and synchronization of the PV system with the power grid. This controller not only mitigates the power quality issues but also transfer active power into the power system with unity power factor. Results obtained from the present analysis indicate that the power quality issues did not exceed the permissible limits as imposed by the IEEE 1547 and IEC standards, i.e. current THD less than 5%, voltage fluctuations under 6%, voltage unbalance not exceed 1% for 0.1 seconds, power factor higher than 0.9, and the frequency fluctuated with allowable limits. In sum, the current-controlled VSI is an effective controller in GCPSs. This study will potentially be a foundation for the power system operators, developer of PV system inverters, and manufacturers with regard to the future compliance verification of the recent power quality interconnection requirements.

APPENDIX A SYSTEM PARAMETERS

Numbers of array modules = 2412, numbers array strings = 268, numbers of the series modules = 9, maximum current = 1573 A, maximum voltage = 653.4 V, dc output power = 997.6 kW. Grid voltage V_g =11 kV, voltage of the dc-link V_{dc} = 650 V, capacitor of dc-link C_{dc} = 0.321 F, grid frequency f = 50 Hz, switching frequency f =2 kHz, filter resistance R=1.25 Ω, filter inductance L=0.01 mH, parameters of PI current loop K_p=0.4, K_{i}=21, parameters of PI voltage loop K_p=4, K_i=200.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Ali Q. Al-Shetwi (A.Q.A.), Muhamad Zahim Sujod (M.Z.S.), and M. A Hannan (M.A.H), conducted the research; A.Q.A., Majid A. Abdullahd (M.A.A.), Ali Saadon Al-Ogaili (A.S.A.) and Ker Pin Jern (K.P.J) proposed the methodology; A.Q.A. conducted the simulation; M.A.H., M.Z.S, and M.A.A carried out the validation; M.A.A., K.P.J. and A.S.A. prepared the resources; M.A.H. and K.P.J are in charge of project administration; A.Q.A., M.Z.S. wrote the original draft; M.A.A., M.A.H., K.P.J., and A.S.A. reviewed and amended the final manuscript. All authors have read and agreed to the published version of the manuscript.

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