Implementation of Single-Phase Grid-Tied Inverter with Voltage Controller for Preventing Over-voltage Problem in Distribution Networks with Solar PV Rooftops

Piyadanai Pachanapan*, Apirak Tadthip and Sakda Somkun

Abstract— *The rapid growth of solar photovoltaic (PV) rooftops in low voltage (LV) distribution networks brings new challenges including the overvoltage issues. An unacceptable voltage rise is one of the restrictive factors for enhancing solar PV rooftops penetration in LV networks. In this work, the overvoltage problem is mitigated by using the reactive power control of the PV's grid-tied inverter, which is localised control method provided by customers. The grid-tie inverter will absorb the reactive power when the voltage level is higher than the reference value, without active power curtailment. It is probably effective and economic solutions for the LV grid integrated with PV rooftop systems. The detailed modeling, design, and control of a 1.5 kVA single phase grid-tied voltage source converter with an LCL filter is presented. The unbalanced synchronous reference frame with PI controllers is employed to regulate the active and reactive powers of the grid-tied inverter. The dynamic performances of this implemented grid-tied inverter are preliminarily examined based on computer simulations in DIgSILENT PowerFactory software. Hence, the simulation results are verified with an experimental setup of 1.5 kVA grid-tied inverter with a voltage controller in the laboratory. The results show that the reactive power absorption by PV's grid-tied inverter can mitigate the voltage rise in the LV network with high PV penetration successfully.*

Keywords— **Grid-tied inverter, overvoltage prevention, photovoltaic, unbalanced synchronous reference frame, volt-var control.**

1. INTRODUCTION

The installation of solar photovoltaic (PV) rooftop systems for the residential buildings has grown dramatically in the Greater Mekong Subregion since the year 2010 [1]. The solar PV rooftops will produce electricity for use in conjunction with the utility's electricity during the solar irradiance is available. Therefore, this support from PV systems gives the benefits in terms of saving the electricity bill and improving the voltage level at the point of common coupling (PCC). However, the high penetration of PV rooftop systems can introduce an unacceptable voltage rise in low voltage (LV) distribution networks, when the aggregated residential consumption is relatively small during high PV generation periods. This is one of limitation of the LV networks to increase the PV rooftops hosting capacity.

Limiting the maximum PV installation per customer is one of the solutions, widely used by many distribution system operators (DSOs), to avoid the overvoltage in the LV networks. For example, in Thailand, a residential customer is allowed to connect the PV rooftop to a single-phase 220 V distribution system, only if the PV supplied capacity is not more than 5 kW [2]. However, the maximum possible PV installation differs considerably for each LV network according to the grid structure, types of conductor and the location of PV systems [3].

To enhance PV hosting capacity in LV networks, various methods are proposed to prevent the overvoltage problems as reviewed in [4]. Those overvoltage prevention methods are divided into centralised and localised control strategies. In addition, the centralised methods are usually applied by DSOs while the localised methods are provided by customers.

Many centralised control methods are introduced including grid reinforcement and active distribution transformer. The grid reinforcement by changing the network structure or upgrading the type of conductors is an effective method for improving the voltage profiles in the condition of high PV generation [5]. Furthermore, the conventional off-load tap changing transformers, which tap position is fixed, can be replaced by the automatic on-load tap changer (OLTC) fitted transformer or solid-state and full power-electronic based transformer. The application of OLTC control strategies gives a high technical potential for increasing the PV penetration, as they can prevent voltage rises over the feeder impedances [6]. Although the centralised methods can improve the PV hosting capacity in LV networks effectively, the main drawback of conductor's reinforcement or applying active transformers is the high cost associated with these methods.

In case of localised control methods, the applications of energy storage system (ESS) and active and reactive powers management by PV inverter are introduced. The ESSs is used to store the excessive energy supplied by the PV systems to prevent the unacceptable voltage rise

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in high PV penetration conditions. A battery is commonly applied as the ESS, which it can be either connected into the DC bus of the PV inverter or be connected separately to the LV feeder [7]. On the other hand, the electric vehicle (EV) can be consider as an ESS solution for overvoltage prevention. Prioritising EV charging around peak PV generation hours can effectively mitigate the voltage rise [8]. However, the customers would trend to start charging their EVs when they back home; hence, the most of EV charging happens at the time which no or low PV generation [9]. Furthermore, the initial investment and optimising the size of energy storage units are still two main concerns about applying the ESSs for enhancing the PV connection in the LV network [10].

Another localised control strategies are applying the active power curtailment and reactive power control into customer's PV inverter. The active curtailment should be operated as a little due to the PV should produce the power into the network as much as possible. Then, the reactive power control is preference for the overvoltage prevention. Two main methods for reactive power control of PV inverters are the reactive as a function of generated active power [*Q*(*P*)], and the reactive power as a function of voltage level at the PV connecting point [*Q*(*V*)] [11]. In the *Q*(*P*) mode, the PV inverter is required to operate at lower power factor for supporting the reactive power during the PV generation is high. Although the PV hosting capacity can be increased by adjusting the power factor of PV inverter, this method increases the power losses and congestion of distribution line [12].

Operating PV inverter in the *Q*(*V*) mode can provide the lower power losses due to the reactive power is absorbed only when the voltage is higher than the reference value. The weak point of this method is that the PV inverters located near the LV side of transformer do not participate in voltage control effectively [13]. Although, the modern grid-tied inverter, based on the voltage source converter (VSC), can provide the voltage controllability with the fast response, this control function is only included in a three-phase converter used in large solar PV rooftop systems such as on the warehouse building. On the contrary, most residential PV rooftop systems is still using single phase grid-tied inverter, which are operating at a constant power factor (usually at unity power factor) and unable to provide the active Volt-Var support to deal with the changes of voltage level in the LV networks.

In this work, the 1.5 kVA single phase grid-tie inverter with voltage controller is implemented. This inverter will automatically absorb reactive power from the grid, when the voltage level at the PCC is over the prescribed limits allowed by Grid Code. For example, in Thailand, the level of phase-voltage in LV networks should be within the range of 200 to 240 V, all the time. This grid-tied inverter is developed based on the VSC structure which an isolated gate bipolar transistor (IGBT) is used as a switching device. The output of VSC is generated by using the pulse width modulation (PWM) controlled by using the unbalanced synchronous reference frame current control technique [14]. In addition, the *LCL* filter is employed in order to attenuate the high frequency PWM harmonics injecting into the grid [15]. The dynamic performances of overvoltage mitigation using reactive power supported by PV inverter is demonstrated based on computer simulation and experimental setup in the laboratory.

The paper is structured as follows: section 2 explains the background of voltage change in radial LV network with/without PV systems. The control structure of grid-tied PV inverter is described in section 3. Section 4 investigates the overvoltage control performances of proposed PV inverter based on DIgSILENT *PowerFactory* software. The experimental setup of 1.5 kVA grid-tied VSC is implemented to examine the proposed control system and verifying the simulation results, as demonstrated in Section 5. Finally, the conclusion is drawn in Section 6.

2. VOLTAGE CHANGE IN LV NETWORKS

In traditional LV distribution networks, without PV systems, the power will flow in one direction, from the distribution transformer to the customers. However, the injection of electric power from PV systems affects the power flow direction and the voltage level of the network. The change in the voltage level when PV system is injecting power to a certain location of a LV radial feeder, as shown in Fig. 1, can be explained as follow.

Adopt from [16], the voltage drop (ΔV), without PV system, can be written as in (1).

$$\Delta V = V_1 - V_2 = \frac{PR + QX}{V_2} \tag{1}$$

where P and Q are the active and reactive power sent from bus 1, respectively. R and X are the resistance and the inductive reactance of the circuit, respectively. In per unit, the voltage at the PV bus can be assumed as 1.0 p.u., so (1) can be approximated as:

$$\Delta V = PR + QX \tag{2}$$

In the case that PV system supplies active and reactive power, P_{PV} and Q_{PV}, respectively, to the system, then (2) can be writen as:

$$\Delta V = \left(P - P_{PV}\right)R + \left(Q - Q_{PV}\right)X \tag{3}$$

It is found that the injection of apparent power from PV system can reduce the term (P - P_{PV}) and (Q - Q_{PV}), thus the value of ΔV decreases. Then, the voltage at the PV bus, V_2, will be increased. As PV system usually operates at unity power factor, with Q_{PV} equals to zero, the voltage change is mostly due to the P injected from PV system.

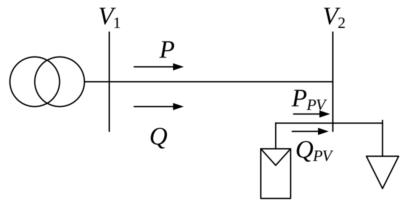


Fig. 1. Simple radial distribution network with PV system.

From (1) to (3), it is found that the three main factors that have an impact on voltage change in distribution system with PV systems are as follows;

Load demand and PV generation: the light load condition, the higher PV generation leading to a higher level of voltage rise especially at the end of feeder.

Line impedance: The higher line impedance, the higher level of voltage changes over the LV feeder. The line impedance can be reduced by increasing the size of distribution line.

Adjusting the power factor of PV inverter: If PV inverter operates in inductive mode (absorbing the reactive power from the network), the voltage rise can be reduced. On the other hand, the voltage at PV bus will be increased if PV inverter is in capacitive mode (injecting the reactive power into the network). The certain amount of reactive power from PV inverter, at time *t*, depends on PV's power factor which can be calculated as;

$$Q_{PV}(t) = P_{PV}(t) \times \tan(\cos^{-1} PF_{pv}) \quad (4)$$

where PF_{pv} is the range of power factor that PV system can be adjusted. Furthermore, it should be noted that the provision of reactive power can lead to a reduction of active power feed-in, if

$$\sqrt{P_{PV}(t)^2 + Q_{PV}(t)^2} > S_{PV,\max} \quad (5)$$

where $S_{PV,\max}$ is the maximum apparent power of the PV inverter. This effect can negatively affect the economic profitability and hence the payback period becomes further [17].

3. MODELING OF SINGLE-PHASE GRID-TIED INVERTER

This grid-tied inverter is developed in a form of VSC which IGBTs are used as a switching device, as illustrated in Fig. 2. The inverter is integrated with the LV networks through the *LCL* filter for attenuate the high order harmonics. At the DC side, the PV panels and DC/DC boost converter are modeled as the DC source and coupling with the grid-side inverter via the DC-link capacitor.

The control scheme is based on the unbalanced synchronous rotating reference frame (SRF) with a phase lock loop (PLL) for grid synchronisation. The unbalanced SRF is similar to the ideal proportional-resonance controller which provide the infinite gain at the fundamental frequency to achieve zero steady state line current error. Moreover, this technique does not require an orthogonal signal generator to shifting the phase of the measured feedback current, which ensures the stability of the current control loop for all parameters of the controller [15].

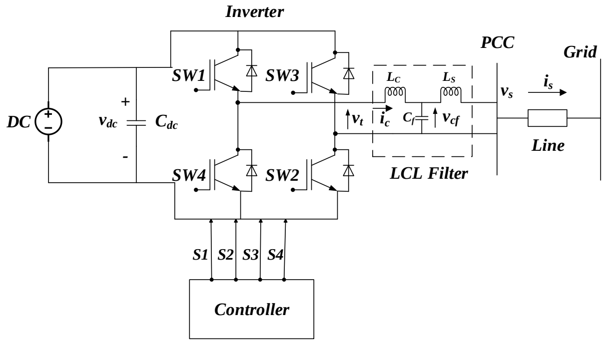
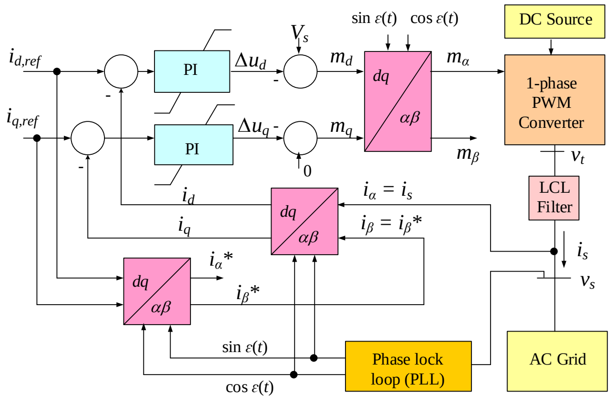
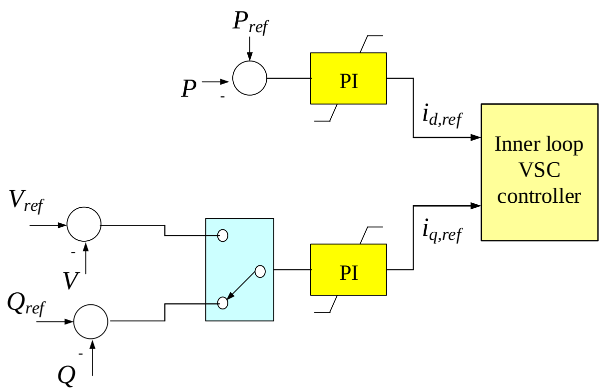


Fig. 2. Single-phase grid-tied voltage source converter.



(a) Inner loop controller



(b) Outer loop controller

Fig. 3. Control scheme of grid-tied inverter.

The close-loop control consists of two cascaded control loops to control active and reactive powers exchanged by the grid-tied inverter with the AC network. The inner control loop decouples the control for the real and imaginary current components. This control method consists of two main classes of two-dimensional frames, which are *αβ*-frame (or stationary reference frame) and *dq*-frame (or synchronous reference frame). Therefore, the two current components, i_d and i_q, are controlled independently, as shown in Fig. 3 (a). The reference values for the i_d and i_q controls are provided by the outer control loop, as demonstrated in Fig. 3 (b). The $i_{d,ref}$ is from the active power (P) controller on the d-axis, while the $i_{q,ref}$ is from reactive power (Q) or bus voltage (V) controllers on the q-axis. The error signals in both control loops are compensated by using PI controllers, which providing fast control response and robustness.

Under the normal condition, P and Q from the grid-tied VSC are controlled to maintain the maximum power extraction of energy source with the constant power factor. Additionally, the P reference (P_{ref}) is defined from a DC/DC boosted converter to operating at the maximum power point tracker (MPPT) while the Q reference (Q_{ref}) is a fixed value. This grid-tied VSC will change to control the bus voltage after the over-voltage problem is detected. Therefore, the i_q will be adjusted until the voltage level is staying within the statutory limit, or the supported Q is reaching the allowance capacity.

From the unified structure of the unbalanced SRF in Fig. 3 (a), the grid current feedback $i_s(t)$ is given to the stationary reference frame, as the α-axis while the fictitious current $i_\beta*(t)$ is assigned to the β-axis. In addition, this imaginary current is converted from the active and reactive reference currents ($i_{d,ref}$ and $i_{q,ref}$) based on Park transformation as

$$\begin{bmatrix} i_\alpha^*(t) \\ i_\beta^*(t) \end{bmatrix} = \begin{bmatrix} \cos\varepsilon(t) & -\sin\varepsilon(t) \\ \sin\varepsilon(t) & \cos\varepsilon(t) \end{bmatrix} \begin{bmatrix} i_{d,ref}(t) \\ i_{q,ref}(t) \end{bmatrix} \quad (6)$$

In case of a constant-frequency system, $\varepsilon = \varepsilon_0 + \omega_0 t$, where ω_0 is the AC system operating frequency and ε_0 is an initial phase angle between the real axis of the $\alpha\beta$- and dq- frames (constant value). The value of ε can be obtained by using a PLL.

Hence, the feedback currents in the synchronous reference frame can be determine from;

$$\begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} = \begin{bmatrix} \cos\varepsilon(t) & \sin\varepsilon(t) \\ -\sin\varepsilon(t) & \cos\varepsilon(t) \end{bmatrix} \begin{bmatrix} i_s(t) \\ i_\beta^*(t) \end{bmatrix} \quad (7)$$

The changes of active and reactive powers of grid-tied inverter can be done by adjusting the currents $i_d(t)$ and $i_q(t)$ independently. To regulate the $i_d(t)$ and $i_q(t)$, the PI controllers are employed. The stationary frame equivalence of the unbalanced synchronous reference frame controller, $G_{ci}^s(s)$ is given by

$$G_{ci}^s(s) = K_p + \frac{sK_i}{s^2 + \omega_0^2} \quad (8)$$

where K_p and K_i are the proportional and integral gains.

The amount of reactive power is limited by the ability to adjust the power factor of grid-tie inverter, as explained in (5). Therefore, the maximum value of q-axis current, $i_{q,\max}(t)$, is considered from

$$i_{q,\max}(t) = i_d(t) \times \tan\left(\cos^{-1} PF_{PV}\right) \quad (9)$$

The Δu_d and Δu_q from the inner-current controllers in Fig. 3 (a) are the input signals to PWM generators, which are limited to ensure that PWM operates in its linear range. Those input voltages will be referred to the modulation signal references, m_d and m_q, in the dq-frame. Hence, the modulation signal references in dq-frame are converted into $\alpha\beta$-frame using Park transformation, similar to (6). The terminal voltage of grid-tied VSC, $v_t(t)$, can be accomplished by applying the α-axis modulation signal reference, $m_\alpha(t)$, into the PMW generator. Therefore,

$$v_t(t) = m_\alpha(t) V_{dc}(t) \quad (10)$$

Applying KVL and KCL in Fig. 2, the state equations at the LCL filter are given by

$$L_c \frac{di_c(t)}{dt} = m_\alpha(t) v_{dc}(t) - v_{cf}(t) \quad (11)$$

$$C_f \frac{dv_{cf}(t)}{dt} = i_c(t) - i_s(t) \quad (12)$$

$$L_s \frac{di_s(t)}{dt} = v_{cf}(t) - v_s(t) \quad (13)$$

From (11) to (13), the closed loop block diatreme of the single-phase grid-tied VSC with an LCL filter in the stationary reference frame equivalence is illustrated in Fig. 4. Additionally, the time delay, T_d, is added to the PI controllers in the current loop considering the computational and processing delay caused by the digital PWM [18].

4. COMPUTER SIMULATIONS AND RESULTS

The preliminary investigation of using reactive power control by PV inverter to prevent the voltage rise in LV network is examined based on RMS transient simulations in DIgSILENT PowerFactory Software. The test system is a single phase 220 V, 50 Hz radial distribution network. The resistance and inductance of distribution line between inverter and utility grid are 4 Ohm and 5 mH, respectively. A 1.5 kVA single-phase PV system is installed at the end of feeder, as presented in Fig. 5.

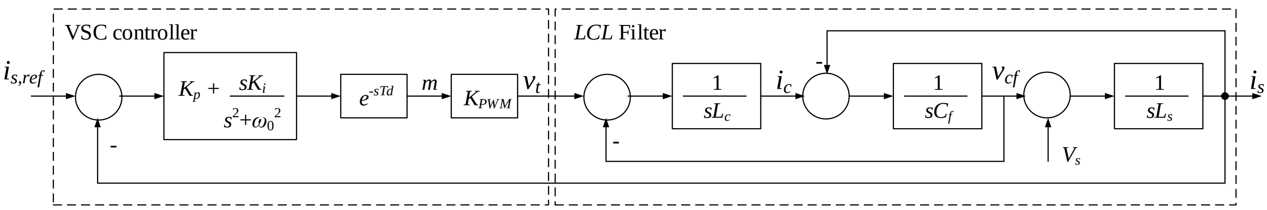


Fig. 4. Closed loop block diagram of the stationary frame equivalence.

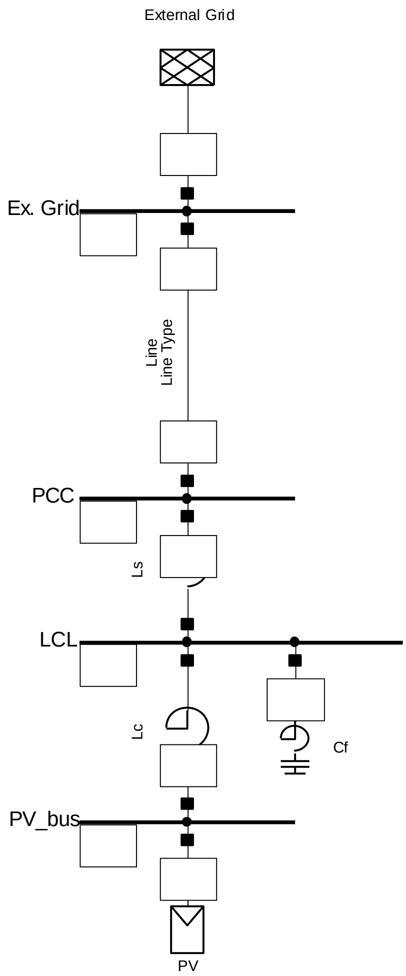


Fig. 5. The modeling of test system

In *RMS* transient simulations, the PV system with grid-tied inverter is modeled as a static generator [19], which behaves like a constant current source. From the control scheme in Fig. 3 (b), active power (*P*) of the grid-tie VSC and voltage level (*V*), at the PCC, are controlled in the outer control loop, while the real and imaginary parts of PV's current output is calculated from

$$\begin{aligned} \mathrm{Re}\left[i_s(t)\right] &= i_{d,ref}(t)\cdot\cos\varepsilon(t) - i_{q,ref}\cdot\sin\varepsilon(t) \\ \mathrm{Im}\left[i_s(t)\right] &= i_{d,ref}(t)\cdot\sin\varepsilon(t) + i_{q,ref}\cdot\cos\varepsilon(t) \end{aligned} \quad (14)$$

To avoid the resonance problem which makes the system unstable, the parameters of *LCL* filter are chosen following a step-by-step design procedure introduced in [16]. It is found that L_c and L_s are 1.03 mH and 983 μH, respectively, while the filter capacitor, C_f, is 2 μF.

No Voltage Controller

At an initial condition, assuming the voltage level at the PCC is 230 V. The PV system is injecting active power = 100 W into the grid, while the reactive power is zero (operating as unity power factor). The range of operational voltage changes is defined as 200 – 240 V. The overvoltage condition is created by gradually increasing the power output from the PV system. The change of PV generation over the simulated time = 80 s is illustrated in Fig. 6 (a).

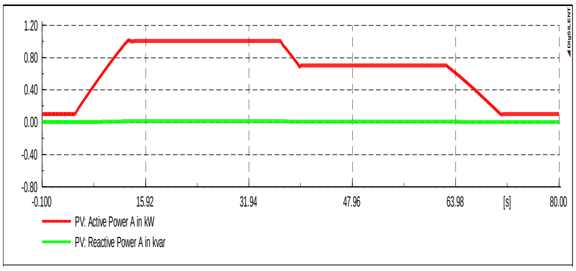
Without the Volt-Var support from PV system, the reactive power remains zero and PV's power factor = 1.0, all the time (see Fig. 6 (b)). The simulation results in Fig. 6 (c) show that the voltage level at the PCC starts to higher than 240 V since the PV generation is over than 650 W. Then, the unacceptable voltage rise will reach approximately 245.5 V when PV output = 1 kW.

With Voltage Controller

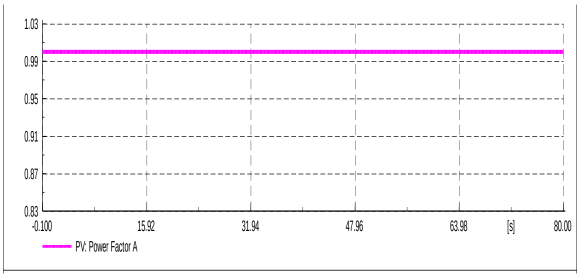
To avoid this overvoltage problem, the voltage controller is applied into the PV controller. Additionally, the PV system keeps operating at the unity power factor until the voltage level at the PCC is higher than 237 V (about 1.08 p.u.). The amount of reactive power is limited by the minimum power factor of PV system, which is 0.85. Active power and voltage level are regulated by using PI controllers which both have K_p = 2 and K_i = 10. In consequence, the outputs from *P* and *V* controls in the outer control loop, which are $i_{d,ref}$ and $i_{q,ref}$, will be converted into the current output of PV system by using the transformation in (14). When the voltage controller is executed, the PV system will maintain operating at power factor = 0.85 until the voltage level at the PCC is lower than 237 V. Then, the PV system resumes to operate at power factor = 1.0 and the reactive power is back to zero.

In case of PV system with voltage controllability, the simulation results in Fig 7 (a) – (c) show that the overvoltage problem can be mitigated by using the reactive power absorption of PV system. This PV system starts to absorb reactive power from the grid since t = 8 s; which is the time that the voltage level is above 237 V.

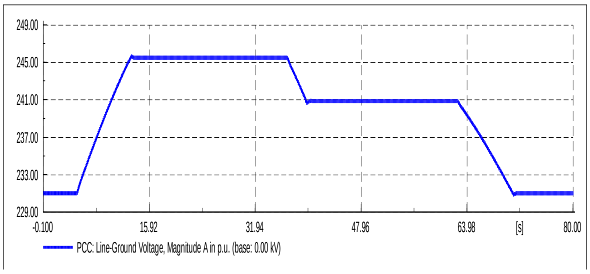
The voltage level can be controlled effectively until the power factor of inverter changing from 1.0 to 0.85, which the reactive power supporting should not be over than 619 Var during the PV system is supplying the active power = 1.0 kW. Hence, the voltage level remains over 241 V, after the reactive power from grid-connected inverter reaching the allowance capacity, since t = 13 s. The active power from inverter is gradually reduced since t = 37 s, making the voltage level has been declined slowly. The inverter remains operating at the power factor = 0.85 until the voltage level is below the value of 237 V at t = 63 s. After that, the inverter is completely back to operating at a unity power factor again since t = 66 s.



(a) Active and reactive powers

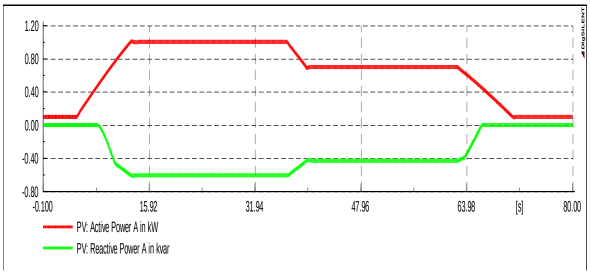


(b) Power factor

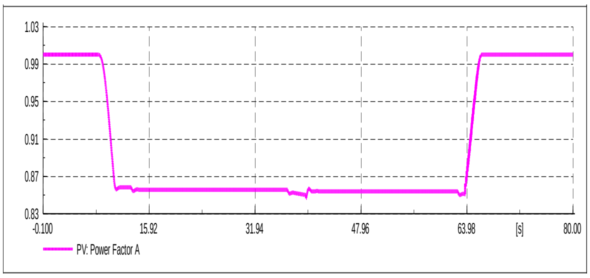


(C) Voltage at the PCC

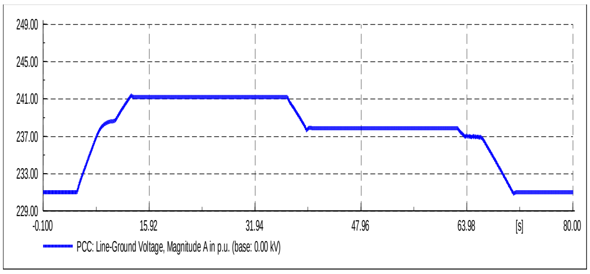
Fig. 6. Simulation results in case of no voltage control by PV system



(a) Active and reactive powers



(b) Power factor



(C) Voltage at the PCC

Fig. 7. Simulation results in case of PV system with voltage control

5. EXPERIMENTAL SETUP AND RESULTS

To confirm the preliminary results from computer simulations, the implementation of a 1.5 kVA single phase grid-connected inverter in the laboratory as shown in Fig. 8 and the technical parameters are in Table 1. The details of test system and *LCL* filter are the same as the simulation model in the section 4. To control active power and voltage level, the unbalanced SRF with PI regulators, as proposed in the section 3, is employed as the grid-tied VSC controller. At the DC side, the DC power is supplied by using a DC constant voltage source. In addition, there is no active power control in the outer loop controller; hence, the active power of grid-tied inverter will be controlled directly from the adjusting of $i_{d,ref}$.

This inverter is operating at the unity power factor based on the Q controller (Q_{ref} = 0) at the outer control loop until the voltage level at the PCC is higher than the setting value at 237 V. Hence, the controller will switch to the voltage controller to regulate the $i_{q,ref}$ according with the change of voltage level. The extra reactive power for supporting the voltage control is limited by the power factor controllability of VSC; which, in this work, the inverter can operate with the power factor of 0.85 (both leading and lagging). This means that the voltage level cannot be further reduced, if the absorbing reactive power by the inverter making its power factor is lower than 0.85.

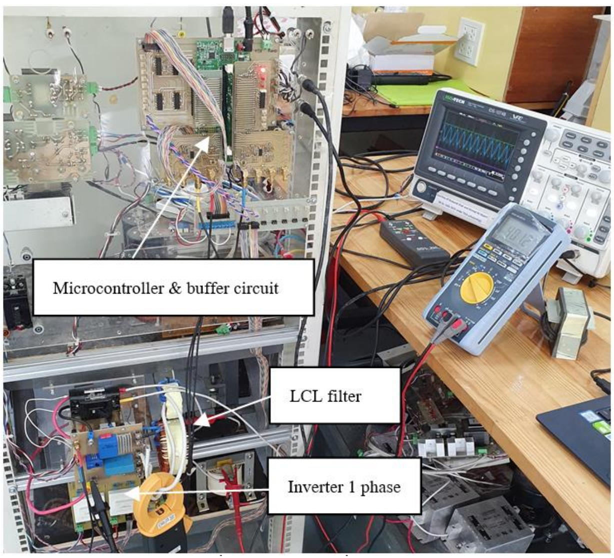


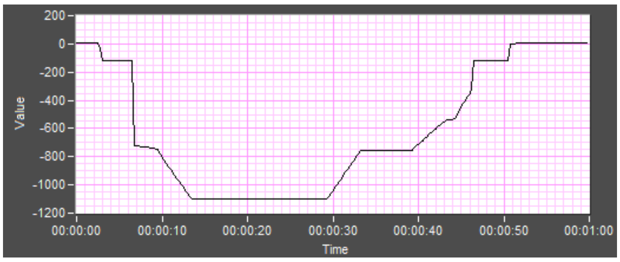
Fig. 8. Grid-tied inverter implemented in this work.

Table 1. Technical parameters of the implemented inverter

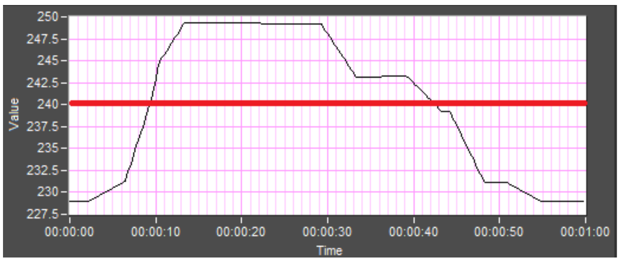
Parameters	Values
RMS line voltage	230 V
Nominal frequency	50 Hz
Maximum apparent power	1.5 kVA
Maximum active power	1 kW
Power factor	0.85
Switching and sampling frequencies	10 kHz
PWM mode	Unipolar
Base voltage	$\sqrt{2}\times 220$ V
Base current	6.15 A
DC voltage	420 V
DC link capacitor	1,100 µF
Microcontroller	TMS320F28069

No Voltage Controller

The over-voltage condition is created by gradually increasing the active power injection from the grid-tie inverter, as shown in Fig. 9 (a). The negative value of active power means that the power flows from the PV system to the grid. Without the voltage controller, the experimental result in Fig. 9 (b) shows that the voltage level at PCC has been over the upper voltage limit (i.e. 240 V) allowed by the utility, since t = 10 s. The unacceptable voltage rise will reach approximately 249 V when PV output = 1.1 kW. After t = 30 s, the voltage level has slowly declined until this grid-tied inverter stops to supplying the active power to the grid. It is found that this test system has been in the over-voltage condition for approximately 35 s.

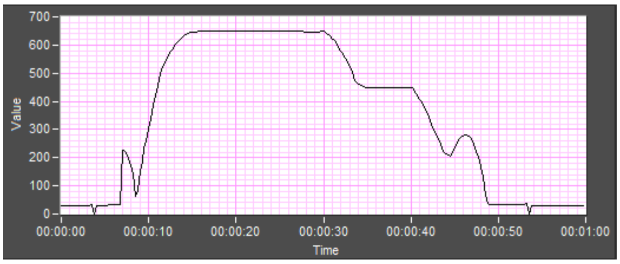


(a) Active power (W)

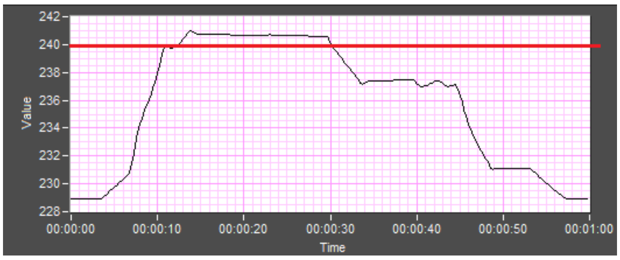


(b) Voltage at the PCC (Vrms)

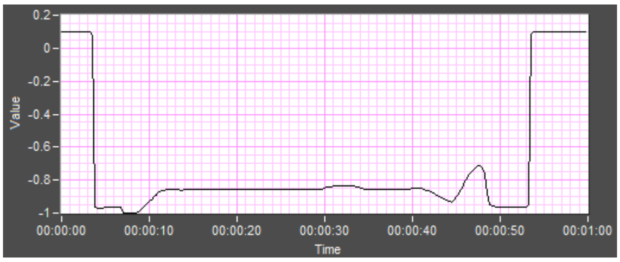
Fig. 9. Experimental results in case of the grid-tied inverter has no voltage controller.



(a) Reactive power (Var)



(b) Voltage at the PCC (Vrms)



(c) Power factor

Fig. 10. Experimental results in case of the grid-tied inverter with voltage controller.

With Voltage Controller

In case of grid-tie inverter with automatic voltage controllability, it is found that this inverter starts to absorb Q from the grid since t = 8 s; which is the time that the voltage level is above 237 V, as can be seen in Fig. 10 (a) to (c). The grid-tied VSC prevents the voltage rise successfully until the power factor of inverter is reduced to 0.85, which the reactive power supporting cannot be over than 680 Var when the PV system is injecting the active power = 1.1 kW. Hence, the voltage level remains over 241 V, after the Q from grid-connected inverter reaching the allowance capacity, since t = 12 s (see Fig. 10 (b)). The Volt/Var controllability of this experimental test is about 12 V/kVar.

The active power from inverter is gradually reduced since t = 29 s, making the voltage level has been declined slowly. The PV inverter remains operating at the power factor = 0.85 until the voltage level is below the value of 237 V at t = 40 s. After that, the inverter is completely back to operating at a unity power factor again since t = 48 s. Moreover, the changes of i_d, i_q and the waveforms of voltage and current are illustrated in Fig. 11.

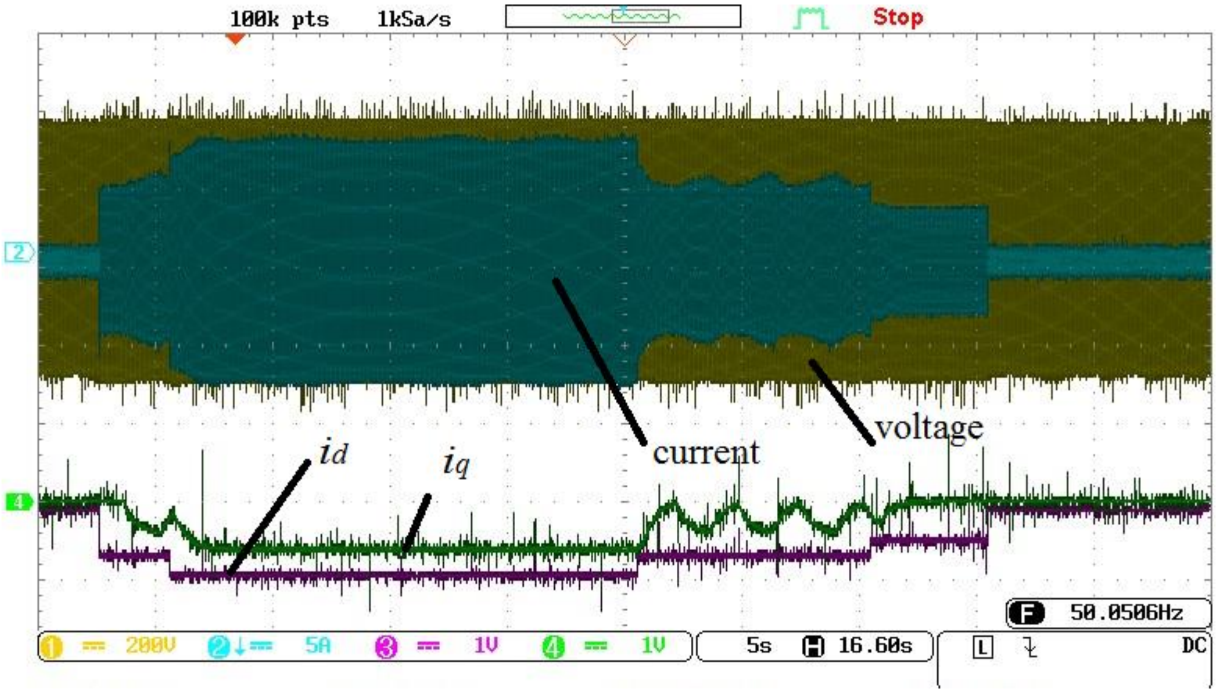


Fig. 11. The changes of i_d, i_q, voltage and current in case of the inverter with voltage controller.

6. CONCLUSION

The single-phase grid-tied inverter with voltage controllability is implemented in this work to prevent the overvoltage problem in LV networks with high penetration of PV rooftops. The detailed modeling, design, and control of 1.5 kVA single-phase grid-tied VSC with *LCL* filter is presented. The preliminary study based on *RMS* transient simulations found that the reactive power supporting by grid-tied VSC can mitigate the voltage rise due to the high PV generation effectively, similar to the use of active compensation devices such as DSTATCOM.

To verify the simulation results, the experimental setup of 1.5 kVA single-phase grid-tied VSC is also implemented in the laboratory. A proper design of the current controller, based on the unbalanced synchronous reference frame, is done to avoid the system instability from the resonance of the *LCL* filter. The results from the practical tests show that the grid-tied inverter with the proposed control scheme can deal with the voltage variations with the fast voltage control response. Moreover, due to the amount of supporting reactive power is limited by power factor and rated apparent power of inverter, the voltage control capability can be enhanced by enlarging the size of a grid-tied inverter to exchange more reactive power into the LV network.

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