Linear Over-Modulation Strategy for Current Control in Photovoltaic Inverter

Yongsoon Park and Seung-Ki Sul
Dept. of Electrical and Computer Engineering
Seoul National University
Seoul, Korea

Ki-Nam Hong
LG U+ Corp.
Seoul, Korea

Abstract— Photovoltaic (PV) inverters autonomously adjust their DC-link voltages to maximize power generation. Around sunrise or sunset, a PV inverter may operate at much lower DC-link voltage than the nominal level due to the low irradiance. The inverter would be under over-modulation if the DC-link voltage is relatively low to the grid voltage at the point of common coupling. In this paper, a series of implementation schemes are proposed to keep the current regulation under over-modulation. After the proposed method is detailed, its fundamental operations are verified by a small-scale prototype inverter and further evaluated by the 250 kW PV inverter installed at a proving ground.

Keywords—current control, over-modulation, photovoltaic inverter.

I. INTRODUCTION

Recently, the number and capacity of the grid-connected photovoltaic (PV) inverters have been enormously increased, and their unit power rating has reached to MW-scale. In general, the grid-connected inverter has a lower limit in the DC-link voltage in order to regulate the grid current into Point of Common Coupling (PCC). The PV panel connected to the inverter may be constructed such that the maximum power point tracking (MPPT) is mostly achieved in a voltage range well above the lower limit. However, in some cases, depending on irradiance and temperature, the DC-link voltage may have to be lower than that limit and PV inverter should be operated to generate available power.

Usually, the minimum DC-link voltage where the PV inverter has to stall is determined by the manufacturer with some margin. If MPPT has to be carried out near the lower limit due to low irradiance, the inverter’s stall could occur frequently. It would be inconvenient to disconnect the PV inverter from the grid whenever the DC-link voltage crosses the limit. In addition, these types of disconnections would impede the consistent power transfer from the PV inverter to PCC.

The primary reason to disconnect the inverter at low DC voltages is that voltage outputs cannot be correctly synthesized according to their references. As shown in Fig. 1, a voltage hexagon can be drawn if a DC-link voltage is given [1]. When the voltage reference vector is outside the hexagon, how to synthesize the references is so called as over-modulation (OVM).

One category of OVM is to modify the spatial position of the reference vector in the voltage plane partitioned by the hexagon [1]-[6]. In the other category, the actual fundamental voltages had been investigated as per pulse width modulation (PWM) methods when the pole voltage magnitudes were simply limited by a half of DC-link voltage under OVM [7]-[9]. In this paper, how to implement OVM is discussed when the switching functions are regarded. In particular, grid-connected inverters should comply with the corresponding regulations on harmonic currents to PCC [10]. In this paper, the appropriate selection of OVM method is discussed to meet those harmonic regulations.

Because the active and reactive powers must be under control in PV applications, the feedback control on output currents should be used under OVM. If the integrator is incorporated in the feedback controller, an anti-windup control block should be considered against the saturation of actuator output [11]. By virtue of the proposed method, the power factor of the fundamental currents could be aptly maintained even if the voltage output is limited under OVM.

The effectiveness and performance of the proposed method are fundamentally confirmed with a laboratory-scale prototype inverter. Then, the feasibility of the proposed method for commercialization is discussed with the results from a 250 kW PV inverter installed in Gochang proving ground.

II. OVER-MODULATION

Over-modulation occurs when a voltage reference vector is outside of the voltage hexagon as shown in Fig. 1. If OVM is applied, the outside vector is replaced with a realizable vector within the hexagon. To minimize this magnitude error, the modified voltage vector should be located at a side of the hexagon.
Each switching function, which indicates the on-state of upper switch in a leg, is presented in Fig. 1. For example, the switching function for A-phase is not changed if the reference vector rotates along the sides of the hexagon from $-\pi/3$ to $+\pi/3$. Because the zero vectors are not used for synthesis of the voltage in this rotation, the switching states for A-phase are not changed even during PWM. Based on this observation, the A-phase pole voltage under OVM could be depicted as shown in Fig. 2.

That is, OVM methods can be classified by how to connect the lines between ‘a’ and ‘b’ points and between ‘c’ and ‘d’ points in Fig. 2. Three OVM methods have been simply induced as shown in Fig. 3. Their common features are straight piecewise lines and odd function with respect to the point $x$, which can contribute to simple implementation and prevention of even harmonics. Actually, almost the same shapes to OVM1 and OVM2 in Fig. 3 appear respectively when space vector PWM (SVPWM) and Depenbrock’s discontinuous PWM are used under OVM [7].

In grid-connected PV inverters, OVM methods should be evaluated in terms of harmonic current into PCC to meet the corresponding regulations [10]. Then, weighted selective harmonic distortion (WSHD) in (1) could be used as a criterion to evaluate each OVM method’s harmonic distortion:

$$\text{WSHD} = \sqrt{\left(\frac{V_5}{V}\right)^2 + \left(\frac{V_7}{V}\right)^2 + \left(\frac{V_{11}}{V}\right)^2 + \left(\frac{V_{13}}{V}\right)^2}$$

where the subscript numbers are harmonic orders.

In this paper, modulation index (MI) is defined as the ratio of the fundamental voltage to $V_{dc}/2$, which is a half of DC-link voltage. As shown in Fig. 4, the harmonic distortions of each OVM method are differently varying over the entire OVM range, where MI is between 1.1547 and 1.2732. Because the harmonic distortions have to be minimized, one of OVM methods should be selected depending on MI. In the figure, OVM4 reveals the smallest WSHD when MI is between 1.1547 and 1.1971. The implementation of OVM4 can be done as follows.

A. Over-Modulation Mode I

Before introducing OVM4 in detail, it is important to understand the meaning of the limiter at the final stage of pulse width modulator in Fig. 5. Even if any limiter is not explicitly used in the modulator, the actual output synthesized by an inverter shall be saturated as long as the pole voltage is absolutely larger than $V_{dc}/2$. Due to this limitation, the fundamental voltage of actual output deviates from its reference under OVM if any extra treatment is absent.

If pole voltage references for SVPWM are naturally limited, the actual voltage vector can be synthesized with the minimum magnitude error to the reference vector in the voltage plane [3], [12]. This means that the root mean square (RMS) error of voltage vector under OVM can be minimized through the method limiting the pole voltage references from SVPWM. However, as mentioned earlier, due to the limiting action, the actual MI deviated from the reference MI as shown in Fig. 6. For instance, in order to achieve the actual MI of 1.20, the reference MI must be given as 1.24. This deviation can be offset by using a sort of compensation gain referred as $C_{omv}$. For example, because the actual MI of 1.20 can be achieved with the fictitious MI of 1.24, the necessary $C_{omv}$ is computed as 1.033 ($=1.24/1.2$). When considering Fig. 5, the method marked as OVM4 can be described as follows: (i) SVPWM is applied to the original voltage reference $\hat{V}$, (ii) the present MI is computed from $\hat{V}$, (iii) $C_{omv}$ is calculated from the present MI, and (iv) the limiter is applied after the output of (i) is multiplied by $C_{omv}$. 
The MI distortion in Fig. 6 is reversely used to calculate $C_{\text{ovm}}$. Then, a gain table for $C_{\text{ovm}}$ can be readily obtained as shown in Fig. 7. For practical implementation, the points indicated by circles in the figure are stored in the table, and the other points are linearly interpolated. As shown in Fig. 8, the pole voltage reference and the actual phase voltage have been captured in a prototype inverter when MI was 1.1812 when $V_{dc}$ is 160 V. In the frequency analysis, the actual fundamental voltage was 93.61 V, which presents -0.94% error to the original reference ($V^*$ in Fig. 5).

B. Over-Modulation Mode II

When a required MI is between 1.1971 and 1.24, OVM1 is applied to generate pole voltages. The process to implement OVM1 can be also understood with Fig. 5. In fact, when it comes to pole voltages, OVM4 becomes equal to OVM1 when MI approaches to 1.2732 [7]. However, by utilizing a different table at the block (iii) in Fig. 5, the block (i) can be skipped in OVM1. Namely, the limitation after compensation by $C_{\text{ovm}}$ can generate a quasi-trapezoidal voltage as shown in Fig. 9. This scheme has been adopted in that sine-wave presents almost linear variations near zero-crossing.

In the similar way to OVM4, the compensation gain table has been numerically obtained as shown in Fig. 10. The pole voltage reference and the actual phase voltage have been captured as shown in Fig. 11 when MI is 1.225 under the same $V_{dc}$, 160 V. In the frequency analysis, the actual fundamental voltage was 97.44 V, which means -0.57 % error to the original reference.

C. Over-Modulation Mode III

Both of OVM1 and OVM4 have a demerit when the six-step operation is required. Theoretically, this is because the compensation gain must be infinity to implement the six-step operation. Furthermore, because harmonic currents can be reflected into the voltage references if the current regulation is kept under OVM, the infinite gain can amplify those harmonics as well. In
addition, OVM3 has a merit in the viewpoint of WSHD as shown in Fig. 4 when MI is greater than 1.24.

The phase angle denoted by $\alpha$ in Fig. 12 is the main factor to adjust harmonic voltages in OVM3. When $\alpha$ decreases, MI increases. In particular, if $\alpha$ becomes zero, the inverter would be under the six-step operation. The required $\alpha$ according to MI has been numerically obtained as shown in Fig. 13.

The intervals where the pole voltage is zero in Fig. 12 can be depicted spatially in the voltage plane. This corresponds to the hatched area in Fig. 14. Two normalized vectors, $\hat{n}_{a1}$ and $\hat{n}_{a2}$, can be considered for implementation, whose phase angle is $\alpha$ and $-\alpha$, respectively. What type of pole voltage has to be synthesized can be determined by utilizing (2) and (3):

$$D_{a1} = \hat{V}^* \cdot \hat{n}_{a1} \quad \text{(2)}$$
$$D_{a2} = \hat{V}^* \cdot \hat{n}_{a2} \quad \text{(3)}$$

Because $D_{a1}$ is the inner product, $D_{a1}$ is positive if the phase difference of the voltage reference $\hat{V}^*$ to $\hat{n}_{a1}$ is absolutely smaller than $\pi/2$. Then, for instance, if $D_{a1}$ and $D_{a2}$ are all positive, the voltage vector’s phase is between $-\pi/2 + \alpha$ and $\pi/2 - \alpha$. When considering Fig. 1, the switching function for A-phase is 1, which corresponds to the pole voltage of $+V_{dc}/2$. In addition, it can be readily inferred that the zero clamping occurs when the product of $D_{a1}$ and $D_{a2}$ is negative. For the other phases, the pole voltage implementation is similar except using the $2\pi/3$-shifted normalized vectors.

The voltage synthesis under OVM3 has been captured as shown in Fig. 15 when MI is 1.625 under the same $V_{dc}$, 160 V. In the frequency analysis, the actual fundamental voltage was 100.7 V, which means -0.297 % error to the original reference.

III. CURRENT CONTROL UNDER OVER-MODULATION

The feedback control on output currents at the fundamental frequency should be maintained even under OVM in PV inverters to regulate active and reactive power to PCC [13]. The proposed current control can be understood with Figs. 16-17.

As mentioned earlier, harmonic currents can be reflected into voltage references through the feedback control under OVM. If these harmonics are not aptly mitigated, the voltage outputs would be more distorted than expected. To circumvent this problem, a notch filter in (4) for each harmonic could be used to mitigate the harmonic distortions in the synchronous reference frame. By these notch filters, voltage references can be less distorted under OVM.

$$NF(s) = \frac{s^2 + \omega_{n}^2}{s^2 + 2\zeta \omega_{n} s + \omega_{n}^2} \quad \text{(4)}$$
The notch frequency, $\omega_{nf}$ in (4), is set to 2π360 rad/s to deal with 5th and 7th order harmonics in this paper. In order to specify the damping coefficient $\zeta$ in (4), the current control property has been considered together. The current controller in the synchronous reference frame can be designed to present the following closed loop response [14]:

$$CC(s) = \frac{\omega_{cc}}{s + \omega_{cc}}$$  \hspace{1cm} (5)

where $\omega_{cc}$ is the control bandwidth.

This response is possible only if the pole-zero cancelation is correct with the following PI gains:

$$k_p = \frac{\omega_{cc}}{L} \quad k_i = \frac{\omega_{cc}}{R}$$  \hspace{1cm} (6)

where L and R are line inductance and resistance between PV inverter and the grid.

If harmonic controllers like resonant controller are separately used [15], the control bandwidth for the fundamental current should be limited to prevent interferences between the fundamental and harmonic controllers. Then, $\omega_{cc}$ in (5) has been empirically set below 2π200 rad/s to prevent the interference. Because the notch filters are employed on the feedback loops as presented in Fig. 16, their response should not disturb the original loop property. As shown in Fig. 18, if $\zeta$ is set to 0.1 rather than 1, the magnitude and phase of notch filter can be almost 0 dB and 0 ° within the bandwidth of current control. Because 0 dB and 0 ° in Bode plot mean no disturbance in magnitude and phase, $\zeta$ was set to 0.1.

As shown in Fig. 16, a voltage reference vector is limited by circle rather than hexagon. This circular limiter can preserve the voltage vector’s phase even after its magnitude is reduced. The radius of the limiting circle is determined by $M_{I_{\text{max}}}$:

$$\left| \hat{V} \right|_{\text{max}} = M_{I_{\text{max}}} \frac{\sqrt{2}}{2}.$$  \hspace{1cm} (7)

where $M_{I_{\text{max}}}$ is the maximum available MI. Up to $M_{I_{\text{max}}}$, PWM is expected to be linear in terms of the fundamental voltage in the proposed method. Because the harmonic distortion monotonically increases with respect to MI as shown in Fig. 4, $M_{I_{\text{max}}}$ can be determined by considering the worst degree of harmonic currents.

In addition to the PI gains of $k_p$ and $k_i$ in (6), the feedback gain denoted by $k_r$, which is an anti-windup gain, must be specified in Fig. 17. This gain prevents integrator’s divergence even if the current error $i_e$ does not vanish. From Fig. 17, the following equation can be derived:

$$V^* = k_r \cdot i_e + k_i \cdot \frac{(1 - k_r \cdot k_p) \cdot i_e + k_r \cdot (V - \hat{V})}{s} + \hat{V}_{\text{ref}}.$$  \hspace{1cm} (8)

where $\hat{V}$ is the processed output by the circular limiter from voltage reference $V^*$. $\hat{V}_{\text{ref}}$ indicates feed-forwarding voltage.

The controller output $V'$ is derived as (9) from (8):

$$V' = k_r \cdot i_e + k_i \cdot \frac{(1 - k_r \cdot k_p) \cdot i_e + k_r \cdot (V - \hat{V})}{s + k_i k_p} + \hat{V}_{\text{ref}}.$$  \hspace{1cm} (9)

Because $k_r$ has no meaning if $\hat{V}$ is equal to $V'$, (9) should be regarded when the circular limiter works. Through the midterm in (9), the integrator’s response can be explained. If $k_r$ is set to 1/k_p, distortions caused by $i_e$ can be minimized in integrator’s output. In addition, if the PI gains in (6) are used, (10) can be deduced. Under these settings, the converging response to the limiting value $\hat{V}$ depends only on the system parameter of R/L.

$$V' = \frac{R/L}{s + R/L} \cdot \hat{V} + \frac{s}{s + R/L} \cdot \hat{V}_{\text{ref}}.$$  \hspace{1cm} (10)

When $i_e$, $\hat{V}$, and $\hat{V}_{\text{ref}}$ are assumed to be step-varying, and the final value theorem is applied to (10), $V'$ finally
converges to $L_0i_{q}+\nabla$. This meaning of steady state needs to be extended in vector space as shown in Fig. 19. If the voltage reference vector in the synchronous reference frame is in steady state, its next state is the same with its present state. However, as shown in Fig. 19(a), if the limited voltage vector $\tilde{V}_{\text{ref}}$ is not in phase with the current error vector $\tilde{i}_{q}$, the voltage vector has to be changed after the limiting. That is, as shown in Fig. 19(b), even if the current error vector does not become null, the voltage reference vector is modified by the proposed method so that its limited one is in phase with the current error vector. This would finally enable the inverter to keep the power factor of the fundamental currents even if the circular limiter operates.

IV. EXPERIMENTAL RESULTS

Initially, the proposed method has been fundamentally tested with a laboratory-scale prototype inverter. After the current control performance of the prototype inverter is verified, data logged from a large-scale PV inverter are discussed.

A. Fundamental operation under OVM

The small-scale PV inverter was connected to 110 Vrms grid. All proposed algorithms were implemented in a DSP board based on TMS320F28335. The sampling frequency was 15 kHz, and the switching frequency was 7.5 kHz. The phase locked loop (PLL) was based on [16].

To discuss the control dynamics on output currents, the DC-link voltage of the inverter was supplied by a constant voltage source. Initially, when $V_{dc}$ was 179 V, the $q$-axis current reference was changed in step manner from 5 A to 15 A. As presented in Fig. 20, the normal current control response was captured as reference while MI was always lower than 1.1547.

For comparison, the same step change with Fig. 20 was tested when $V_{dc}$ was 159 V. With this DC-link condition, the inverter operated under OVM after the step change as shown in Fig. 21. Because harmonic currents increased right after entering OVM, the current control dynamics was not exactly the same with that under normal modulation. However, in a series of repeated tests, it has been confirmed that the rising time under OVM at least did not increase when compared to that under normal modulation.

Even though the inverter was under OVM at the test of Fig. 21, the limiter in Fig. 16 did not work at all. This means that the inverter could still synthesize given voltage references at the fundamental frequency. It is important to check the proposed method’s performance when the voltage references cannot be synthesized any more.

In order to consider the circular limiter’s transient operation, DC input of the inverter was connected to a PV simulator that emulated the power-voltage curve of a solar panel shown in Fig. 22. At the beginning, the inverter regulated its DC-link voltage as 170 V. When $M_{\text{Imax}}$ was set to 1.26, the DC-link voltage was decreased toward 140 V with the rate of 150 V/s as shown in Fig. 23.

The DC-link voltage was settled down to 143 V whereas its reference was 140 V. In result, MI was reached to its preset maximum value of 1.26 in steady state. This indicates that the magnitude of voltage vector was limited by the proposed method. The dashed box in Fig. 23 has been magnified in Fig. 24 to carefully investigate the output currents. Though lots of harmonics were included in the currents, the average of $d$-axis current was 0.64 A, which was negligible in that its reference was 0 A. This means that the proposed method is capable of maintaining the power factor of fundamental currents as expected.
B. Discussion on Data from Gochang proving ground

The proposed method under OVM has been tested in a 250 kW PV inverter connected to PV panels in Gochang PV generation proving ground. The inverter and PV panels are shown in Fig. 25. In fact, for higher efficiency, the PV inverter is based on T-type three-level topology shown in Fig. 26. However, if three-level inverter is under OVM, it is hard to use the small vectors [17]. This can cause instability on the neutral potential control. Because the T-type topology is a hybrid one, it can be operated as a two-level inverter by opening the bidirectional switches. Through this two-level operation, the PV inverter under test can operate under OVM.

The test data were obtained at Feb. 28, 2014, and the weather was cloudy. Because the temperature around sunset was about 6 °C, the open circuit voltage of PV panels was relatively high when compared to 280 V rms grid. The OVM mode by the proposed method has been briefly observed on that day. Test data have been logged by analyzing instruments.

As shown in Fig. 27, the inverter continued to transfer power from PV panels to grid even if the DC-link voltage was decreased due to sunset. Because 450 V was officially the lower limit for MPPT in the inverter’s catalogue, the power generation after 17:50 (in x-axis of Fig. 27) is related to the proposed system operation. The variation of MI up to the preset MImax of 1.223 can be confirmed with Fig. 28. Considering Figs. 27 and 28, it can be inferred that the inverter entered into OVM near 420 V (around 17:55).

It was important to check the harmonic distortions of output currents. Although data associated with harmonic distortions in Fig. 29 were not smoothly obtained, distortion trend could be roughly identified. As shown in Fig. 4, the harmonic distortion increases as MI under OVM increase. Therefore, the inverter would comply with IEEE std. 1547 if MI max, which determine the radius of limiting circle in Fig. 16, were aptly smaller than 1.223.

V. CONCLUSIONS

In this paper, an over-modulation strategy has been proposed for the grid-connected PV inverters. Initially, over-modulation methods have been designed to linearly modulate the fundamental voltage according to its reference. In conjunction with this linear over-modulation,
the circular limiter has been utilized instead of voltage hexagon. The settings for current control have been carefully detailed so that the current control property is kept even under over-modulation. After the proposed method’s fundamental operations were tested in a small-scale inverter, its feasibility has been examined with 250kW PV generation system in a proving ground. Although the weather condition was not optimal to extensively test the proposed method, it has been confirmed that the PV inverter can execute MPPT at very low DC-link voltages by the proposed method.

REFERENCES