Grid Voltage Modulated Control of Grid-Connected Voltage Source Inverters under Unbalanced Grid Conditions

Mingshen Li, Yonghao Gui, Juan C. Vasquez, Josep M. Guerrero
Microgrid Research Programme, Department of Energy Technology, Aalborg University
Aalborg, Denmark
{msh, yog, juq, joz}@et.aau.dk

Abstract—In this paper, an improved grid voltage modulated control (GVM) with power compensation is proposed for grid-connected voltage inverters when the grid voltage is unbalanced. The objective of the proposed control is to remove the power ripple and to improve current quality. Three power compensation objectives are selected to eliminate the negative sequence components of currents. The modified GVM method is designed to obtain two separate second-order systems for not only the fast convergence rate of the instantaneous active and reactive powers but also the robust performance. In addition, this method converts the system into a linear invariant system through designing a new voltage input. Simulation results are presented to verify the correctness and validity of the proposed control strategy and power compensation method.

Keywords—Grid-connected voltage inverter; grid voltage modulated control; power compensation; unbalanced grid.

I. INTRODUCTION

The energy crisis and environmental pollution are becoming more serious around the world, so it is an inevitable trend to take full advantage of renewable power generation, such as photovoltaics, wind, and so on. As an interface between renewable generation sources and the utility grid, the grid-connected voltage source inverter (VSI) fulfills several roles supporting grid operation [1]-[3]. For example, owing to the flexibility of the grid-connected VSI control, it can achieve high power factor, DC voltage regulation, harmonic current elimination and independent control of bidirectional active and reactive powers [4], [5]. During normal grid conditions, the conventional control of grid-connected VSI has been designed based on either virtual-flux oriented vector control (VFOC) [6]-[7] or direct power control (DPC) [8]-[9] to realize the output power balance. Generally, the VFOC is able to decompose the grid voltage and current into active and reactive power in the asynchronous rotating reference frame, and a decoupled proportional integral (PI) controller can be applied to regulate the error in current inner loop. However, in order to control instantaneous active and reactive powers directly without the need for any inner-loop current regulators, various DPC methods have been proposed for power converters [4], [10]-[12].

The most common fault of the grid power quality problems is unbalanced grid voltage, which will lead to current harmonic and power ripple which deteriorate the operational performance of VSI if the negative sequence is not considered in the control system. Thus, the control strategies of VSI have been studied in depth under unbalanced grid voltage conditions. In order to eliminate the negative sequence components, it is necessary to detect the grid voltage amplitude and phase angle in the \(d-q\) synchronous frame [13]-[15]. Thus, the synchronous reference frame phase lock loop (SRF-PLL) is essential to employ. However, the SRF-PLL will affect the dynamic response of system in unbalanced network [16].

In [17], the VFOC Proportional Resonant (PR) control strategy in \(\alpha-\beta\) frame was proposed to improve the system dynamic response, which transferred the current control into power control. In the case of robust control, a DPC with sliding mode control (SMC) method was proposed for VSI in the stationary reference frame. The SMC-DPC method in [18] was designed in sliding manifold considering the tracking error and its integral term to bring exponential convergence of the tracking error on the manifold. In [19], three selective control targets were proposed and achieved based on SMC-DPC control, thus obtaining sinusoidal and symmetrical grid currents and removing active power and reactive ripples. However, THD of current are still higher after compensation. In [20], the novel passivity-based control method was proposed based on port-controlled Hamiltonian system, but the power ripples in both active and reactive powers still exist, in particular the conditions of unbalanced grid. Gui et al. proposed a grid voltage modulated (GVM)-DPC to control the instantaneous active and reactive powers independently [21].

In this paper, a modified GVM-DPC based on power compensation is proposed under the unbalanced grid voltage conditions, and three power compensation control objectives are selected to eliminate the negative sequence components of currents and improve current quality, e.g. the active power compensation, the reactive compensation, and both powers compensation. Considering the robust performance of system, the GVM method is designed to control the instantaneous active and reactive powers in stationary frame independently, and then it generates new voltage inputs to transfer the multi-
input-multi-output feedback linearize system into a linear time invariant system. In addition, regarding the performance, the current THD using the proposed method is much less than 2% under an unbalanced grid.

The paper is organized as follows. Section II explains the modeling of system that includes the VSC modeling and power compensation design. In Section III, the GVM control system designed is presented. In Section IV, the simulation results are given to validate GVM method under unbalanced network with comparison to SMC-DPC. Finally, the conclusion are highlighted in Section V.

II. SYSTEM MODELING

A. Mathematical Model of VSI

The grid-connected VSI structure with the L-filter is shown in Fig.1, where L and R are the filter inductor and resistor. The grid voltage is denoted as \( u_{ga} , u_{gb} , u_{gc} \). The inverter output current and voltage are \( i_a , i_b , i_c \) and \( V_a , V_b , V_c \) respectively.

![Fig.1. Structure of grid-connected VSI.](image)

According to the Kirchoff’s law, the relationship among inverter current, inverter voltage and grid voltage of one phase in the stationary \( \alpha-\beta \) reference frame can be obtained:

\[
\begin{align*}
    u_a &= u_{ga} + L \frac{di_a}{dt} + R_i i_a \\
    u_\beta &= u_{gb} + L \frac{di_\beta}{dt} + R_i i_\beta
\end{align*}
\]  

(1)

By setting the line current direction against the active and reactive power direction, the instantaneous active and reactive powers in the stationary \( \alpha-\beta \) reference frame are derived as:

\[
\begin{align*}
    P &= \frac{3}{2}(u_{ga} i_a + u_{gb} i_\beta) \\
    Q &= \frac{3}{2}(u_{gb} i_a - u_{ga} i_\beta)
\end{align*}
\]  

(2)

By differentiating (2) with respect to time, the variations of active and reactive powers can be given as:

\[
\begin{align*}
    \frac{dP}{dt} &= \frac{3}{2}(i_a \frac{du_{ga}}{dt} + u_{ga} \frac{di_a}{dt} + i_\beta \frac{du_{gb}}{dt} + u_{gb} \frac{di_\beta}{dt}) \\
    \frac{dQ}{dt} &= \frac{3}{2}(i_\beta \frac{du_{gb}}{dt} + u_{gb} \frac{di_\beta}{dt} - i_a \frac{du_{ga}}{dt} - u_{ga} \frac{di_a}{dt})
\end{align*}
\]  

(3)

When the grid voltage is unbalanced, regarding the positive and negative sequence components, the grid voltage and current can be expressed as:

\[
\begin{align*}
    u_{ga} &= u_{gα}^+ + u_{gα}^- , \quad i_a = i_a^+ + i_a^- \\
    u_{gb} &= u_{gβ}^+ + u_{gβ}^- , \quad i_\beta = i_\beta^+ + i_\beta^-
\end{align*}
\]  

(4)

Differentiating \( u_{ga} \) and \( u_{gb} \) with respect to the time, the instantaneous grid voltage variations can be expressed as follows:

\[
\begin{align*}
    \frac{du_{ga}}{dt} &= -\omega u_{gα}^- \sin(\omega t) = -\omega i_{gα}^- \quad \text{and} \\
    \frac{du_{gb}}{dt} &= \omega u_{gβ}^+ \sin(\omega t) = -\omega i_{gβ}^+
\end{align*}
\]  

(5)

where \( \omega \) and \( U_g = \sqrt{u_{ga}^2 + u_{gb}^2} \) are the magnitude and angular frequency of grid voltage, respectively. Likewise, the positive and negative sequence components of voltage and current are obtained as:

\[
\begin{align*}
    \frac{du_{gα}^+}{dt} &= -\omega i_{gα}^- \quad \text{and} \\
    \frac{du_{gβ}^+}{dt} &= \omega i_{gβ}^- \\
    \frac{du_{gα}^-}{dt} &= -\omega i_{gα}^+ \quad \text{and} \\
    \frac{du_{gβ}^-}{dt} &= \omega i_{gβ}^+
\end{align*}
\]  

(6)

Substituting (1) and (5) into (3), the dynamic model of the instantaneous active and reactive powers is obtained as:

\[
\begin{align*}
    \frac{dP}{dt} &= -\frac{R}{L} P + 3 \omega \frac{3}{2}(u_{gα}^+ V_a + u_{gβ}^+ V_\beta - U_g^2) \\
    \frac{dQ}{dt} &= -\frac{R}{L} Q + 3 \omega \frac{3}{2}(u_{gβ}^+ V_a - u_{gα}^+ V_\beta)
\end{align*}
\]  

(7)

Substituting (4) into (2) yields:

\[
\begin{align*}
    P(t) &= P_0 + P_2 + P_3 \\
    Q(t) &= Q_0 + Q_2 + Q_3
\end{align*}
\]  

(8)

where \( P_0 \) and \( Q_0 \) are the average components of active and reactive power, respectively, and \( P_2 , P_3 \) and \( Q_2 , Q_3 \) are instantaneous active and reactive power at twice the grid frequency respectively. Transferring (8) into the state-space:

\[
\begin{align*}
    P_0 &= 0 \quad P_2 = \frac{3}{2}(u_{gα}^+ V_a + u_{gβ}^+ V_β - U_g^2) \\
    Q_0 &= 0 \quad Q_2 = -\frac{3}{2}(u_{gβ}^+ V_a - u_{gα}^+ V_β)
\end{align*}
\]  

B. Power Compensation

According to (8), the twice frequency power ripples are generated by negative sequence voltage components and positive sequence current components. In order to remove the twice frequency ripple, it should be addressed by:

\[
\begin{align*}
    P_2 + P_3 &= 0 \\
    Q_2 + Q_3 &= 0
\end{align*}
\]  

(9)

However, the two constraints cannot be satisfied at the same time because the \( P \) and \( Q \) are varying simultaneously in unbalanced network [19]. We define the compensation
components $P_c$ and $Q_c$ that are injected into power references to keep power steady and output current sinusoidal. To remove the power ripples and reduce harmonics of the output current, the three objectives are selected: 1) active power negative sequence compensation; 2) reactive power negative sequence compensation; 3) both P/Q negative sequence compensation.

In order to remove the power ripples, the active or reactive power should be kept constant. Therefore, the constraints for first objective and second objectives are $P_{c2} + P_{s2} = 0$ and $Q_{c2} + Q_{s2} = 0$. According to (9), the active power compensations can be obtained as:

$$P_c = -\frac{3}{2}(u_{g\alpha}^+I_{\alpha}^- + u_{g\beta}^+I_{\beta}^- + u_{g\alpha}^-I_{\alpha}^+ + u_{g\beta}^-I_{\beta}^+)$$

Similarly, in order to remove the reactive ripple, the reactive power compensations can be expressed as:

$$Q_c = -\frac{3}{2}(u_{g\alpha}^+I_{\alpha}^- - u_{g\alpha}^-I_{\alpha}^+ + u_{g\beta}^+I_{\beta}^- - u_{g\beta}^-I_{\beta}^+)$$

For both powers compensation, the negative sequence current should be eliminated, namely, then $P_{c2}$ and $Q_{c2}$ must be zero. Actually, $P_{c2}$ and $Q_{c2}$ which just include the positive sequence components will still exist in the active and reactive powers, and it will not generate the current distortion in an unbalanced network. According to (9), the both powers compensation can be expressed as:

$$P_c = -\frac{3}{2}(u_{g\alpha}^+I_{\alpha}^- + u_{g\beta}^+I_{\beta}^-)$$

$$Q_c = \frac{3}{2}(u_{g\alpha}^+I_{\alpha}^- - u_{g\beta}^+I_{\beta}^-)$$

III. PROPOSED GRID VOLTAGE MODULATED CONTROL SCHEME

According to (7), the dynamics of instantaneous active and reactive powers are a multi-input-multi-output system and are coupled by states and inputs. In order to simplify this system into a state feedback linearization system, this part focuses on the decoupled the outputs from the two inputs. The grid voltage modulated (GVM) control inputs can be expressed as:

$$U_p = u_{g\alpha}V_{\alpha} + u_{g\beta}V_{\beta}$$

$$U_q = u_{g\alpha}^+V_{\alpha}^- - u_{g\beta}^+V_{\beta}^-$$

It is obvious that the voltage inputs can be expressed in $d$-$q$ frame:

$$\begin{bmatrix} U_p \\ U_q \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} V_{\alpha} \\ V_{\beta} \end{bmatrix}$$

We can see (12) can present the control inputs in $d$-$q$ frame from Fig.2. Although the system is presented in $d$-$q$ frame by the new inputs, there is no need to use the synchronous coordinate transformation.

Therefore, (7) can be rewritten in the state-space:

$$\begin{bmatrix} \dot{P} \\ \dot{Q} \end{bmatrix} = \begin{bmatrix} \frac{R}{L}P - \omega Q + \frac{3}{2L}(U_p - U_q) \\ \frac{R}{L}Q + \omega P + \frac{3}{2L}U_q \end{bmatrix}$$

Based on (13), the GVM can be expressed as:

$$\begin{bmatrix} U_p \\ U_q \end{bmatrix} = \begin{bmatrix} p + 2q^2 - \frac{2R}{3}P + \frac{2L}{3}\omega Q \\ -q + \frac{2L}{3}\omega P - \frac{2R}{3}Q \end{bmatrix}$$

Then, the output errors are defined as follows:

$$e_p = P_{ref} - P$$

$$e_Q = Q_{ref} - Q$$

where $P_{ref}$ and $Q_{ref}$ is the active and reactive power reference respectively. According to the (13), we design the control scheme for $P$ and $Q$ as follows:

$$P = \dot{P}_{ref} + K_{Pp}e_P + K_{Pq}\int_0^\infty e_P(t)$$

$$Q = \dot{Q}_{ref} + K_{Qp}e_Q + K_{Qq}\int_0^\infty e_Q(t)$$

From (17), the tracking dynamics are ideal second-order systems, and then it is obvious that the closed-loop system is globally exponentially stable. Therefore, the inverter voltage in $\alpha$-$\beta$ frame can be calculated as follows:

$$V_{\alpha} = \frac{1}{U_g}(u_{g\alpha}U_p + u_{g\beta}U_q)$$

$$V_{\beta} = \frac{1}{U_g}(u_{g\beta}U_p - u_{g\alpha}U_q)$$

Fig. 2. Inputs voltage vector at coordinate system.
The block diagram of the GVM method is presented in Fig. 3. It can be seen that the PI controller is implemented to regulate the direct components error of power, and modulated grid voltage we defined can be calculated for generating voltage reference. The system diagram is shown in Fig. 4. The positive and negative sequences of grid current and voltage are extracted to calculate the power compensation components for the three control objectives.

IV. SIMULATION RESULTS

The performance of the proposed method was verified in MATLAB/Simulink and PLECS environment. The system parameters are described in Table I. In addition, we compared the compensation performance of both the proposed GVM technique with the SMC-DPC method [18] under unbalance grid conditions.

At first, we compared the performance of the proposed method with compensation and non-compensation under an unbalanced grid voltage condition. When the inverter regulated 2 kW active power and 0 Var reactive power, the grid voltage had a 20% voltage sag in the phase A at 0.05s as shown in Fig. 5(a). However, grid current was affected by the unbalanced grid voltage condition as shown in Fig. 5(b), THD of the current was increased as 7.9%. Without the power compensation, the active and reactive powers are still smoothly regulated to their references, as shown in Figs. 5(c) and 5(d).

Regarding active power compensation, it was injected to active power’s reference. It can be seen from Figs. 6(a) and 6(b) that the system has 10ms transient response to get steady without oscillations. There are ripples in the active power after compensation, and the reactive power keeps zero. Fig. 6(c) shows that the phase B and C currents injected to the grid were affected by the unbalanced grid voltage condition, but still compensated to be sinusoidal and symmetrical, and the THD was decreased as 1.9%. Note that the method needs two cycles (40 ms) for the start-up calculations.

Moreover, with the reactive power compensation of GVM, the active power regulated smoothly and the reactive power had ripples as shown in Fig. 7(a) and 7(b), but the grid current is still quite sinusoidal and symmetrical in Fig. 7(c).

![Fig. 3. Controller block diagram of the GVM method.](image)

![Fig. 4. Power stage and proposed control block diagram.](image)

![Fig. 5. Simulated result without power compensation when the grid voltage has a 20% sag in phase A at 0.05 s.](image)

![Fig. 6(a) Grid voltage with 20% sag in phase A at 0.05 s](image)

![Fig. 6(b) Grid current](image)

![Fig. 6(c) Output active power of inverter](image)

![Fig. 6(d) Output reactive power of inverter](image)

![Fig. 7(a) Phase A current with 10% sag at 0.05 s](image)

![Fig. 7(b) Phase B current with 10% sag at 0.05 s](image)

![Fig. 7(c) Phase C current with 10% sag at 0.05 s](image)

![Fig. 7(d) Active power with 10% sag at 0.05 s](image)

![Fig. 7(e) Reactive power with 10% sag at 0.05 s](image)

![Fig. 7(f) Grid current with 10% sag at 0.05 s](image)
In order to compare the performance with GVM method, we applied the both power compensation components to the SMC-DPC method in advance. The results are shown in Fig. 8. It can be seen that there exist different ripples of both active and reactive powers in Figs. 8(a) and 8(b). Since the SMC-DPC uses different values of boundary layer to active and reactive controls. It is difficult to decide the values of the boundary layer satisfying ripples and stability in both active and reactive powers. As shown in Fig. 8(c), the grid current is distorted seriously (THD=13.52%) even implementing the negative compensation.

Figs. 9(a) and 9(b) show the active and reactive powers regulation performance of GVM method with the both powers compensations. The compensation was injected to active and reactive power’s references. Fig. 9(c) shows that the phase B and C currents injected to the grid were affected by the unbalanced grid voltage condition. As shown in Fig. 9(c), the current injected to the grid is sinusoidal and symmetrical, and the THD was decreased as 1.8%. Unlike to SMC-DPC, the GVM results in significantly reducing ripples both in active and reactive powers, and improving current quality without
deciding boundary layer values and considering switching delay. To summarize, the GVM control method with power compensation are capable of realizing the power control independently, and reducing current THD without loss of active and reactive powers transient response performance.

Fig. 10 shows that comparison of harmonic content with different conditions by GVM method. From this figure, the THD was decreased largely after compensation, i.e. from 7.9% to 1.9%.

![Fig. 10. Comparison of harmonic content with different conditions.](image)

V. Conclusion

A grid voltage modulated control and power compensation strategy for grid-connected VSI under unbalanced grid conditions has been proposed in this paper. Based on the mathematical model of VSI and by considering the unbalanced grid, the basic control scheme of power control in the \( \alpha-\beta \) stationary frame is presented. According to the three control objectives we designed, precise power compensation components are provided to the respective power references. What is more, the origin of the error dynamics of active and reactive powers are exponentially stable in the whole operating range.

The GVM method was verified based on MATLAB/Simulink with PLECS block-sets. Simulation results shown the proposed method presented a good tracking performance in both active and reactive powers compared with the SMC-DPC method. By using the proposed method, the current THD was less than 2%, and both in active and reactive powers ripples are reduced under 20% voltage sag in one phase. Hence, the propose method can improve the adaptability and robustness of VSI connected to unbalanced grid. In future work, the nonlinear loads conditions will be considered in this control scheme and use of \( LCL \) filters influence to the GVM control will also be studied further.

REFERENCES


