Article

A Virtual Negative Resistor Based Common Mode Current Resonance Suppression Method for Three-Level Grid-Tied Inverter with Discontinuous PWM

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Abstract: The output LC filter of a photovoltaic (PV) string three-level grid-tied inverter that connects the filter capacitor neutral point to dc-link capacitor neutral point can reduce the common-mode (CM) current injected to the grid by letting the CM current circulate within the inverter. However, the internal CM current may resonate because of the existence of the resonant frequency of the internal CM LC circuit. Compared with the traditional continuous pulse-width modulation (CPWM), the resonance can be worse if discontinuous pulse-width modulation (DPWM) is applied, for the zero sequence quantity of DPWM contains more harmonics than that of CPWM. In this paper, a virtual negative resistor based common mode current resonance suppression method for a three-level grid-tied inverter is proposed to overcome the CM current resonance problem in DPWM application. Different positions of the virtual negative resistor in the equivalent CM circuit with different feedback variables are analyzed theoretically. The virtual negative resistor connected in series with the inductor in the equivalent CM circuit is selected to damp the CM current resonance for simplification and damping performance. Different from the implementation in CPWM where a pair of small voltage vectors exist and are used to adjust the CM voltage directly, the proposed method for DPWM application is implemented indirectly by adding the CM adjustment quantity to differential-mode (DM) control quantity with appropriate coefficients. Depending on the sector of DM control quantity in the αβ reference frame, the coefficients are calculated using one of three specific voltage vectors. Experimental results are given to demonstrate the effectiveness of theoretical analyses and the proposed method.

Keywords: CPWM; DPWM; virtual negative resistor; common mode current resonance suppression

1. Introduction

Among all renewable energy sources, photovoltaic (PV) systems have experienced rapid growth both in residential and commercial applications. The power quality of current generated by the PV grid-connected inverter is of importance for the grid. According to IEEE Std 519-2014, the recommended harmonic distortion limit of line-to-neutral voltages is that the voltage total harmonic distortion (VTHD) at the point of common coupling (PCC) is 8% for the bus voltage less than or equal to 1 kV, 5% for the bus voltage between 1 and 69 kV, 2.5% for the bus voltage between 69 and 161 kV, etc., [1]. Switching ripple filters (SRFs), like L, LC, LCL, and LLCL filter, is a significant part of PV grid-connected inverter interfacing with the grid. On one hand, SRFs can maintain a coupling connection and integration
between grid and grid-connected inverter. On the other hand, SRFs can filter the switching ripple currents of inverter-side inductor current [2]. However, these filters can potentially cause a harmonic resonance for system operation if not properly designed [3].

In order to suppress the harmonic resonance problems, researchers have proposed passive damping (PD) and active damping (AD) techniques [3–5]. PD is a simple and stable technique but increases the damping power loss and volume of an inverter. Compared with PD, AD technique is flexible and does not increase the damping power loss. The three most cited AD techniques in literature are capacitor current feedback based method [6], capacitor voltage feedback based method [7], and notch-filter based method [8]. Different feedback of output filter state corresponds to different impedance position in a LCL filter: the feedback of the converter current forms a virtual impedance in series with the inverter side inductor \(L_f\), capacitor voltage, or current feedback in grid current control forms a virtual impedance in parallel with filter capacitor, grid current feedback forms a virtual impedance in parallel with grid side inductor [9]. In [10], the authors give a comprehensive study of a virtual resistor based AD for the LCL resonance frequency. The virtual resistor based AD technique is simple and effective in damping the LCL resonance current. However, to the best knowledge of the authors, the virtual resistor mentioned above is used only for damping the harmonics resonance of differential-mode (DM) current injected to the grid.

An improved LCL (ILCL) filter is proposed in [11,12] to reduce the leakage current. The ILCL filter is acquired simply by connecting the common point of LCL filter capacitors to the dc-link neutral point without adding any additional components. Letting the common-mode (CM) current circuiting within the inverter, the leakage current injected into the grid can be reduced significantly. However, the CM current circuiting path within the inverter is a LC circuit, in which a LC resonance frequency \(f_r\) exists. The CM current resonance suppression methods for inverter using the ILCL filter are proposed in [13,14] to reduce the leakage current injected to grid. In [14], the authors use a PI controller to control the CM current to be zero by real-time adjusting zero-sequence duty ratio in space vector modulation (SVM) technique. In [13], the CM voltage which is injected into DM voltage to extend the inverter modulation index is controlled to suppression CM current resonance. Both the methods are useful and effective, and are based on a pair of small voltage vectors to adjust the CM voltage.

In order to improve the switching efficiency of three-phase rectifier/inverter, discontinuous pulse-width modulation (DPWM) is proposed by researchers [15,16]. The basic idea of DPWM is to select appropriate voltage vectors to compose the reference voltage vector so that the switches have a minimum switching loss. One of its characteristics is that there is no a pair of small voltage vectors, only one of the two small voltage vectors is used to compose the reference voltage vector. Since the CM AD methods in [13,14] are based on a pair of small voltage vectors to adjust the CM voltage, they cannot be used directly in DPWM application.

In this paper, a virtual negative resistor based AD (VNRBAD) method is proposed to damp the CM current resonance for a three-level inverter with an improved LC (ILC) filter in DPWM application. The originality lies in two points: (1) a virtual negative resistor based CM current resonance suppression method and (2) its implementation in DPWM application.

This work is organized as follows. The model of CM current resonance in three-level grid-tied inverter with an ILC filter is presented in Section 2. In Section 3, the comparison of the harmonics of the zero sequence of DPWM and continuous pulse-width modulation (CPWM) is presented. VNRBAD for CM current resonance suppression in DPWM application is proposed in Section 4. Experiments and discussions are given in Section 5 to demonstrate the proposed VNRBAD. In Section 6, conclusions are reached.

2. Model of CM Current Resonance in Grid-Tied Inverter with ILC Filter

Figure 1 shows the topology of a general PV string three-level grid-tied inverter with an ILC filter [12,17]. Boost converter is usually used as the DC-DC stage to increase the dc voltage and to track the maximum power point of the PV array, the inverter stage is used to convert DC power into AC
power and inject it to AC grid. $i_{CM}$ and $v_{CM}$ is the CM LC circuit current and voltage respectively, and is defined by Equations (1) and (2). Detailed modeling derivation of CM voltage and current of the topology can be found in [14]. Here, only the CM circuit model is given in Figure 2. Its transfer function $G_p$ and bode diagram is given in Equation (3) and Figure 3, respectively. The CM resonance frequency in the bode diagram is given in Equation (4). The CM current resonance would be excited in the CM current path if no CM current resonance suppression technique is applied. Such resonance current would be more serious when DPWM is used as the modulation algorithm of PV string inverter, which is explained next.

![Figure 1. Grid-connected transformer less three-level I-type inverter with ILC filter.](image1)

$\begin{align*}
    V_{cm} &= V_a + V_b + V_c \\
    i_{cm} &= i_a + i_b + i_c \\
    \text{Vx} &= \text{Vi} + \text{Vc} \\
    \text{Lx} &= \text{L}_a + \text{L}_b + \text{L}_c \\
    \text{C}_x &= \text{C}_1 + \text{C}_2 + \text{C}_3 \\
    \text{S}_1, \text{S}_2, \text{S}_3, \text{S}_4 &= \text{Switches} \\
    \text{Io} &= \text{Current} \\
    \text{Gx} &= \text{Grid} \\
    \text{Vc} &= \text{Capacitance} \\
    \text{Lf} &= \text{Inductance} \\
    \text{Cf} &= \text{Filter} \\
\end{align*}$

$\text{Figure 2. Common-mode (CM) voltage and current equivalent circuit for three-level inverter with ILC filter, without } C_{pv} \text{ considered.}$

$\text{Figure 3. Bode diagram of CM LC circuit.}$
\[ i_{CM} = i_a + i_b + i_c \]  
(1)

\[ v_{CM} = v_Ao + v_Bo + v_Co \]  
(2)

\[ G_p = \frac{i_{CM}}{v_{CM}} = \frac{C_f S}{L_f C_f S^2 + 1} \]  
(3)

\[ f_r = \frac{1}{2\pi \sqrt{L_f C_f}} \]  
(4)

where, \( i_{CM} \) and \( v_{CM} \) are the CM current and voltage, \( i_a, i_b, i_c \) are three-phase inductor current, respectively. \( v_Ao, v_Bo, \) and \( v_Co \) are three-phase bridge output voltage. \( G_p \) and \( f_r \) are the model and the resonant frequency of the equivalent CM circuit, respectively. \( L_f \) and \( C_f \) are the inductance and capacitance of LC filter. \( S \) is a complex variable in \( S \) domain, and \( S = 2\pi f i \), \( f \) is the frequency of current and voltage.

3. Harmonics Comparison of Zero Sequence Quantity of DPWM and CPWM

The symmetrical PWM [18,19] is used as CPWM in this paper. The zero sequence quantity of symmetrical PWM is given by Equation (5). A detailed description of DPWM used in this paper can be found in [16]. The zero sequence quantity of DPWM used in this paper is given by Equations (6) and (7) [20]. DPWM is widely used in the PV string inverter for its higher efficiency than that of CPWM.

\[ V_z = -0.5(V_{max} + V_{min}) \]  
(5)

\[ V'_x = (V_x + \frac{V_{dc}}{2}) \mod(\frac{V_{dc}}{2}) - \frac{V_{dc}}{4} \]  
(6)

\[ V_z = \text{sign}(V'_{x_{max}}) \cdot \frac{V_{dc}}{4} - V'_{x_{max}} \]  
(7)

where \( V_z \) is zero sequence quantity, \( V_x \) is three-phase voltage, \( V'_x \) is the intermediate variable, \( x = a, b, c \). \( V'_{x_{max}} \) is the voltage among \( V'_x \) which have maximum absolute value. \((a \mod b)\) delivers the remainder of the division \( a/b \).

The zero sequence quantity of CPWM and DPWM according to different modulation index and time are shown in Figure 4a,c, respectively. Using discrete Fourier transform, the harmonics comparison of zero sequence quantity between CPWM and DPWM are shown in Figure 4b,d respectively, which shows that the zero sequence quantity of DPWM contains more harmonics than that of CPWM. Hence, the zero sequence quantity of DPWM can lead to more serious CM current resonance than that of CPWM. As is shown in Figure 5, when the modulation method is changed from DPWM to CPWM, the resonance of CM current in \( i_o \) is alleviated.
The proposed, as is shown in Figure 6. Although the same method as in [10] is used, it should be noticed that the analysis equivalent circuit are the major difference: model in [10] is for and only for DM circuit and DM current resonance damping, model in this paper focus on CM circuit and CM current resonance damping.

4. The Proposed VNRBAD Method for CM Current Resonance

4.1. VNRBAD for CM Current Resonance

In order to suppress the CM current resonance, VNRBAD is proposed in this subsection. Using the same method as in [10], a general block diagram of the equivalent CM current power stage is proposed, as is shown in Figure 6. Although the same method as in [10] is used, it should be noticed that the analysis equivalent circuit are the major difference: model in [10] is for and only for DM circuit and DM current resonance damping, model in this paper focus on CM circuit and CM current resonance damping. $G_{ad}$ is a VNRBAD controller and is given by Equation (8). $G_{i}$ is the transfer function from $i_{CM}$ to inductor current $i_{L}$, capacitor current $i_{c}$, or capacitor voltage $v_{c}$, and is given by Equation (9). The virtual negative resistor has three positions in the modified equivalent CM circuit, and the feedback variable can be $i_{L}$, $i_{c}$ or $v_{c}$. The modified power stage and its corresponding $G_{ad}$ is given in Table 1 without considering the delay effects.

Figure 4. Harmonics comparison between continuous pulse-width modulation (CPWM) and discontinuous pulse-width modulation (DPWM). (a) CPWM zero sequence quantity. (b) PPWM zero sequence quantity. (c) Single-sided amplitude spectrum of $Z_{CPWM}$. (d) Single-sided amplitude spectrum of $Z_{DPWM}$.

Figure 5. CM current resonance comparison between CPWM and DPWM at 30A $i_{L}$. 

Table 1.
where, $G_p$ is the power stage circuit transfer function, $G_{pm}$ is the modified power stage circuit transfer function, $G_t$ is the transfer function from $i_{CM}$ to $i_L, i_c$ or $v_c$.

$$G_{ad} = \frac{G_p - G_{pm}}{G_{pm}G_pG_t}$$

(8)

Figure 6. Block diagram of CM power stage. (a) Power stage, (b) modified power stage.

Table 1. Different forms of $G_{ad}(s)$ with different filter state variables for active damping (AD).

| Connection Type of the Virtual Negative Resistor $R_v$ | Modified Power Stage | Variable Feedback for the Active Damping $G_t$ |
|------------------------------------------------------|-----------------------|---------------------------------------------|
|                                                      | $i_L, i_c, v_c$       | $G_{ad}$                                    |
|                                                      | $i_L, i_c$            | $R_v$                                      |
|                                                      | $v_c$                 | $R_vCS$                                    |
|                                                      | $i_L, i_c$            | $-\frac{L^2S^2}{L^2S+R_c}$                 |
|                                                      | $v_c$                 | $-\frac{L^2CS^2}{L^2S+R_c}$                |
|                                                      | $i_L, i_c$            | $-\frac{R_{CS}+1}{R_{CS}}$                 |
|                                                      | $v_c$                 | $-\frac{CS}{R_{CS}S^2+CS}$                 |

Using the parameters in Table 2, the bode diagram comparison between the original equivalent power stage and the three modified equivalent power stages are given in Figures 7–9, respectively. From these bode diagrams, it can be seen that the virtual negative resistor connected in series with the inductor has the best AD performance. Once the connection type of virtual negative resistor is selected, $G_{ad} = R_v$ is selected from Table 1 for simple implementation purposes.
Table 2. Photovoltaic (PV) string inverter parameters.

| Item                      | Symbol | Value          |
|---------------------------|--------|----------------|
| Filter capacitor          | $C_f$  | 18 µF          |
| Inverter-side filter inductor | $L_f$ | 95 µH at 80A   |
| rate power                | $P$    | 80 kW          |
| grid line voltage         | $V_g$  | 540 V          |
| DC voltage                | $V_{dc}$ | 800 V        |
| switch frequency          | $f_s$  | 16 kHz         |

Figure 7. Bode diagram of CM power stage: without $R_v$ and with $R_v$ connected in series with $L_f$.

Figure 8. Bode diagram CM power stage: without $R_v$ and with $R_v$ connected in parallel with $L_f$.

Figure 9. Bode diagram CM power stage: without $R_v$ and with $R_v$ connected in parallel with $C_f$.

The virtual negative resistor connected in series with the inductor and $G_{ad} = R_v$ is applied in this paper. The 1.5 times sample period $T_s$ delay is considered, and is given in Equation (10) which composed of computational and PWM delays in the digital control [10]. Since only the harmonics at
CM resonance frequency $f_r$ is the harmonics needed to damp and usually it is high-order harmonics, the high pass filter (HPF) is applied to cut off the low frequency harmonics in $i_{CM}$, and is given in Equation (11). The cutoff frequency $f_c$ can be chosen as a frequency which lower than $f_r$. In this paper, $f_r$ is higher than 2000 Hz, and 1000 Hz is used as $f_c$. The CM current resonance AD control loop with delay and HPF considered is shown in Figure 10. Its bode diagram with different virtual negative resistor values is shown in Figure 11, which shows that the admittance at resonance frequency can be effectively damped with a proper $R_v$.

$$G_d = e^{-1.5TsS}$$  \hspace{1cm} (10)  

$$\text{HPF} = \frac{S}{S + 2\pi f_c}$$  \hspace{1cm} (11)  

where, $T_s$ is the sample period, $f_c$ is the cutoff frequency of the first order high pass filter.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Figure10.png}
\caption{Common mode current suppression control loop.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Figure11.png}
\caption{$i_i$ or $i_c$ feedback based virtual negative resistor with delay considered.}
\end{figure}

### 4.2. The Implementation of VNRBAD for DPWM Application

In [14], the output of CM current controller $d_{CM}$ is added into three final modulation quantities in CPWM application, as is shown in Figure 12 and Equation (12). However, it cannot be used in DPWM application. For example, if phase A is clamped to positive bus voltage, $m_a$ is clamped to 1, and $d_z$ can be arrived in Equation (13). Substituting Equation (13) into Equation (12), the final three modulation quantity $m_a$, $m_b$, $m_c$ can be calculated in Equation (14). From Equation (14), it can be seen that $d_{CM}$ have no effects on $m_a$, $m_b$, and $m_c$, which means the $d_{CM}$ cannot be added directly into three final modulation quantities in DPWM application.

$$\begin{bmatrix}
m_a \\
m_b \\
m_c
\end{bmatrix} =  \begin{bmatrix}
d_{DMa} \\
d_{DMb} \\
d_{DMc}
\end{bmatrix} + \begin{bmatrix}
d_z \\
n_{DMa} \\
n_{DMb}
\end{bmatrix} + \begin{bmatrix}
d_{CM} \\
d_{CM} \\
d_{CM}
\end{bmatrix}$$  \hspace{1cm} (12)  

where, $m_a$, $m_b$, $m_c$ are three final modulation quantities, respectively; $d_{DMa}$, $d_{DMb}$, $d_{DMc}$ are three-phase components of DM current controller outputs; $d_{CM}$ is the CM $R_v$ outputs, $d_z$ is the zero sequence quantity of DPWM.

$$d_z = 1 - d_{DMa} - d_{CM}$$  \hspace{1cm} (13)
From Equation (17), it can be seen that DM current and CM duty cycle which controls inductor CM current are decoupled by a pair of small CM voltage given as a constant voltage vector, the dwell times the voltage space vectors in the synthesis principle, once a reference DM voltage vector without needing to adjust dwell times.

Equation (15) when using CPWM and in Equation (16) when using DPWM. Similarly, the CM voltage $V_{\text{CM, cpwm}}$ using CPWM and $V_{\text{CM, dpwm}}$ using DPWM is acquired in Equations (17) and (18). From Equation (17), it can be seen that $V_{\text{CM, cpwm}}$ can be controlled by adjusting the distribution factor $k$ without needing to adjust dwell times $t_1$, $t_{11}$ and $t_{01}$, which means that there is no coupling relationship between $V_{\text{CM, cpwm}}$ and $V_{\text{ref}}$. In CPWM application, DM duty cycle which controls inductor DM current and CM duty cycle which controls inductor CM current are decoupled by a pair of small voltage vectors. In this example, the small voltage vectors are $V_{01\, \text{POO}}$ and $V_{01\, \text{ONN}}$.

$$\begin{bmatrix} m_a \\ m_b \\ m_c \end{bmatrix} = \begin{bmatrix} 1 \\ d_{\text{DMb}} + 1 - d_{\text{DMa}} \\ d_{\text{DMc}} + 1 - d_{\text{DMa}} \end{bmatrix}$$ (14)

$$V_{\text{ref}} = \frac{t_1V_1 + t_{11}V_{11} + kt_{01}V_{01\, \text{POO}} + (1-k)t_{01}V_{01\, \text{ONN}}}{T_s} \quad (15)$$

$$V_{\text{ref}} = \frac{t_1V_1 + t_{11}V_{11} + t_{01}V_{01\, \text{POO}}}{T_s} \quad (16)$$

$$V_{\text{CM, cpwm}} = \frac{-t_1\frac{V_b}{2} + t_{01}k\frac{V_c}{2} - t_{01}(1-k)V_{dc}}{T_s} \quad (17)$$

Figure 12. $d_{\text{CM}}$ implementation in CPWM application [14].

The implementation of the proposed method for DPWM application is indirect. Figure 13 show the voltage space vectors in the $\alpha\beta$ reference frame for a three-level inverter. Based on voltage vector synthesis principle, once a reference DM voltage vector $V_{\text{ref}}$ in sector I in the $\alpha\beta$ reference frame is given as a constant voltage vector, the dwell times $t_1$, $t_{11}$ and $t_{01}$ will be known constant quantities, as is shown in Equation (15) when using CPWM and in Equation (16) when using DPWM. Similarly, the CM voltage $V_{\text{CM, cpwm}}$ using CPWM and $V_{\text{CM, dpwm}}$ using DPWM is acquired in Equations (17) and (18). From Equation (17), it can be seen that $V_{\text{CM, cpwm}}$ can be controlled by adjusting the distribution factor $k$ without needing to adjust dwell times $t_1$, $t_{11}$ and $t_{01}$, which means that there is no coupling relationship between $V_{\text{CM, cpwm}}$ and $V_{\text{ref}}$. In CPWM application, DM duty cycle which controls inductor DM current and CM duty cycle which controls inductor CM current are decoupled by a pair of small voltage vectors. In this example, the small voltage vectors are $V_{01\, \text{POO}}$ and $V_{01\, \text{ONN}}$.

Figure 13. Voltage space vectors for three-level inverter.
when phase A is clamped to negative bus voltage, the vector $V$ with $V$ is for the phase which is clamped to bus positive, negative, or neutral point voltage. The value $1$ is for the phase which is clamped to bus positive, negative, or neutral point voltage. It can be arrived that $V$ vector voltage when using CPWM and DPWM respectively.

In Equation (21), $K_{fa}$, $K_{fb}$, and $K_{fc}$ are coefficients which determine the angle of $V_{cm}$ which means that there is a coupling relationship between $V_{cm}$ and $V_{ref}$, which means that there is a coupling relationship between $V_{cm}$ and $V_{ref}$ by dwell time $t_1$ and $t_0$. The only way to control $V_{cm}$ is to adjust $t_1$ and $t_0$, which means that $V_{cm}$ can only be controlled by adjusting $V_{ref}$. $V_{ref}$ can be adjusted by compensating one of the three specific compensating vector $V_{cpi}$ ($i = A,B,C$). The three specific compensating voltage vectors are shown in Figure 14a. As is shown in Figure 14b, when phase A is clamped to positive bus voltage, the vector $V_{cpa}$ can be used to compensate $V_{ref}$ to increase the dwell time $t_1$ of voltage vector $V_1$ in Equation (18) [21], which can decrease $V_{cm}$. In Figure 14c, $V_{ref}$ is clamped to bus neutral point O. By compensating $V_{ref}$ with $V_{cpa}$, the dwell time of voltage vector $V_{03}$ is decreased, which can decrease $V_{cm}$. Similarly, when phase A is clamped to negative bus voltage, the vector $V_{cpa}$ can be used to compensate $V_{ref}$ to decrease the dwell time of voltage vector $V_4$, which can decrease $V_{cm}$. To sum up, when phase A is clamped to DC bus positive, negative, or neutral point voltage, the vector $V_{cpa}$ can be used to compensate $V_{ref}$ to decrease $V_{cm}$.

![Figure 14](image-url)

**Figure 14.** (a) Three compensation vectors for phase A,B,C; (b) $V_{ref}$ compensation when phase A is clamped to positive bus voltage; (c) $V_{ref}$ compensation when phase A is clamped to bus neutral point O.

Similar analysis can be implemented when phase B,C is clamped to DC bus positive, negative, or neutral point voltage. It can be arrived that $V_{cm}$ can be decreased by compensating $V_{ref}$ with $V_{cpi}$ ($i = A,B,C$) when phase $i$ ($i = A,B,C$) is clamped to bus positive, negative, or neutral point voltage.

$V_{ref}$ compensation is implemented in an abc reference frame. As is given in Equation (19), the compensating voltage vector $V_{cpi}$ ($i = A,B,C$) in $\alpha\beta$ reference frame can be converted to three-phase components $d_{cpi}$, $d_{cpi}$, and $d_{cm}$ in the abc reference frame using inverse Clarke transform seen in Equation (20). $d_{cm}$ is the output CM voltage of $R_c$ and determine the amplitude and sign of $V_{cpi}$ ($i = A,B,C$). $K_{fa}$, $K_{fb}$, and $K_{fc}$ are coefficients which determine the angle of $V_{cpi}$ ($i = A,B,C$). As is given in Equation (21), $K_{fa}$, $K_{fb}$, and $K_{fc}$ is a value chosen from 1, −0.5, and −0.5 for simplification purposes. The value 1 is for the phase which is clamped to bus positive, negative, or neutral point voltage. The value −0.5 is for the remaining two phases. The judgment of clamped phase is based on sector detection
algorithm in [21] and DPWM method in [16]. The final three-phase modulation quantities are given in Equation (22). The implementation diagram of VNRBAD for DPWM application is given in Figure 15.

\[
\begin{bmatrix}
    d_{CM-DMa} \\
    d_{CM-DMb} \\
    d_{CM-DMc}
\end{bmatrix} = d_{CM} \begin{bmatrix}
    K_{fa} \\
    K_{fb} \\
    K_{fc}
\end{bmatrix}
\]

(19)

\[
T_{adj2abc} = \begin{bmatrix}
1 & 0 \\
-\frac{1}{2} & \frac{\sqrt{3}}{2} \\
-\frac{1}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix}
\]

(20)

\[
\begin{bmatrix}
    K_{fa} \\
    K_{fb} \\
    K_{fc}
\end{bmatrix} = \begin{cases}
    1 & \text{(when } A \text{ is clamped)} \\
    -0.5 & \\
    -0.5 & \text{(when } B \text{ is clamped)} \\
    1 & \text{(when } C \text{ is clamped)} \\
    -0.5 & \\
    -0.5 & \\
\end{cases}
\]

(21)

\[
\begin{bmatrix}
    m_a \\
    m_b \\
    m_c
\end{bmatrix} = \begin{bmatrix}
    d_{DMa} \\
    d_{DMb} \\
    d_{DMc}
\end{bmatrix} + \begin{bmatrix}
    d_{CM-DMa} \\
    d_{CM-DMb} \\
    d_{CM-DMc}
\end{bmatrix} + \begin{bmatrix}
    d_z \\
    d_z \\
    d_z
\end{bmatrix}
\]

(22)

where, \(d_{CM-DMa}, d_{CM-DMb}, d_{CM-DMc}\) are the CM adjust quantity added to \(d_{DMa}, d_{DMb}, \) and \(d_{DMc}\), respectively. \(K_{fa}, K_{fb}, K_{fc}\) is the coefficient which transfers \(d_{CM}\) into three DM quantity \(d_{DMa}, d_{DMb}, \) and \(d_{DMc}\), respectively.

**Figure 15.** (a) The implementation of virtual negative resistor based AD (VNRBAD) for DPWM application. (b) The DM current controller.
5. Experiments and Discussion

In order to verify the effectiveness of the proposed VNRBAD method, experiments are implemented in a string inverter produced by TBEA Xi’an Electric Technology Co., Ltd. Grid simulators are used as load and PV simulators are used as DC power supply in the experiment. The specification of the inverter and experiment conditions are given in Table 2. Note that the inductance value of $L_f$ is variable with current conducting through it. The value of 95 $\mu$H is a measurement value of $L_f$ at 80A. The model number of devices used in the experiment are shown in Table 3.

Table 3. Model number of devices used in the experiment.

| Device                          | Model Number                  |
|---------------------------------|--------------------------------|
| PV simulator                    | Chroma 62150H-1000S           |
| Regenerative grid simulator     | Chroma 61860                  |
| PV String inverter              | TBEA TS80KTL_PLUS             |

5.1. The Value of $R_v$

As is shown in Figure 11, the smaller $R_v$ value it is, the better CM current resonance suppression performance it is. However, $R_v$ cannot be too small for better CM current resonance suppression, because it will degrade DM current injected to grid. Since the CM voltage is controlled by compensating DM voltage, the CM current resonance will be suppressed better when $R_v$ is smaller, while the DM current will be overcompensated and is degraded. As is shown in Figure 16, when $R_v$ is changed from $-3$ to $-1.5$, the CM current in $i_o$ is worse, while the inductor current $i_L$ and grid current $i_g$ are better. Although the damp performance of $i_o$ is better when $R_v = -3$, an apparent current distortion can be observed in $i_L$ and $i_g$, which is because the amplitude of the compensated vector is too big. There must be a compromise between the damping performance of $i_o$ and THD of $i_g$.

![Figure 16. Waveform of $i_o$, $i_L$, $i_g$, and $v_c$ with $R_v$ varied from $-3$ to $-1.5$.](image)

In practical application, there exist delays in the control loop which will degrade the CM current resonance suppression performance, so it is suggested that the value of $R_v$ can be adjusted from $-3$ to 0 by hand.
5.2. Comparison between VNRBAD and Without VNRBAD under Different $i_L$

Based on the analysis of $R_v$ above, $-2$ is chosen as the value of $R_v$ in the experiments. The waveform comparison of $i_o$, $i_L$, $i_g$, and $v_c$ between VNRBAD and without VNRBAD under different values of $i_L$ is given in Figures 17 and 18, respectively. Note that the CM current in $i_g$ resonates heavily under 80A $i_L$ when without VNRBAD, and the protection program of the control system is triggered to shut down the inverter. The proposed VNRBAD can suppress the CM current resonance effectively, although not completely. The harmonics of $i_g$ is shown in Figures 19 and 20, respectively. The harmonics at CM resonance frequency is reduced effectively.

Figure 17. Waveform comparison of $i_o$, $i_L$, $i_g$, and $v_c$ between AD and without AD under 60A $i_L$.

Figure 18. Waveform comparison of $i_o$, $i_L$, $i_g$, and $v_c$ between AD and without AD under 80A $i_L$.

Figure 19. Harmonics comparison of $i_L$ between AD and without AD at 60A $i_L$. 
5.3. Discussion

The PD method with a 0.61 ohm resistor connected in series with the inductor in the CM circuit is also implemented. The waveform of $i_o$, $i_L$, and $i_g$ using PD method is shown in Figure 21. The RMS value comparison of $i_o$ of three methods under different $i_L$ is shown in Figure 22. It can be seen that PD has a better CM current suppression performance compared with the proposed VNRBAD method.

Two reasons limit the CM resonance suppression performance of the proposed VNRBAD. One is that there is a compromise between the CM current control performance and DM current control performance. If $R_v$ is too small, the CM resonance current damping performance is not good. On the contrary, too small values of $R_v$ overcompensate DM voltage $V_{ref}$ in $\alpha\beta$ reference frame and degrade the quality of DM current $i_g$. Another reason is the delay in the control loop which can be studied further. Although the damping performance of the proposed VNRBAD method is not as good as PD, VNRBAD can suppress the CM current resonance within an acceptable range to let the inverter operate normally in DPWM application.
6. Conclusions

In this paper, VNRBAD is proposed to suppress the CM current resonance for a three-level grid-tied inverter with DPWM. The harmonics comparison of zero sequence quantity between DPWM and CPWM is presented, which shows DPWM has more harmonics than that of CPWM. In DPWM application, the CM voltage and DM voltage is coupled. VNRBAD is implemented by compensating the DM voltage to control the CM voltage. Experimental results demonstrate the effectiveness of VNRBAD. Although VNRBAD is not as good as PD in the experiments, VNRBAD can suppress the CM current resonance within an acceptable range and does not need additional PD power resistor. Future work will focus on the reduction of the delay in the control loop which can enhance the CM current resonance suppression performance of the proposed VNRBAD method.

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