Mixed Conduction Mode Control for Inductor Minimization in Grid-Tied Inverter

Hoai Nam Le, Jun-ichi Itoh
Nagaoka University of Technology
1603-1 Kamitomioka Town
Nagaoka City, Niigata Prefecture, Japan
Tel: +81 / (258) – 47.9533.
E-Mail: lehoainam@stn.nagaokaut.ac.jp
URL: http://itohserver01.nagaokaut.ac.jp/itohlab/index.html

Abstract—This paper proposes a mixed-conduction-mode (MCM) current control for a grid-tied inverter operating in both continuous current mode (CCM) and discontinuous current mode (DCM) in order to minimize an interconnected inductor. In general, a low interconnected inductor value worsens disturbance suppression of current controller, and leads to an increase in grid current total harmonic distortion (THD). In DCM, the disturbance-to-current transfer function becomes nonlinear and the disturbances such as the dead time voltage error are effectively suppressed. Therefore, the grid-tied inverter operating in MCM can achieve a low grid current THD. However, another DCM nonlinearity occurs in the duty-to-current transfer function, which makes control gain characteristic in DCM completely different from that in CCM. Therefore, the DCM nonlinearity compensation is proposed by using duty at previous calculation. The validity of the proposed current control is confirmed with a 1-kW 100-kHz prototype. Even when using the interconnected inductor with a normalized impedance of 0.16%, the grid current THD is reduced from 14.8% to 2.9% at rated load compared to the conventional CCM control. Furthermore, the inductor volume is reduced by 77.0%, whereas the converter loss is reduced by 36.5%.

Keywords—Single-phase grid-tied inverter, Continuous current mode, Discontinuous current mode, Mixed conduction mode, Disturbance compensation.

I. INTRODUCTION

In recent years, researches on photovoltaic system (PV) has attracted many attentions due to the increasing demand of renewable resources [1]-[3]. H-bridge inverters are usually used in the PV system in order to convert DC power from solar panel into AC power in the conventional AC single-phase grid. In such grid-tied inverters, LCL filters are generally employed between the inverter and the grid in order to suppress current harmonics and meet grid current harmonic constraints as defined by standards such as IEEE-519-1992 [4]-[5]. This LCL filter, especially the interconnected inductor, accounts for a majority of the inverter volume [6]-[7]. By increasing switching frequency and reducing an inductor value, the interconnected inductor volume can be minimized. However, the grid-tied inverter generally operates in CCM, where the disturbance suppression performance worsens with the reduced inductor value. This leads to the increase in the grid current THD. In order to overcome this problem, a disturbance observer which is designed based on CCM transfer function is utilized. The disturbance observer can suppress the disturbance effects on the current control and allows the reduction of the inductor value. Nevertheless, this method requires high speed controllers such as, e.g. field-programmable gate array (FPGA), in order to estimate the rapidly-changing disturbances, e.g. the dead-time error voltage [8].

As another approach, the disturbance effects can be reduced by DCM. The zero-current interval in DCM introduces the nonlinearity into the disturbance-to-current transfer function, which effectively suppresses the disturbance effects such as the dead time voltage error. However, another nonlinearity occurs in the duty-to-current transfer function, which makes the current control gain in DCM completely different from that of CCM [9]-[10]. A nonlinearity compensation has been proposed and effectively achieves the current command response as same as CCM [10]. Nevertheless, the proposed DCM current controller can be applied only in DCM, which implies that the grid-tied inverter has to operate in DCM over entire load range. This design significantly increases conduction loss of switching devices due to high current ripple of DCM at rated load. Therefore, many control methods which allow the inverter to operate in both CCM and DCM have been proposed to improve the conversion efficiency [11]-[14]. However, these MCM control method becomes dependent on the inductor value, which decays the robustness of the controller against the change of the inductor value [15].

This paper proposes a novel MCM current control for the grid-tied inverter operating in both CCM and DCM. The DCM nonlinearity in the disturbance characteristic is used to reduce the grid current THD, whereas the DCM nonlinearity in the duty-to-current transfer function is compensated by using the duty at the previous calculation period. Meanwhile, the current mode determination between CCM and DCM is accomplished by comparing the DCM duty and the CCM duty at the output of the controller. Thank to this method, the current feedback control is independent of the inductor value and can operate at any load condition. This paper is organized as follows: first the problems with the increasing grid current THD when the inductor value is reduced in CCM operation is explained. Next, two DCM nonlinearities are
investigated when the power factor is lower than one in order to stably operate the grid-tied inverter at any load condition. Then the MCM current control for both CCM and DCM is proposed in order to obtain the low grid current THD with the small inductor value. Finally, the effectiveness of the proposed current control is confirmed experimentally with a 1-kW prototype. The comparisons of the grid current THD and the conversion efficiency are demonstrated.

II. PROPOSED MIXED CONDUCTION MODE CURRENT CONTROL

A. Current Distortion in Conventional Continuous Current Mode Control

Fig. 1 indicates the circuit configuration of the single-phase grid-tied inverter. In this paper, a single-phase H-bridge inverter is applied due to its simplicity. The LCL filter connects the inverter to the grid in order to suppress the current harmonics of the inverter output current i_{out}. Note that the grid has its own intrinsic inductor L_g, the value is different depending on the type and the condition of the grid.

Fig. 2 indicates the conventional CCM feedback current control block with a typical dead-time error voltage compensation. Note that the grid current i_g and the grid voltage v_g are assumed to be as same as i_{out} and the voltage v_{gf} across the filter capacitor C_f, respectively, because the cutoff frequency of the LCL filter is designed to be much higher than the bandwidth of the current control loop. The amplitude of the disturbance-voltage-to-current transfer function in CCM which is also entitled the gain of the disturbance response |G_{dis, CCM}| is derived from Fig. 2 and expressed as in

$$G_{dis, CCM} = \frac{1}{L\omega_n} \sqrt{\frac{4\zeta^2 + \frac{\omega^2}{\omega_n^2}}{1 - \frac{\omega^2}{\omega_n^2}}} \quad \cdots(1),$$

where L is the inverter-side inductor value, \omega is the disturbance angular frequency, \omega_d and \omega_n are the damping factor and the angular frequency of the current controller, respectively.

Fig. 3 depicts the gain of the disturbance response in CCM under different conditions of L. Because |G_{dis, CCM}| is inversely proportional to L, the disturbance effects increase 10 times when L is reduced from 1 p.u. to 0.1 p.u.. Consequently, this worsens the disturbance response. In general, when the typical dead-time error voltage compensation is applied with the high L, the current distortion is effectively reduced. However, when L is greatly reduced, only a small mismatch between the estimated and actual dead-time error voltage (v_{deadtime_est} and v_{deadtime}) which is caused by such as the current detection delay, results in a high current distortion due to the greatly-increasing gain of the disturbance response |G_{dis, CCM}|. Note that by increasing the angular frequency of the current controller \omega_n, the gain of the disturbance response |G_{dis, CCM}| can be reduced, i.e. the current distortion can be reduced. However, a high bandwidth current control requires a high speed controller, which is an undesired solution.

B. Compensation of Discontinuous-Current-Mode Nonlinearity in Duty-To-Current Transfer Function

Fig. 4 indicates the grid-tied inverter operation under different conditions of the power factor. Fig. 4(a), (b) shows the relationship between the grid voltage v_g and the output current i_{out} of the inverter at the unity power factor and the power factor below one, respectively. Meanwhile, Fig. 4(c), (d) depicts the inverter operation mode and the output current waveform when the inverter operates in powering mode at interval ii in Fig. 4(b) and generation mode at interval i in Fig. 4(b), respectively. Note that the grid-tied inverter is operated in bipolar modulation in order to reduce common current, whereas the grid-side inductors L_g, L_f, and the filter capacitor C_f are omitted due to the simplification. As shown in Fig. 4(a), the inverter operates in only the powering mode when the power factor is unity. On the other hand, the in-
**Grid-tied inverter operation under different conditions of power factor.** Different from the CCM operation, the inverter operation mode in DCM depends on the relationship between the grid voltage $V_g$ and the output current $i_{out}$ of the inverter, i.e. the powering mode or the generation mode. This is because the zero-current interval introduces nonlinearities into the DCM operation.

Considering the inverter operation and the output current waveform in the powering mode shown in Fig. 4(c) (cf. interval ii of Fig. 4(b)), $D_1$, $D_2$ and $D_3$ denote the duties of the first, the second and the zero-current interval. The equation based on the average model of the inverter shown in Fig. 4(c) is given by (2) [9]-[10],

\[
V_i = D_1(V_{dc} - V_g) - D_2(V_{dc} + V_g) \quad \text{(2)}
\]

where $V_L$ is the average inductor voltage, $V_{dc}$ is the DC-link voltage and $V_g$ is the grid voltage. The average current $i_{avg}$ and the current peak $i_{peak}$ which are shown in Fig. 4(c) are expressed as,

\[
i_{avg} = \frac{i_{peak}}{2} (D_1 + D_2) \quad \text{(3)}
\]

\[
i_{peak} = \frac{V_{dc} - V_g}{L} D_1 T_{sw} \quad \text{(4)}
\]

where $T_{sw}$ is the switching period. Substituting (4) into (3) and solving the equation for the duty $D_2$. The duty $D_2$ is expressed by

\[
D_2 = \frac{2L i_{avg}}{D_1 T_{sw} (V_{dc} - V_g)} - D_1 \quad \text{(5)}
\]

Substituting (5) into (2) in order to remove the duty $D_2$ and represent (2) as a function of only the duty $D_1$, then (6) is obtained.
Then, the inverter model in DCM is established based on (6).

Fig. 5 illustrates the circuit model of the inverter operating in DCM at powering mode which is based on (6). In CCM, the dash line part does not exist, because the average current $i_{\text{avg}}$ equals to the half peak current $v_{\text{peak}}/2$. On the other words, this makes the zero-current interval $D_1T_{\text{sw}}$ shown in Fig. 3 become zero. However, in DCM, the zero-current interval introduces the nonlinearities into the DCM transfer function. The design of the compensation part for the DCM nonlinearity is explained as in [10]. The circuit model in Fig. 5 is linearized and discretized at steady state points.

Fig. 6 depicts the discretized circuit model at powering mode. Note that $V_{dc}, V_{g},$ and $D_{1,s}$ are the DC-link voltage, the grid voltage and the duty at steady state points, whereas $\Delta V_{g}, \Delta D_1,$ and $\Delta i_{\text{avg}}$ are the small signals of the grid voltage, the duty and the average current, respectively. The zero-current interval introduces nonlinearities in the grid-voltage-to-current transfer function and the duty-to-current transfer function.

Fig. 7 (a)-(c) indicates the proposed DCM current controls for the powering mode, for the generation mode and for any conditions of the power factor, respectively. As shown in Fig. 7(a), in order to compensate the DCM nonlinearities at the output of the PI controller designed in CCM, the nonlinearity in the duty-to-current transfer function in Fig. 6 is set as 1, whereas the nonlinearity in the grid-voltage-to-current transfer function is eliminated by feeding forward the grid voltage to the output of the PI controller. In principle, the current control in Fig. 7(b) is the same as that in Fig. 7(a). However, the sign of the absolute value of the grid voltage in Fig. 7(b) is opposite to that in Fig. 7(a), because as shown in Fig. 5(c), (d), the applying order of mode 1 and mode 2 in the powering mode is flipped compared to that in the generation mode. In order to control the DCM current under any conditions of the power factor, the combination of the current control from Fig. 7(a) and (b) is required. By using the information of the output current polarity, the proposed DCM nonlinearity compensation can be employed over entire range of the power factor.

Fig. 8 shows the gain of the disturbance response in CCM and DCM under different conditions of the steady-state duty-ratio $D_{1,s}$. In CCM, the minimization of the inductor value $L$ worsens the disturbance response. On the other
hand, in DCM when the steady-state duty-ratio $D_{avg}$ becomes smaller, the disturbance response gain in DCM decreases. The reason is that the proposed DCM nonlinearity compensation for the current command response does not compensate for the DCM nonlinearity in the disturbance response. Consequently, the disturbance response depends on the steady-state duty-ratio $D_{avg}$. Therefore, by utilizing this non-linearity characteristic in which the disturbance gain decreases greatly with the small steady-state duty-ratio $D_{avg}$, i.e., the interval near the current zero-crossing point or the light load, the current distortion can be reduced.

### C. Current Mode Determination

Fig. 9 shows the relationship among the CCM duty, the DCM duty and the current mode. In conventional current mode determination, the average current (the detection value $i_{avg}$ or the command value $i_{avg,*}$) is compared with the current value $I_{BCM}$ at the boundary between CCM and DCM, which is calculated by using the inductor value. Consequently, when the actual inductor value is different from the nominal value, the current mode cannot be accurately determined by the conventional method. On the other hand, the proposed current mode determination focuses on the relationship between the CCM duty and the DCM duty when the current mode alternates. In particular, when the circuit operates in DCM, the DCM duty becomes smaller than the CCM duty and vice versa. Therefore, using this relationship, the proposed current mode determination is achieved without using the inductor value. This makes the MCM controller robust against the change of the inductor value.

Fig. 10 indicates the proposed MCM current control and the waveform of the current mode alternation. The CCM duty $D_{d_{CCM}}$ is calculated without using the inductor value. Similarly, the inductor value is unnecessary in the calculation of the DCM duty $D_{d_{DCM}}$, because the inductor value is not used in the DCM nonlinearity compensation. Consequently, the relationship between the CCM duty and the DCM duty which is independent from the inductor value is achieved. Thank to this, the proposed MCM current control can be applied even when the inductors with high tolerance are used.

### III. LABORATORY SETUP

Table I depicts the experimental parameters. The operation frequency of the current controller is synchronized with the sampling frequency of 20 kHz despite of the high switching frequency of 100 kHz, which enables the use of low speed controllers.

Fig. 11 depicts the prototypes of the inverter-side inductors $L$ under different conditions of the inductor impedance %$Z_L$ normalized by the based impedance. Ferrite is chosen...
to be the core material in order to minimize the core loss at the switching frequency of 100 kHz, whereas Litz wire is used in order to minimize the winding loss coming from the proximity effect and the skin effect. By the application of DCM, the normalized impedance of the inductor impedance $\%Z_L$ can be minimized without worsening the disturbance response as shown in Fig. 8. Consequently, by reducing the impedance of the inverter-side inductor $\%Z_L$ from 3.1% to 0.16%, the inductor volume is reduced by 77%.

Fig. 12 and Fig. 13 shows the grid voltage, the grid current and the inverter output current of the conventional CCM current control and the proposed MCM current control at rated load of 1kW and at light load of 200W, respectively. The IEEE-519-1992 standards require the grid current THD below 5% at rated load, which can be accomplished simply with the high impedance of the inverter-side inductor $\%Z_L$ as shown in Fig. 12 (a). However, as $L$ is reduced to minimize the interconnected inductor, the disturbance effects in CCM increase with small $\%Z_L$ as shown in Fig. 3. Consequently, the grid current THD increases from 1.5% to 14.8% when $\%Z_L$ is reduced from 3.1% to 0.16%. This problem can be overcome by increasing the control bandwidth of the current controller, which is difficult to employ with low speed microprocessors. On the other hand, when the inverter is operated in MCM, the disturbance effects naturally reduce at low duties as shown in Fig. 8, i.e. the zero-crossing intervals, due to the nonlinearity in the disturbance response. Therefore, the low grid-current THD of 2.9% is achieved with the proposed MCM current control even when $\%Z_L$ is reduced to 0.16%. Similarly, the grid current THD at light load of 200W is also reduced from 27.6% to 2.5%.

Fig. 14 shows the comparison of the grid current THD and the conversion efficiency between the conventional CCM current control and the proposed MCM current control with different of normalized impedances. Even when the normalized impedance of the grid-side inductor $\%Z_L$ is min-

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<tr>
<th>TABLE I</th>
<th>SYSTEM PARAMETERS.</th>
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<tbody>
<tr>
<td>Circuit Parameter</td>
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<tr>
<td>$V_{DC}$</td>
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<tr>
<td>$v_g$</td>
<td>Grid Voltage</td>
</tr>
<tr>
<td>$P_n$</td>
<td>Nominal Power</td>
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<td>$C_b$</td>
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<td>$\zeta$</td>
<td>Damping Factor</td>
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<tr>
<td>$f_c$</td>
<td>Cutoff Frequency</td>
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Fig. 11. Prototypes of inverter-side inductors under different conditions of inductor impedance normalized by base impedance. By reducing the impedance of the inverter-side inductor $\%Z_L$ from 3.1% to 0.16%, the inductor volume is reduced by 77%. |
occurs in the conventional CCM current control, whereas the proposed MCM control can achieve both the low grid current THD and the high efficiency.

Fig. 15 depicts the proposed MCM current control operation at the rated current and under different power factors. The low grid current THD can still be achieved at low power factor with the proposed MCM current control. On the other words, the proposed MCM current control provides the grid-tied inverter the capability of fault-ride-through. The effectiveness of the proposed MCM current control is confirmed by these experimental results.

IV. CONCLUSION

When the grid-connected inductor is minimized by reducing the inductor impedance, the disturbance effects increases highly in the CCM operation, which distorts the grid current. On the other hand, in the DCM operation, the non-
The main contribution of this paper is that the proposed MCM current control is independent from the inductor value because the inductor value is not used in both the DCM nonlinearity compensation and the current mode determination.

REFERENCES


