DC current rejection for a half-bridge current-mode control grid-connected inverter

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***Abstract*—the dc current rejection of a single phase half-bridge grid-connected inverter with a line-frequency isolation transformer is researched in this paper. The impact of the magnetic dc bias of the transformer is given out from the mathematic model of the transformer in current-mode control. For the half-bridge current-mode inverter, the dc current rejection method is presented based on the relationship of dc current component and voltages across the filter capacitors of the dc bus. Simulation and experiment results indicate that the dc component of inverter current saturates the transformer and degrades the quality of current injected into the grid. With voltage balance control of the filter capacitors, the dc current control of half-bridge current-mode grid connected inverter is realized.**

Keywords-Current-mode control; Grid-connected inverter; Magnetic dc bias of a transformer; DC current component

I. INTRODUCTION

Generally, grid-connected inverter works in current control mode [1-3]. Incorrectness of current sample deduced by precise of transform of analog to digital and the temperature shift of elements, discrepancy between drive circuit and power devices lead to output current of the inverter involves direct current component [4-5] and interfere with the grid and load. Standards of many countries and zones give the restriction about direct current component of the grid-connected inverter [6-8]. If output port of the inverter connects with the grid by the line-frequency isolation transformer, the DC component will not flows into the grid by the transformer, but it will make the transformer saturate, the loss and noise increased, and the quality of grid-connected current decreases. In this paper, magnetic process of the transformer influenced by DC component is analyzed according to mathematical model in current-controlled mode. Meanwhile, take the case of a half-bridge grid-connected inverter, the control method about transformer dc current component was researched and verified by experiments.

II. CURRENT-CONTROL TRANSFORMER MATHEMATICAL MODEL

Equivalent circuit of current-control mode grid-connect inverter was shown in Fig1. R_1 and L_1 are reluctance and leak-inductance of primary winding of the transformer; i_φ is the excite current; Rc is iron loss reluctance; Lm is magnetic inductance; R'2 and L'2 are equivalent impedance of primary side acted by the reluctance and leak-inductance of secondary side; v_1 is the voltage of the grid; v_2 is output voltage of the inverter; main flux is contributed by the magnetic-motive force produced by the primary and secondary sides. i_φ was the exciting current producing main flux, which embodies Non-sinusoidal because of magnetic route of the iron is nonlinear. Normally, current-control mode is often applied in the inverters, and the inverter can be looked upon current source controlled by i_2. i_2' is the current that i_2 reflected to the primary side. N_2/N_1 is the ratio between the secondary and the primary sides of the transformer.

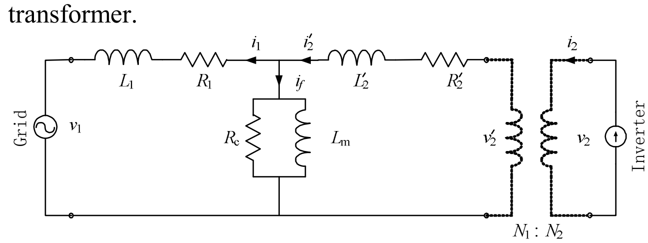

Fig.1 Equivalent circuit of the current-mode control grid-connected transformer

From the current and magnet motive force of the transformer relationship, we can get the formula as follows:

$$N_1 i_\varphi = N_2 i_2 - N_1 i_1 = N_2 i_2 - N_1 (i_2' - i_\varphi) \tag{1}$$

From the expression above,

$$i_2' = \frac{N_2 i_2}{N_1} \tag{2}$$

If output current i_2 include the dc component, then

$$i_2 = i_{2\_ac} + i_{2\_dc} \tag{3}$$

Where, i_{2_ac} and i_{2_dc} are alternant current component and direct current component of the current i_2 respectively, from expression (1):

$$N_1 i_\varphi = N_2 (i_{2\_ac} + i_{2\_dc}) - N_1 i_1 \tag{4}$$

The grid can be looked as alternant voltage source, so the current i_1 can not imply the dc component. From the

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expression (4), the dc component lies in the exciting current is produced by the dc component of the current i_2, and

$$i_\varphi = i_{\varphi\_ac} + i_{\varphi\_dc} \tag{5}$$

Where, i_{φ_ac} and i_{φ_dc} are alternant current component and direct current component the current i_φ respectively, and

$$\begin{cases} i_{\varphi\_ac} = (N_2 i_{2\_ac})/N_1 - i_1 \\ i_{\varphi\_dc} = (N_2 i_{2\_dc})/N_1 \end{cases} \tag{6}$$

As known from the expression (4) and (6): the dc current magnetic depth of the transformer depends on the dc current component of output current of the inverter. The current i_1 composes of two components: one is the load current component, which cancels the equivalent alternant current deduced by the secondary alternant current component reflect to the primary; the other is the exciting alternant current i_{φ_ac}, which is decided by alternant current magnetic progress of the transformer. Under the bias-magnet condition of the transformer, the magnetic reluctance is dissymmetry during two and half periods. So, i_{φ_ac} is also asymmetry. This condition will lead to the current i_1 distorts, and waveform quality will be influenced. Moreover, asymmetry of the exciting impedance will also influent the output current control steady state characteristic of the inverter, and lead to output current of the inverter get ring and distortion so that decrease the quality of grid-connected current.

In this paper, the parameters of 1kW isolated transformer in the prototype as follows: the ratio N_1/N_2 is 93:230, leak-inductance and reluctance of the primary windings is 360μH and 0.48Ω respectively. Leak-inductance and reluctance of the secondary windings is 58μH and 75mΩ respectively. Rms of the exciting current is 51.6mA, and peak-peak value is 240mA. Grid-connected current waveform at rated power of 1kW/230V/50Hz grid-connected inverter was shown in Fig2. From the current waveform, we can know the dc component of the current is 76mA in positive direction and 76mA in negative direction, and transformer work in magnetic-bias condition. So, the exciting current drawn from the grid is asymmetry between the positive and negative area, and the current across the zero get distortion because that the exciting current lags behind the grid voltage about 90 degrees.

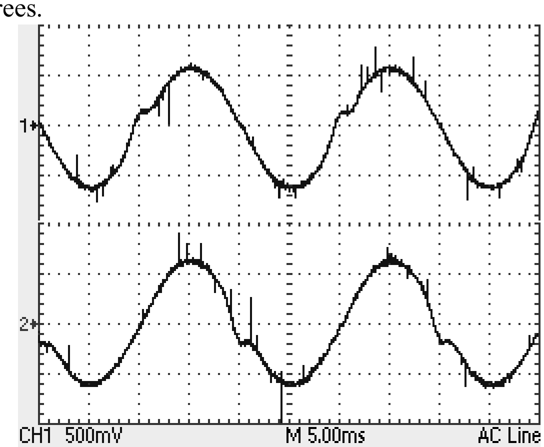


Fig.2 Influence of magnetic dc-bias on current injected into the grid

III. DC CURRENT REJECTION OF HALF-BRIDGE INVERTER

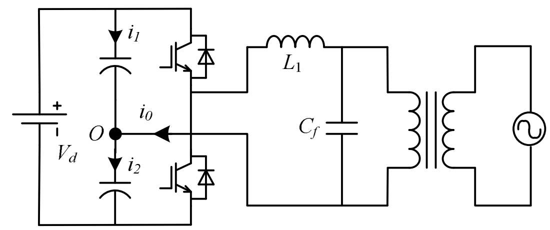
The topology of a half-bridge current-control mode grid-connected inverter was shown in Fig3 (a). Leak-inductance of the transformer and equivalent reluctance didn't express in the Fig3. Control strategy of the inverter is current control mode. That's to say, the current of the inductor will be sampled and tracked by close-loop control so that feed the current into the grid. Where, filter capacitors C_1=C_2=3300μF, filter inductor L_1=3mH, output filter capacitor C_f=10μF, 。 $i_1$and i_2 are the currents follow by the filter capacitor C_1 and C_2. i_0 is the output current of the inverter. As to node "O", the expressions as follows were established.

$$\begin{cases} i_2 = i_1 + i_0 \\ v_{c1} + v_{c2} = V_d \end{cases}$$

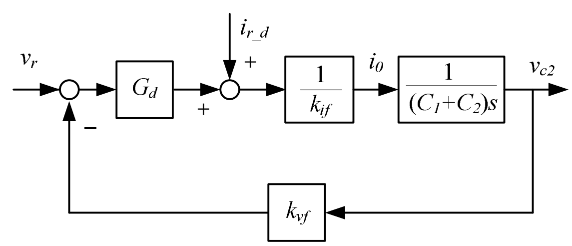
$$\Rightarrow \begin{cases} C_2 \dfrac{dv_{c2}}{dt} = C_1 \dfrac{dv_{c1}}{dt} + i_0 \\ C_1 \dfrac{dv_{c1}}{dt} = -C_1 \dfrac{dv_{c2}}{dt} \end{cases} \tag{7}$$

From the expression (5),

$$(C_1 + C_2)\frac{dv_{c2}}{dt} = i_0 \tag{8}$$



（a） topology of the grid-connected inverter



（b） bus voltage balance control diagram

Fig.3 Diagram and voltage balance control block of half-bridge inverter

When output current of the inverter contains dc current component, the expression above can be expressed as follows:

$$i_0 = I_0 + I_m \sin(\omega t) \tag{9}$$

Where, I_0 is the dc current component, I_m is peak-peak value of the current. So

$$\begin{aligned} v_{c2} &= \int_0^t \frac{i_0}{C_1 + C_2} dt \\ &= V_0 + \frac{I_0}{C_1 + C_2} t + \frac{I_m}{(C_1 + C_2)\omega} \cos(\omega t) \end{aligned} \tag{10}$$

Where, V_0 is initial value of voltage v_{c2}. From the expression (10), we know that alternate current component lies in output current of the inverter make the voltage v_{c2} include alternate current ripple and alternate current frequency is equal to the frequency of the grid. The dc current component of i_0 will make the average current value of the voltage v_{c2} changed gradually, and make the voltage of capacitors C_1 and C_2 unequal so that system stop because of protect function was triggered in the end. If v_{c2} (or v_{c1}) is controlled to keep the capacitor voltage to be a half of dc bus voltage V_d, then the inverter current is controlled, and the dc component of output current is zero.

Filter capacitor voltage balance control diagram was shown in Fig3 (b). i_{r_d} express dc current bias error of inverter current close-loop control signal given. Feedback value of the v_{c2} compares with value given v_r, and the signal got by controller G_d can be looked up as compensation of the dc bias signal. Because bandwidth under voltage balance control much less than grid frequency, alternate current component of the inverter output current influence on the voltage balance control may not considered. Inverter can be looked as current source controlled, and amplifier coefficient is the reciprocal of the inverter current feedback coefficient k_{if}. Dc current rejection and stability of v_{c2} can be realized by adjust dc current component of the inverter output current.

IV. SIMULATION AND EXPERIMENTAL RESULTS

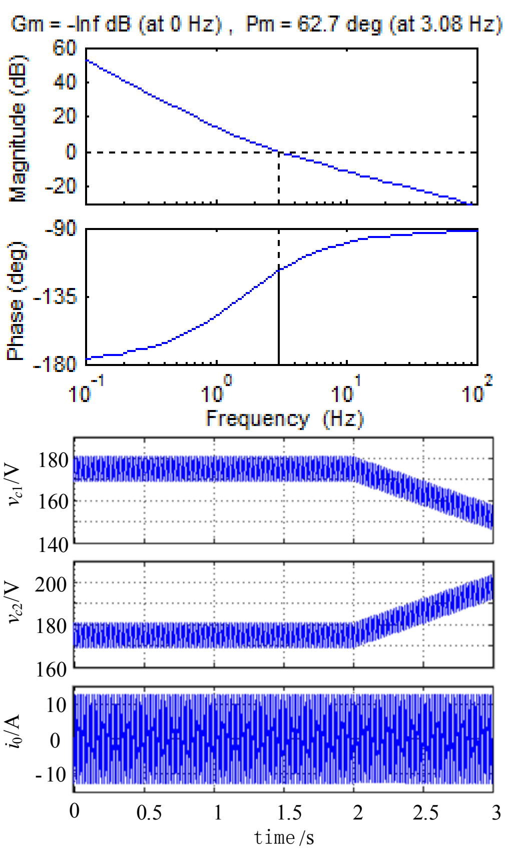


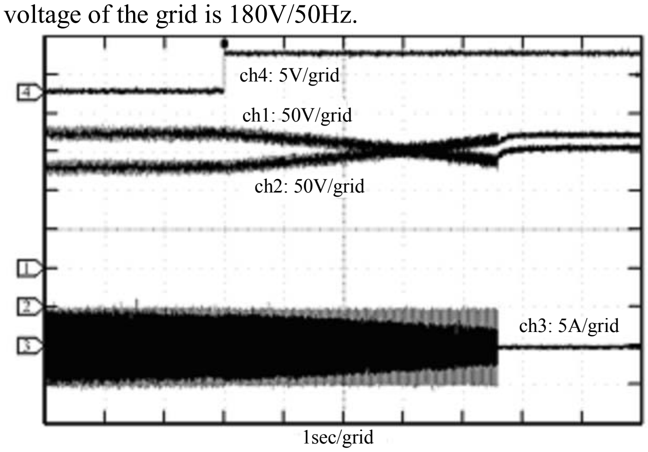
Fig.4 Margin of the voltage balance control and simulation results

Prototype parameters of the half-bridge current-mode control grid-connected inverter as follows: dc bus voltage is 350V; the ratio of the transformer is 2.47:1; current feedback coefficient is 0.066; output rated current of the inverter is 10.7A; k_{vf}=0.005; k_{if}=0.066; V_d=350V; C_1=C_2=3300μF; v_r=0.875; controller transfer function G_d=1.5+15/s. Fig4 (a) shows relative stability of the voltage balance control system, and the system has great stability margin. Simulation results of capacitor voltage balance control were shown in Fig4 (b), and the current given signal is

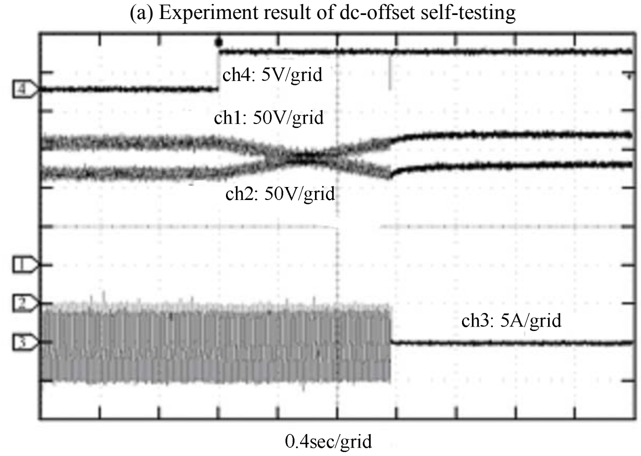
$$i_r = 0.01 + \sin \omega t \tag{11}$$

That's to say, error given of dc component i_{r_d}=0.01. Under the condition without dc component control, dc component of output current i_0=i_{r_d}/k_{if}= 152mA. From equation (8), we can know that the rising rate of the capacitor voltage v_{c2} is 23V/s. Simulation results in Fig 4(b) show that voltage of capacitor C_1 and C_2 got balance under voltage balance control during the first 2 seconds. At the 2th second time, voltage balance control was cancelled, v_{c2} increased with the voltage rate of 23V/s while v_{c1} decreased with the same voltage rate, and this situation satisfied with the calculation results of equation (8).

In the experiment, the peak current given is 0.8, which is corresponding with 5A grid-connected peak current. The voltage of the grid is 180V/50Hz.



(a) Experiment result of dc-offset self-testing



(b) Experiment result of dc-bias disturbance

Fig.5 Experiment result of control for voltage balance control

Fig (5) shows experiment results of the voltage balance control. Where, channel ch1 shows capacitor voltage of up leg; channel ch2 shows capacitor voltage of down leg;

channel ch3 shows grid-connected current waveform; channel ch4 shows trigger signal. When trigger signal jump to high level from low level, voltage balance control was cancelled. Seen from the waveforms in Fig5 (a), dc bias signal of grid-connected current control loop has been detected before the system began to generate. Channel 4 shows that filter capacitor voltage can be balanced after voltage balance control was adopted at low level time. When the voltage balance control was cancelled at the rising time of channel 4, the voltage of capacitor begin to loose the balance, the system voltage protection will be triggered in the end, and bias voltage of capacitor change rate is 8V/s. We can get relative dc current component is about 53mA. If dc bias signal was increased 0.01 based on the experiments in Fig5 (a), the voltage change rate of the capacitor is 34V/s, corresponding with dc component about 224mA after the voltage balance control has been cancelled. Compared with experiments in Fig5 (a), Error increase of dc bias signal will get the voltage change rate of capacitor increased after voltage balance control was cancelled.

V. CONCLUSIONS

Dc component control of grid-connected inverter is vital to system safety. Proper control strategy can avoid interfering with grid. If output port of the inverter is connected with the grid by isolate transformer, dc component will make the transformer saturate partly so that grid-connected current waveform get bad. As to a half-bridge current-mode control inverter, dc component of transformer output current will result in capacitor voltage of up and down legs unbalance. Filter capacitor voltage balance control and dc bias signal compensation of inverter current closed control can realize the voltage balance of the capacitor and dc current rejection.

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REFERENCES

[1] J. Selvaraj, N. A. Rahim, C. Krismadinata, Digital PI current control for grid connected PV inverter[C]. IEEE 3rd conference on industrial electronics and application, June 2008, Singapore: 742-746.

[2] Hossein Madadi Kojabadi, Bin Yu, Idris A. Gadoura, et al.. A novel DSP-based current-controlled PWM strategy for single phase grid connected inverters [J]. IEEE Transactions on power electronics, July 2006, 21(4): 985-993.

[3] Yao zhilei, Wang zan, Xiao lan, et al.. A novel control strategy for grid-interactive inverter in grid-connected and stand-alone modes[C]. IEEE 21st annual applied power electronics conference and exposition, March 2006, Dallas: 779-783.

[4] Liu gang, Zhang donglai, Zeng jianyou. Investagation and Restraining of Magnetic Baic for the Output Transformer of Full Bridge Single-phase Inverter Circuit[J]. Power Electronics, 2006, 40(3): 77-79.

[5] Duan shanxu, Liu bangyin, Peng li. etal. The Analysis and Eliminating Techniques of Magnetic Bias for Output Transformer in the Fully Digitized Intermediate Frequency Inverters [J]. High Voltage Engineering, 2003, 29(10): 1-3.

[6] IEEE Standards Coordinating Committee 21. IEEE standard for interconnecting distributed resources with electric power systems [S]. IEEE Std 1547™_2003, 2003.

[7] Underwriters Laboratories Inc.. Inverters, converters, and controllers for use in independent power systems[S]. UL 1741, 2001.

[8] Standards Australia, Grid connection of energy systems via inverters part 2: Inverter requirements[S]. AS4777.2_2005.

[9] Chen Tong, Zhao Rongxiang. Design of Single-phase Low-power Grid-Connected Inverter for Distributed Generation[J]. Power Supply Technologies and Applications, 2005, 8(11): 22-25.

[10] Soeren Baekhoej Kjaer, John K. Pedersen, Frede Blaabjerg. A review of single-phase grid-connected inverters for photovoltaic modules [J], IEEE Transactions on industry applications, 2005, 41(5): 1292-1306.

[11] Linsuo Zeng, Zhanxin Zhu, Baodong Bai, et al.. Research on influence of dc magnetic bias on a converter transformer[C]. Proceeding of international conference on electrical machines and systems, Oct. 2007, Korea: 1346-1349.