Two-Degree-of-Freedom PID Digital Control of A Bidirectional Quasi-Single-Stage Push-pull Forward High Frequency Link Inverter

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***Abstract*— In this paper, a high performance circuit topology and control techniques are developed. The proposed bidirectional quasi-single-stage push-pull forward high frequency link inverter consists of a push-pull forward converter, a bidirectional active rectifier, an active clamp branch and a SPWM inverter bridge. In particular, a two-degree-of-freedom PID digital controller is applied to achieve high performance in both the command tracking and the load disturbance regulation. The modulation and control strategy are realized by using the TMS320LF2407A DSP and EPM7128 CPLD. The principles of circuit operation are also discussed in this paper. Theoretical analysis and experimental results indicate that the proposed topology and control scheme are promising for the applications of DC/AC power supply.**

I. Introduction

There are many applications for DC/AC inverter. With the development of technology, the major concern of the inverters focuses on the high efficiency and high performance. In most case, in order to achieve relatively small size, light weight and high efficiency, the inverters has a higher switching frequency and high frequency link inverter topology, which is at the sacrifice of the complication of its structure and control. The block diagram of the proposed bi-directional high frequency link inverter with active clamp circuit is shown in Fig.1[1][2]. It causes some problems such as difficulty in implementation and imperfect waveform resulting in polluting power line badly.

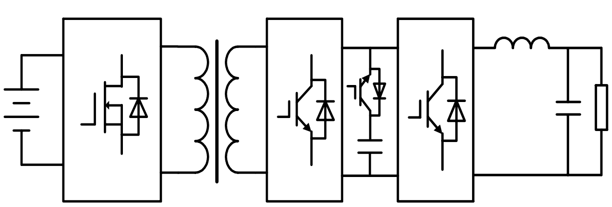

Figure 1. High frequency link bi-directional inverter with active clamp

However, the problems mentioned above can be solved by introducing the advanced SPWM modulation methods. Generally, the high performance SPWM inverter is required to maintain:

1. A sinusoidal output waveform under various types of loads.
2. Fast command tracking response without overshoot.
3. The change of output voltage due to load disturbance must be kept small as much as possible.
4. The steady-state errors of both the tracking and load disturbance responses must be zero.

To achieve the requirements listed above, only closed-loop control techniques can be employed in application of high performance ac conditioning systems. Among various types of closed-loop control techniques, PID control plays a leading role as its brief algorithm, easy implementation, good dynamic and static performance. However, based on the principle of compromising between the command tracking and load disturbance responses parameters, this conventional PID controller has only one degree freedom, it generally can not obtain good dynamic responses both in the command tracking and load disturbance regulation characteristic.

The Two-Degree-of-Freedom PID Digital Control is proposed in this paper to solve the problem mentioned above. It has two parameters which can be designed separately. One can make load disturbance regulation characteristic best, and the other can make the command tracking characteristic best. Therefore, it has two degrees of freedom and can overcome the shortcoming mentioned above and improve the controller's quality. In [1]-[5], the 2-DOF PID control strategy has been used in the induction motor servo drive and obtained high dynamic and static performance.

A bidirectional quasi-single-stage push-pull forward high frequency link inverter using DSP-based 2-DOF PID controller is designed and implemented in this paper. The parameters of the controller are found by model building, theoretical deduction according to the desired specifications.

II. Description

The proposed bidirectional quasi-single-stage voltage mode high frequency link inverter consists of a push-pull

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forward converter, a high frequency transformer, a bidirectional active rectifier, an active clamp branch, a SPWM inverter bridge and a low pass output filter. The diagram of the proposed system is shown in Fig.2.

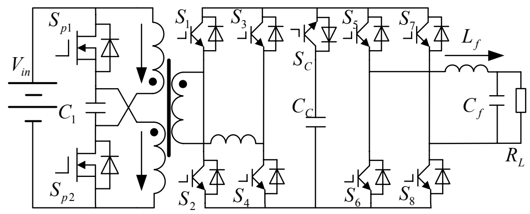

Figure 2. The diagram of the proposed system

In the proposed modulation strategy[6], 50% fixed duty-cycles are applied to all the switches on the primary side and the active rectifier on the secondary side, the SPWM signals are only directed to the output bridge together with the clamp switch. Through the low pass output filter, it produces a 50Hz, high-voltage and low distortion sinusoidal output wave. It is worthy of being mentioned that modulating triangle carrier wave and two inverse sinusoidal modulation waves is a special modulated method and can produce SPWM signals of the output bridge. There is no need of checking the pole of the output voltage to inverse the modulated signal. The improved modulated strategy is able to weaken the zero-crossing distortion of the output voltage and improve the stability of the closed-loop system. It features seamless four-quadrant operation and transition smoothly among four quadrants without detecting the polarity of the output current and switching the control logic.

III. System Control Scheme

A. Modeling of the Inverter

A uniform circuit model, shown in Fig.3, is used to represent a single-phase, two-level SPWM inverter with LC filter.

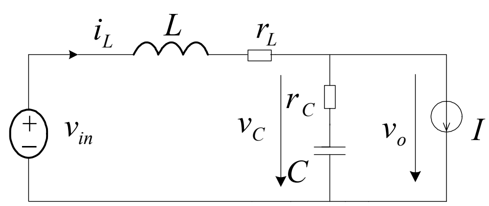

Figure 3. Uniform circuit model of the inverter

In Fig.3, v_{in} is the output voltage of the inverter bridge. It is a unipolar SPWM pulse sequence. I is the load current, which has any shape waveform and is determined by specific load. r_L is the inductor equivalent resistance (ESR) and other kinds of damp factor of the inverter. r_C is the capacitor ESR which hardly affects the circuit, which can be ignored in most cases.

The LC filter can be modeled as a continuous time second-order system. Define r_L and v_C as the state variables, v_{in} and I as the input variables, v_o as the output variable. The dynamic equations can be derived as follows:

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_C \end{bmatrix} = \begin{bmatrix} \frac{-r_L}{L} & \frac{-1}{L} \\ \frac{1}{C} & 0 \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ \frac{-1}{C} \end{bmatrix} \begin{bmatrix} v_{in} \\ I \end{bmatrix} \quad (1)$$

$$[v_o] = [v_c] = [1 \quad 0] \begin{bmatrix} v_{in} \\ I \end{bmatrix} \quad (2)$$

The transfer function of the inverter output voltage to the filter output voltage is:

$$G_p(s) = \frac{v_o(s)}{v_{in}(s)} = \frac{1}{LCs^2 + r_L Cs + 1} \quad (3)$$

Where the load disturbance is neglected. It is equal to the transfer function of the inverter without the load.

B. Two-Degree-of-Freedom (2-DOF) PID controller

Conventional PID controller of the SPWM inverter is shown in Fig.4. $G_V(s)$ and $G_I(s)$ represent the transfer function of the voltage regulator and the current regulator separately. $D(s)$ represents the transfer function of the inverter output voltage to the load current. Two regulators are designed according to compromising between the command tracking characteristic and load disturbance regulation characteristic. Therefore, it is difficult to reach the ideal control quality.

Based on automatic control theory, the relationship expressions of output voltage, reference voltage and load current can be deducted.

The transfer function of the output voltage to the command voltage $G_{or}(s)$ is

$$G_{or}(s) = \frac{v_o(s)}{v_{ref}(s)} = \frac{G_V(s)G_I(s)G_p(s)K_{pwm}}{1 + G_p(s)(G_V(s) + sCG_I(s)K_{pwm})} \quad (4)$$

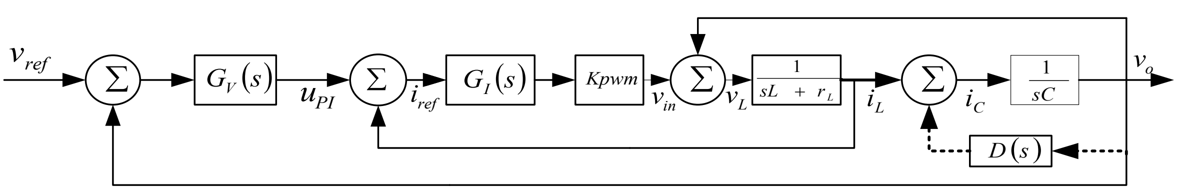

Figure 4. Block diagram of 1-DOF PID controlled system with voltage-current-closed-loop

The transfer function of the output voltage to the load disturbance $G_{od}(s)$ is

$$G_{od}(s) = \frac{v_o(s)}{I(s)} = -\frac{\left(G_I(s)K_{pwm} + sL + r_L\right)G_p(s)}{1 + G_p(s)\left(G_V(s) + sCG_I(s)K_{pwm}\right)} \qquad (5)$$

In these two transfer functions, if one is determined, the other is also determined accordingly. For such a system, if high command tracking performance is desired, it is certain that it is unable to suppress the disturbance, and vice versa. Generally, the parameters are designed according to compromise between the reference voltage tracking and load current disturbance regulation.

In order to solve the problems mentioned above, the target-value-filter-style 2-DOF PID controller is employed. The 2-DOF PID double-closed-loop control system is shown in Fig.5.

$F(s)$ is the target value filter. $F(s)$ and $G_V(s)$ provide two degrees of freedom to handle the tracking and the regulating control problems.

The transfer function of the output voltage to the command voltage $G_{\mathrm{or}}(s)$ is

$$G_{or}(s) = \frac{v_o(s)}{v_{ref}(s)} = \frac{F(s)G_V(s)G_I(s)G_p(s)K_{pwm}}{1 + G_p(s)\left(G_V(s) + sCG_I(s)K_{pwm}\right)} \qquad (6)$$

The transfer function of the output voltage to the disturbance $G_{od}(s)$ is

$$G_{od}(s) = \frac{v_o(s)}{I(s)} = -\frac{\left(G_I(s)K_{pwm} + sL + r_L\right)G_p(s)}{1 + G_p(s)\left(G_V(s) + sCG_I(s)K_{pwm}\right)} \qquad (7)$$

From (6) and (7), for such a system, the command tracking performance is determined by $F(s)$, $G_V(s)$ and $G_I(s)$, but the disturbance suppression performance is only determined by $G_V(s)$ and $G_I(s)$. It indicates that $G_V(s)$ and $G_I(s)$ determines the load disturbance regulation performance, and $F(s)$ affects the command tracking performance. Therefore, such a control system is a two-degree-freedom system.

A simple two-step design procedure of 2–DOF PID controller is proposed as follows. Firstly, design $G_V(s)$ and $G_I(s)$ to improve the load disturbance regulation and feedback performance. Second, design $F(s)$ to improve the command tracking performance.

PID controller's transfer function is

$$G(s) = K_P(1 + \frac{s}{T_I} + T_D s) \qquad (8)$$

where

K_P — proportion amplified multiple

T_I — integral time

T_D — differential time

Commonly, PID controller of current-loop is designed to be a proportional segment. i.e.

$$G_I(s) = K_{P\_i} \qquad (9)$$

PID controller of voltage-loop is designed to be a proportional-integral-differential segment. i.e.

$$G_V(s) = K_{P\_V}(1 + \frac{s}{T_I} + T_D s) \qquad (10)$$

Ziegler-Nichols Threshold Sensitivity Method is strongly able to suppress the load disturbance. So it is adopted to adjust the parameters. Only with proportional segment, the critical oscillation period T_S and the critical proportional coefficient K_S are determined. Then determine the initial PID controller to satisfy the disturbance suppression characteristic:

$$K_{P\_V} = 0.6 / K_S, T_I = 0.5T_S, T_D = 0.125T_S$$

T_S and K_S are determined by analyzing the frequency characteristic [7]. Firstly, get the bode plots. Secondly, observe the bode plots and get the gain margin and the cut frequency. Finally, T_S and K_S are determined as follows:

$$T_S = 2\pi / \omega_C, K_S = 10^{(g_m/20)}$$

In order to obtain the command tracking performance, $F(s)$ is supposed to be designed singly. In this paper, a simplified-practical-style 2-DOF PID algorithm is employed in the proposed controller. Despite abundant simulation, it is thought to be an efficient and simple strategy. Suppose that the parameters are given, $F(s)$ can be represented below:

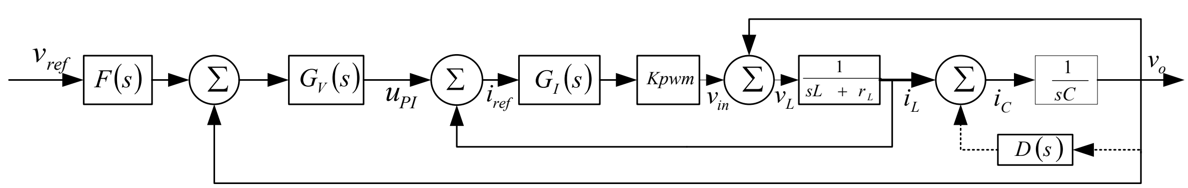

Figure 5. Block diagram of 2-DOF PID controlled system with voltage-current-closed-loop

$$F(s) = \frac{1+\gamma T_D(s)}{1+T_D(s)}\left[\alpha + \left(1-\alpha\frac{1}{1+\beta T_I(s)}\right)\right] \quad (11)$$

Where α is the 2-DOF-ed coefficient of the proportional segment, $0 \le \alpha \le 1$; β is the 2-DOF-ed coefficient of the integral segment, $1 \le \beta \le 2$; γ is the 2-DOF-ed coefficient of the differential segment, $0 \le \gamma \le 1$.

α, β and γ are regulated based on the reference voltage tracking performance. Usually, α and γ are regulated according to CHR (Chian-Hrone-Reswick) method, β is regulated through simulation. In industrial automatic control field, the recommended values are:

α =0.4, β =1.25, γ =0.5.

In the SPWM inverter control system, the group of recommended values needs to be regulated by simulation and experiment.

C. DSP-Based Control of the Inverter System

A TMS320LF2407A DSP and EPM7128 CPLD digital control platform is implemented to obtain the closed-loop control and PWM functions. DSP realizes the complicated control algorithm. Meanwhile, CPLD deals with the synthesis of the control logic signals. The system block diagram is shown in Fig.6.

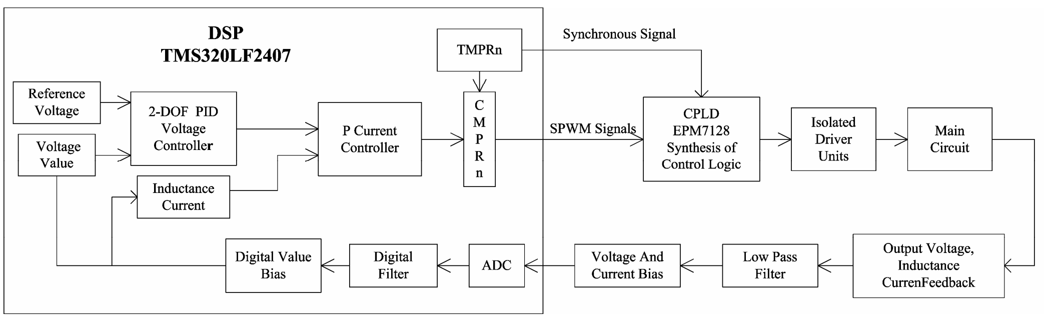

Figure 6. Block diagram for the inverter with double closed-loop control system

IV. Simulation and Experimental Results

The main parameters of this system are listed in TABLE I.

TABLE I. System Parameters

Input battery voltage	48V
Output voltage (RMS)	220V
Switching frequency	25KHz
Sampling frequency	25KHz
Output frequency	50Hz
Filter inductor	1.8mH
Filter capacitor	27.6uF
Dead time	1.6us

The parameters of two-degree-of-freedom PID controller are as follows:

$K_P = 2$, $T_i = 0.12$, $\alpha = 0.4$, $\beta = 0.15$.

In order to testify the advantages of the proposed 2-DOF controller, some comparisons are drawn by means of MATLAB simulation. In Fig.7, 1 stands for the output reference voltage, 2 refers to the output voltage under 2DOF PI control, and 3 refers to the output voltage under conventional PID control. According to the simulation result, it is concluded that the system based on 2-DOF PID control can achieve better performance than under conventional PI control in both the command tracking and load disturbing regulation characteristic

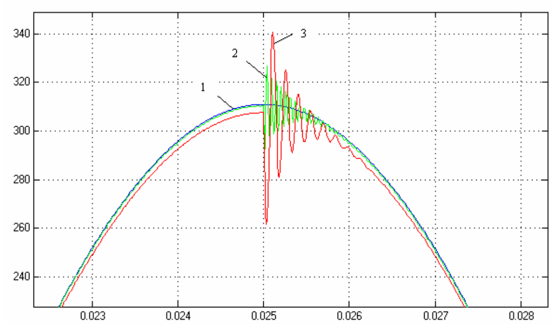

Figure 7. The performance comparison under different controls

In Fig.8 and Fig.9, 1 stands for the output reference voltage, 2 refers to the output voltage, and 3 refers to the output current.

Fig.8 shows the simulation results for inverter output voltage and load current. When the load is changed from no load to full load, it can be shown that there is very small transient interval and very fast response.

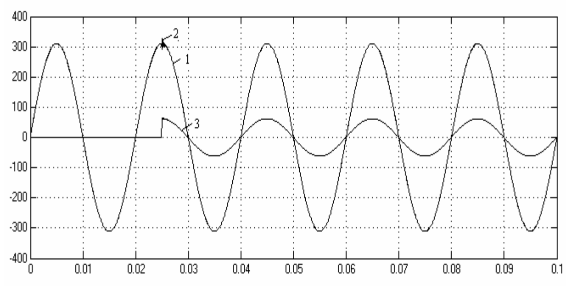

Figure.8 Simulation waveforms of output voltage and current under a step load

Fig.9 shows the simulation waveforms of the inverter output voltage and load current under the rectifier load. From the simulation results below, it can be shown that the distortion of the output voltage is very small and the inverter works well under the rectifier load.

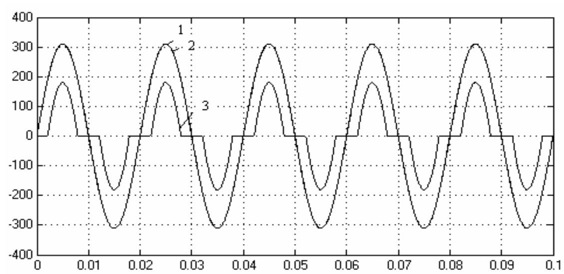

Figure.9 Simulation waveforms of output voltage and current under the rectifier load

To prove the effectiveness of the proposed control scheme, some experiments have been carried out in a prototype of bi-directional voltage mode high frequency link inverter. The experimental results are shown in Fig.10 to Fig.12.

Fig.10 shows the steady-state waveforms of the output voltage and the load current under the full resistive load. It is noticed that the experimental waveforms are nearly perfect sinusoids and the total harmonic distortion (THD) of the output voltage is 2.05%.

Fig.11 shows the transient performance of the system under a step change from no load to the full load. It can be seen that the transient dies out rapidly and the system can achieve a good load disturbing regulation performance.

Fig.12 shows the steady-state waveforms of the output voltage and the load current under the rectifier load. The THD of the output voltage is 4.147% and the crest factor is 3.48. The experimental result verifies that the proposed control can also operate well when the load is nonlinear.

Based on the results above, it is concluded that the simulation waveforms are consistent with the experimental results. The proposed inverter system can achieve high performance in both the command tracking and load disturbing regulation characteristic by employing the 2-DOF PI control strategy.

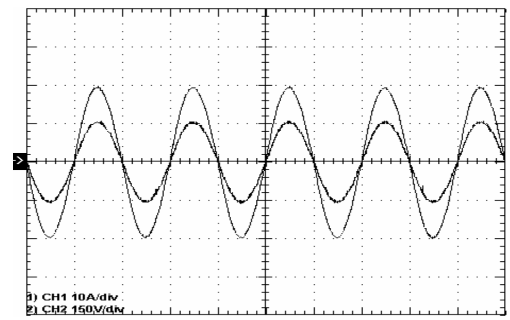

Figure 10. Experimental waveforms of output voltage and current under resistive load

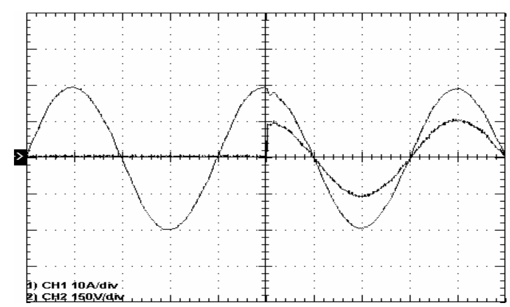

Figure 11. Experimental waveforms of output voltage and current under a step load

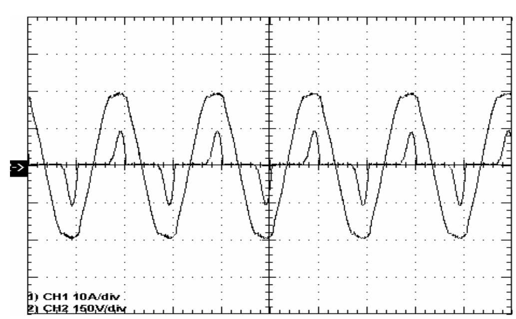

Figure 12. Experimental waveforms of output voltage and current under rectifier load

V. CONCLUSION

A bidirectional push-pull forward soft-switching quasi-single-stage inverter and a Two-Degree-of-Freedom PI digital control scheme are proposed to achieve high performance in both the command tracking and the load disturbance regulation. A set of digital control system including TMS320LF2407A DSP and EPM7128 CPLD is designed to achieve all the results. Analysis and experiments indicate that the proposed topology and control scheme are promising for the applications of DC/AC power supply.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China, NO. 50237020.

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