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Modeling and Analysis of Submerged Arc Weld Power Supply Based on Double Closed-Loop Control

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ABSTRACT

According to the soft-switching pulsed SAW (*Submerged arc weld*) *weld power supply based on the double closed-loop constant current control mode, a small signal mathematic model of main circuit of soft-switching SAW inverter was established by applying the method of three-terminal switching device modeling method, and the mathematic model of double closed-loop phase-shift control system circuit was established by applying the method of state-space averaging method. Dynamic performance of the inverter was analyzed on base of the established mathematic model, and the tested wave of dynamic performance was shown by experimentation. Research and experimentation show that relation between structure of the power source circuit and dynamic performance of the controlling system can be announced by the established mathematic model, which provides development of power supply and optimized design of controlling parameter with theoretical guidance.*

Keywords: *SAW, Double Loop Control, Soft-Switching, Inverter, Mathematic Model*

1. Introduction

The full-bridge phase-shift zero-voltage soft-switching PWM inverter now is widely used in the weld field for its many excellent performances. Through establishing mathematic model and transfer function of soft-switching pulsed metal active gas welding power supply, the relation between structural parameters of circuit and dynamic performance of system is obtained, which is an effective method of designing and development of that power supply [1,2]. In the field of power electronics, problem of linear PWM DC-DC converter modeling was solved, there are many methods of modeling such as three-terminal switching device modeling method, data-sampling, symbol analysis and so on [3-6], and method of space state average applied to inverter modeling [7-10], which provide mathematic model of soft-switching pulsed metal active gas welding power supply with theoretical guidance.

This paper proposes a soft-switching SAW weld power supply based on the double closed-loop constant current control mode, which adopts structure of soft-switching full-bridge circuit and combines the conventional negative feedback of current or voltage and the peak current control mode. A small signal mathematic model of main circuit of soft-switching SAW inverter and the mathematic model of double loop control circuit are established by applying the method of three-terminal switching device modeling method and the method of space state average. According to mathematic model, dynamic performance of the inverter is analyzed, and tested wave of dynamic performance is shown to prove the rationality of the inverter by experimentation.

2. Principles

The sketch map of the double closed-loop feedback control system is shown in figure1. It uses hall sensor to sample current signal from primary transformer, and pouring into control loop after sophisticated high-speed rectifying. The control loop needs a reasonable slope compensation circuit to ensure the system to be stable and get appropriate open-loop frequency.

In the course of operation, the peak current signal $i_s(t)$ is sampled from the peak current of the VT, then plus a peak current slope compensation signal $i_a(t)R_{f1}$, which is a signal substituted traditional triangular wave signal in voltage mode control. The saw tooth signal $i_a(t)R_{f1}$ is synchronized with the signal of inverter cycle, which is mainly used to improve waveform of the peak current signal, reduce the noises from the power circuit, and advance system stability. Meanwhile, average output current of inductance $i_L(t)R_{f2}$ is detected, which is compared to the given signal to get error signal. The error signal is replaced by the given signal of voltage mode control after correcting or compensating, and incises the peak current $i_s(t)$ that adds saw tooth signal $i_a(t)R_{f1}$ to adjust duty cycle of VT, which realizes effective control of the output current.

The main advantages of inner loop control is to improve the overall dynamic response speed of system, protect power tube and realize correction of each current pulse, solve problem of magnetic bias of power transformer; the purpose of outer loop control is to improve control accuracy and technology of power.

3. Modeling and Analysis

3.1 Mathematical Model of Main Circuit

In this paper, mathematical model of main circuit of SAW soft switch inverter is established by the way of three-terminal switching device modeling method. The soft-switching circuit is full-bridge circuit in **Figure 1**; it is still a typical Buck Converter in essence [11,12].

The main circuit of soft-switching inverter equals to circuit According to three-terminal switching device modeling method in **Figure 2(a)**, dynamic low-frequency small signal circuit model in the pluralism domain is shown in **Figure 2(b)**.

According to **Figure 2(b)**, dynamic equations of AC small signal $\hat{i}_L(s)$ of inductance current in pluralism domain are expressed as Equations (1) and (2):

$$\hat{i}_L(s)=\frac{\left(\hat{u}_i(s)+\frac{U_i}{D}\hat{d}(s)\right)D}{Z_i(s)}=\frac{U_i}{Z_i(s)}\left(\frac{D}{U_i}\hat{u}_i(s)+\hat{d}(s)\right) \quad (1)$$

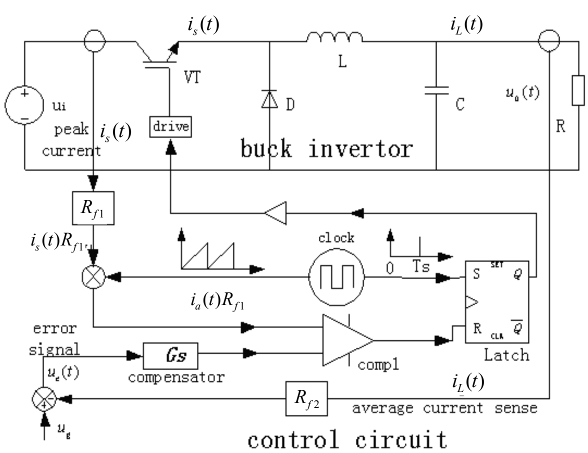


Figure 1. Block diagram of the control system

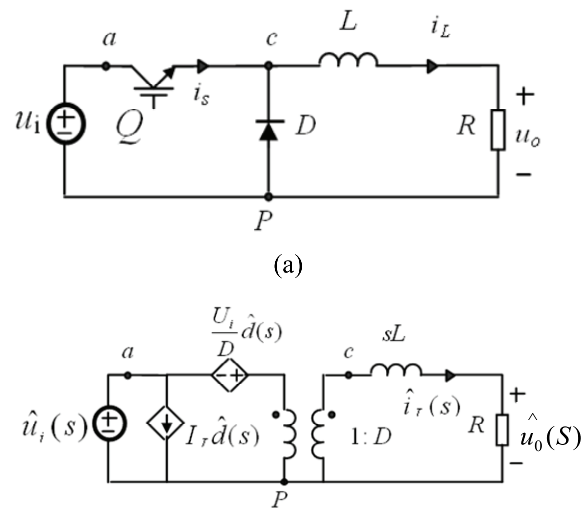


Figure 2. The AC signal model of main circuit

$$Z_i(s)=sL+R \quad (2)$$

Equations (3) and (4) are dynamic equations of small signal of output voltage in pluralism domain.

$$\hat{u}_o(s)=\hat{i}_L(s)Z_o(s) \quad (3)$$

$$Z_o(s)=R \quad (4)$$

From above equations, the transfer function for relation between output current of load and duty cycle can be denoted as Equation (5):

$$G_{id}(s)=\frac{\hat{i}_L(s)}{\hat{d}(s)}\Big|_{\hat{u}_i(s)=0}=\frac{U_i}{sL+R}=\frac{U_i}{R}\frac{1}{\frac{L}{R}s+1} \quad (5)$$

The transfer function for relation between output current of load and duty cycle can be denoted as Equation (6):

$$G_{ud}(s)=\frac{\hat{u}_O(s)}{\hat{d}(s)}\Big|_{\hat{u}_i(s)=0}=G_{id}(s)R=\frac{U_i}{\frac{L}{R}s+1} \quad (6)$$

In Equations (5) and (6), U_i is the equivalent DC input voltage; L is the output filter inductance; R is load resistance. Main circuits of inverter are composed of proportional part and inertia part in view of control structure.

3.2 Mathematical Modeling of Inner Loop Control System

The structure of control circuit of inner loop current is shown in **Figure 3**. The inductance current $i_L(t)$ is gained by input voltage $u_i(t)$ and output voltage $u_o(t)$, $i_L(t)$plus resistor R_f and then change into voltage signals $i_L(t)R_f$. $i_L(t)R_f$ plus the slope compensated voltage $u_a(t)$,which import to the negative terminal of PWM comparator. $u_c(t)$ is reference voltage of positive terminal of PWM comparator. Relations expression of duty cycle d and input

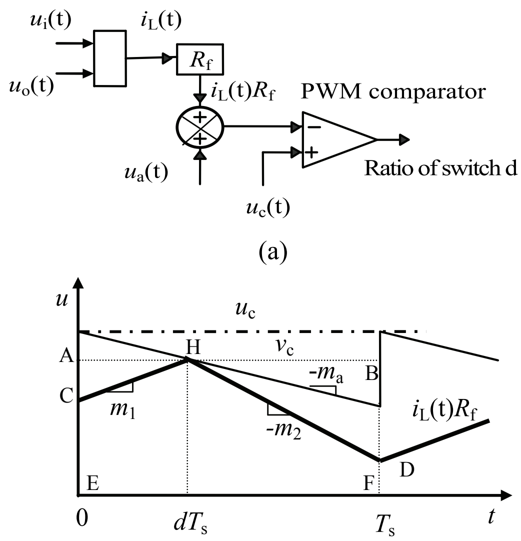


Figure 3. Model of current-injection controller

voltage $u_i(t)$, output voltage $u_o(t)$, slope compensation voltage $u_a(t)$, reference voltage $u_c(t)$ and inductance current $i_L(t)$ are derivatived by application of Space State Average method.

From **Figure 3(b)**, we can indicates expression of average voltage of inductance sampling current in the opening of each cycle as Equation (7).

$$R_f i_{Lavg}(t) = \frac{1}{T_s}\int_0^{T_s} R_f i_L dt = \frac{1}{T_s}\left(S_{ABEF} - S_{\Delta ACH} - S_{\Delta BDH}\right) \quad (7)$$

In the Equation (7), SABEF、S ACH and S BDH are the area of rectangular ABEF, triangle ACH and the triangle BDH in **Figure 3(b)**, according to Equation (7), we have Equation (8):

$$R_f i_{Lavg}(t) = u_c(t) - m_a dT_s - \frac{1}{2}m_1 d^2 T_s - \frac{1}{2}m_2\left(1-d\right)^2 T_s \quad (8)$$

In Equation (8), we can obtain Equation (10) after adding disturbing variable and taking into account that the system state has no relation to the slope compensation voltage shown in Equation (9).

$$m_a(t) = M_a \quad (9)$$

$$R_f\left(I_L + \hat{i}_L(t)\right) = \left(U_c + \hat{u}_c(t)\right) - M_a\left(D + \hat{d}(t)\right)T_s - \frac{1}{2}\left(M_1 + \hat{m}_1(t)\right)\left(D + \hat{d}(t)\right)^2 T_s - \frac{1}{2}\left(M_2 + \hat{m}_2(t)\right)\left[1 - \left(D + \hat{d}(t)\right)\right]^2 T_s \quad (10)$$

In Equation (10), $\hat{i}_L(t)$、$\hat{u}_c(t)$、$\hat{d}(t)$、$\hat{m}_1(t)$、and $\hat{m}_2(t)$ are corresponding disturbing variable .We can obtain Equation (11) after linear treatment of Equation (10)

$$R_f \hat{i}_L(t) = \hat{u}_c(t) - M_a T_s \hat{d}(t) - \frac{1}{2}D^2 T_s \hat{m}_1(t) - \frac{1}{2}\left(1-D\right)^2 T_s \hat{m}_2(t) \quad (11)$$

In view of equation of $\hat{m}_1 = R_f \frac{\hat{u}_i - \hat{u}_o}{L}$ and equation of $\hat{m}_2 = R_f \frac{\hat{u}_o}{L}$ in Buck Converter, the transfer function of inner peak current control circuit shown in Equation (12) can be obtained from Equation (11).

$$\hat{d}(s) = \frac{1}{M_a T_s}\left[\hat{u}_c(s) - R_f \hat{i}_L(s) - \frac{R_f D^2 T_s}{2L}\hat{u}_i(s) - \frac{R_f(1-2D)T_s}{2L}\hat{u}_o(s)\right] \quad (12)$$

3.3 Mathematical Model of Double Closed-Loop Control System

In order to improve accuracy of control system, reduce steady error, the average output current or voltage are sampled in this control system, and compared to the inner given compensation signal $u_c(s)$. Primarily role of outer loop regulator is to improve and optimize system performance; PI regulator is used in this paper. According to Subsection 3.1 and Subsection 3.2, overall control system diagram based on model of double closed-loop current is shown in **Figure 4**, the DC signal $u_i(s)$ can be treated as system disturbance.

According to **Figure 4**, open-loop transfer function of the inner loop current is expressed as Equation (13).

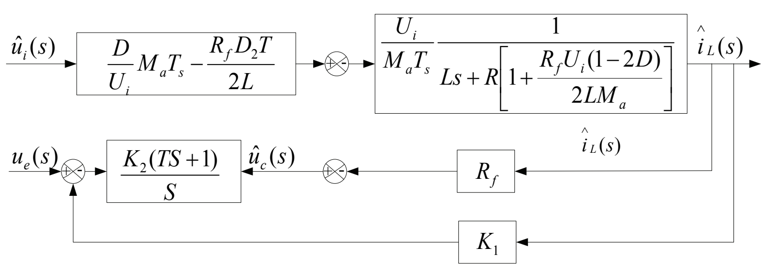


Figure 4. Block diagram of the double loop system

$$G_1(S)=\frac{R_fU_i}{M_aT_S}\frac{1}{LS+R[1+\frac{R_fU_i(1-2D)}{2LM_a}]} \quad (13)$$

Equation (14) is inner closed-loop transfer function.

$$W_1(s)=\frac{i_L(s)}{u_c(s)}=$$

$$\frac{U_i}{M_aT_sLs+M_aRT_s+\frac{RR_fU_i(1+2D)T_S}{2L}+R_fU_i} \quad (14)$$

Equation (15) is transfer functions of entire open double closed-loop system.

$$G(s)=\frac{K_2(TS+1)}{S}\cdot W_1(S)\cdot K_1=$$

$$K_1K_2U_i\frac{TS+1}{S}\cdot\frac{1}{M_aT_sLS+M_aRT_s+\frac{RR_fU_i(1-2D)T_s}{2L}+R_fU_i} \quad (15)$$

Equation (16) is transfer functions of closed-loop transfer function for the entire system.

$$W(S)=$$

$$\frac{K_2U_i(TS+1)}{S(M_aT_SLS+M_aRT_s+\frac{RR_fU_i(1-2D)T_s}{2L}+R_fU_i)+K_1K_2U_i(TS+1)} \quad (16)$$

In Equation (16), D is duty cycle; U_i is inputting DC voltage; *TS* is the inverting cycle; R_f is sampling resistor of the inner current; M_a is the rising slope of compensation voltage; *L* is Output filter inductance; *R* is pulsed arc load; K_1 is feedback coefficient of outer loop current; K_2 is adjusting gain; *T* is time constants of regulator.

3.4 Analysis of Dynamic Characteristic

The cutoff frequency of open-loop that is an important characteristic index that is the embodiment of dynamic response of control system [13]. Dynamic characteristic of welding power are analyzed as mathematical model established in Subsection 3.3. Provided outer loop is a simple proportional control mode, and the open-loop system fc is frequency when open loop gain equals to1, according to Equation (15), and set $\|G\ (j2\pi f_c)\|=1$, we have:

$$\|G\ (j2\pi f_c)\|=$$

$$\left\|\frac{K_1K_2U_i}{M_aT_s}\frac{1}{Lj2\pi f_c+R\left[1+\frac{R_fV_i(1-2D)}{2LM_a}+\frac{R_fU_i}{R}\right]}\right\|=1 \quad (17)$$

In this paper $\|Lj2\pi f_c\|>>\left\|R\left[1+\frac{R_fV_i(1-2D)}{2LM_a}+\frac{R_fU_i}{R}\right]\right\|$,

Equation (17) can be taken form as following:

$$f_c\approx\frac{K_1K_2U_i}{2\pi M_aT_sL} \quad (18)$$

In Equation (18), open-loop traversing frequency f_c is proportional of outer loop resistor, DC input voltage and gain of outer loop adjuster. But the traversing open-loop frequency is inversely proportional to the rising rate of compensation voltage, switching cycle and output inductance. Since outer loop resistor is limited by linear adjustment range of voltage of control circuit, opening traversing frequency of control system can be increased by the way of reducing rising ratio of compensation voltage and output inductance, and increasing frequency of inverter. From above analysis, dynamic response of double closed loop control system is improved greatly by inner loop current control.

4. Experimentation

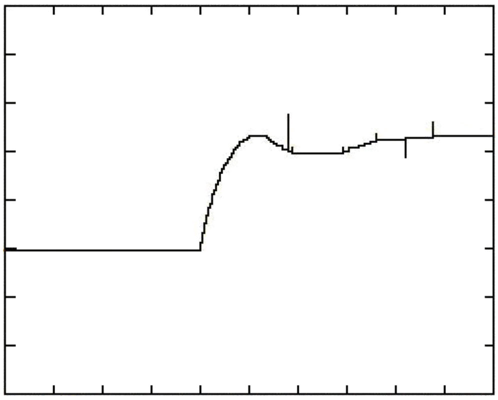
Dynamic characteristics of arc welding inverter are always defined as the relationship between output current or output voltage and time when load instantaneous change, which is a major performance index of arc weld power source. Two sets of experiments of constant current outer characteristic of arc weld power source are done to prove the effect of theatrical analysis based on the double closed-loop constant current control mode. The experiments of arc welding are current response under condition of the instantaneous change of the given signal and current response under condition of instantaneous change of the given load.

The curve of **Figure 5** is current response when current instantaneous change from 0 A to 430 A under the simulated load of 0.1 Ω. In figure5, the current instantaneous change from 50 A to 320 A just needs time of 2 ms, which conclude that system has better dynamic performance through this experimentation.

The curve of **Figure 6** is current response curve measured by given current value of 100A and simulated load changing from 0.09 Ω to 0.03 Ω. In **Figure 6**, the given current instantaneous change from 130 A to 100 A just needs time of 4 ms, which conclude that system has better dynamic performance and a constant current outer characteristic.

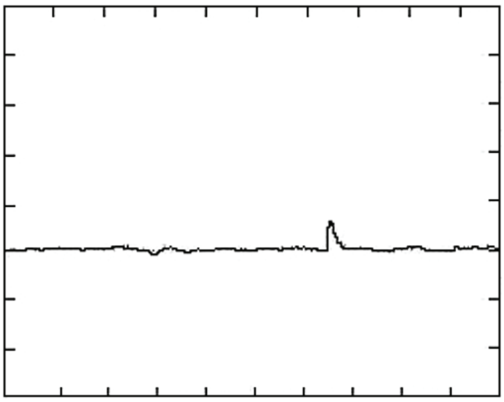
5. Conclusions

Mathematical model of SAW weld soft-switching inverter based on a double closed-loop constant voltage and current control is established. Based on mathematical model, dynamic performance is analyzed, and dynamic characteristic curve of arc weld power source is tested in



1-*I*:200A/div, *T*:1ms/div

Figure 5. The current response curve while instantaneous change from 0 A to 430 A



1-*I*:50A/div, *T*:10ms/div

Figure 6. The current response while the load changing

this paper, it shows that double closed-loop control can improve dynamic characteristics of arc welding power source, which can meet request of SAW technology.

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