Modeling and Analysis of Harmonic in the Mine Hoist Cnverter Based on Double Closed-Loop Control

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***Abstract*—In the process of converter driving mine hoist, the output voltage waveform of the inverter is distorted. A novel feedback control method based on the filter inductor current inside loop and voltage is developed in this study. The transfer function model of the two closed-loop control is builded. Parameters of the PID controller are determined through theoretical calculation after analysis of the impact the controller parameters on system. The simulation results show that the output waveform is good and the THD(Total Harmonic Distortion) values is small.**

***Index Terms*—Mine Hoist, Inverter, Double Closed-Loop Control, Harmonic.**

I. INTRODUCTION

AC(Alternating Current)variable frequency speed regulation system with high efficiency, wide range and high precision, and other characteristics, widely used in mine hoist. However, due to the use of the high-power diode rectifier and transistors inverse in converter, the inverse usually adopted SPWM(Sinusoidal Pulse Width Modulation). SPWM is using sinusoidal signal to modulate carrier led to the harmonic generation associated with the carrier and the signal wave. The harmonic of the output voltage was too large, which resulted in not only increasing the waveform deviation factor and harmonic loss of the power supply network and reducing the output efficiency of converter, and mechanical load vibration is also growing. Moreover, the running speed variation of mine hoist has bad influence on the whole AC variable frequency speed regulation system, especially it will cause an obvious fluctuation of the network voltage in the case of long time and repetitive running of the mine hoist.

The harmonic generation of inverse process in converter can be reduced by selecting the appropriate modulation, sampling methods, modulation depth, accurate carrier wave ratio, and filter circuit. However, the current distortion produced by non-linear loads, such as power electronic transformation device, led to the increase of the output voltage harmonic content, can only be suppressed through feedback control.

Domestic and foreign scholars have made a lot of works on the inverter control recently. The single closed-loop PID control was presented in literature[1-3], The dynamic performance is poor in the case of nonlinear load, and the resisting load disturbance performance of the single-loop controlled is not satisfactory, because when adjusting the corresponding error after the impact of load disturbance is shown in the output voltage, which is obviously difficult to meet the requirements. The hysteresis control is raised in literature[4-6], its switching frequency is not fixed and operation showe irregular, which brings difficulties to the filter design. The state feedback control is proposed in literature[7-10], if the state feedback control not take targeted measures to load disturbance, the steady-state deviation and dynamic performance will change. The deadbeat control is adopted in literature[11-13], its effect depends on the accuracy of the estimation model. In fact it can not make very accurate estimate to circuit model, and the system model will change as the load changed, the robustness of system is not strong. The siliding mode variable structure is raised in literature[14-17], it has some weakeness, such as the ideal sliding mode switching is diffcult to choose, the sampling rate will influence the control effect. Above these in most does not consider the special working conditions under the nonlinear load, and the research for the harmonic distortion is very less.

In order to guarantee the reliability of the frequency control system, reduce the harmonic content and improve power factor of the output voltage, the filter inductor current inside loop and voltage instantaneous feedback

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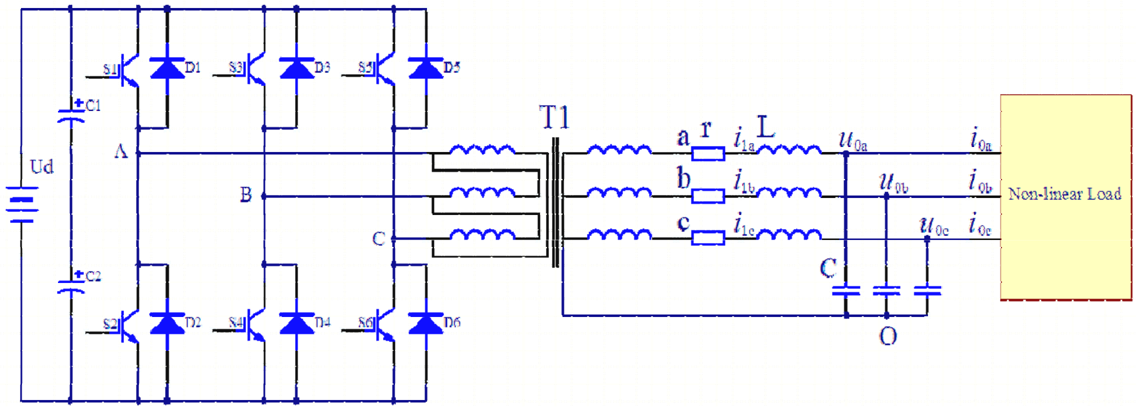


Figure 1. The topology structure of three-phase inverter that connected to non-linear load

control strategy is used to suppress harmonic in this paper. The power switches are working in the "on" and "off", therefore, the inverter is essentially a nonlinear system. To achieve the output voltage and current instantaneous value feedback control of inverter, the difficulty lies in: the controller need to track a given signal, which is changed according to sine rule, the time difference of given signal and feedback signal is the phase difference under the closed-loop control, and this phase is closely related with the load, so the article study the output waveform control by the voltage and current instantaneous value control strategy under non-linear load. The current inner loop of double loop control increases the bandwidth of the inverter control system, accelerates the inverter dynamic reponse, strengthen the ability to adapt nonliner load disturbances, decreases the harmonic content in the output voltage.

II. INFLUENCE OF NONLINEAR LOAD ON OUTPUT VOLTAGE

The process of converter driving mine hoist is a typical nonlinear load, which has made tremendous influence to the invertor, and directly affect the performance of the whole system. The article first analysis the influence of nonlinear load on three-phase invertor from theoretical.

Establishment of the mathematical model of three-phase invertor is the basis for theoretical analysis and experimental study. The inverter is a nonlinear system, considering the inverter switching state, power switchs are working in the "on" and "off" in a switching cycle and circuit is running continuously, thus the classical theory can be used to establish the three-phase invertor mathematical model, but this method will be too complicated. State space averaging method widely applied to engineering practice. The principle is, in the case of inverter output frequency and the system cut-off frequency is much smaller than switching frequency, using the average value of intermittent variables instead of the instantaneous value in a switching cycle, and obtain a continuous state space average model. Fig. 1 is the topology structure of three-phase inverter that connected to non-linear load.

Three-phase filter inductor in the picture is L, three-phase equivalent damping resistance is r and three-phase filter capacitor is C; the output phase voltage of three-phase invertor is respectively u_A, u_B, u_C, u_{AB}, u_{BC}, u_{CA} are line voltage; the three-phase voltage of filter capacitor is respectively u_{0a}, u_{0b}, u_{0c}; filter inductor three-phase current is respectively i_{1a}, i_{1b}, i_{1c}. Assuming the phase voltage of transformer secondary line winding is u_a, u_b, u_c, transformer ratio is $1{:}N$. According to Kirchhoff's current law and voltage law, you can write out the following 6 equations:

$$
\begin{aligned}
C\frac{du_{0a}}{dt} &= i_{1a} - i_{0a} \\
C\frac{du_{0b}}{dt} &= i_{1b} - i_{0b} \\
C\frac{du_{0c}}{dt} &= i_{1c} - i_{0c} \\
u_a &= L\frac{di_{1a}}{dt} + ri_{1a} + u_{0a} \\
u_b &= L\frac{di_{1b}}{dt} + ri_{1b} + u_{0b} \\
u_c &= L\frac{di_{1c}}{dt} + ri_{1c} + u_{0c}
\end{aligned} \tag{1}
$$

According to Δ/Y connection of transformer, there are:

$$
\begin{aligned}
u_a &= Nu_{AB} \\
u_b &= Nu_{BC} \\
u_c &= Nu_{CA}
\end{aligned} \tag{2}
$$

From above equations, the matrix can be written as (3), where i_{0a}, i_{0b} and i_{0c} are current distortion caused by the non-linear load. Simplifying the above equation was:

$$
\begin{bmatrix} \dot{u}_0 \\ \dot{i}_1 \end{bmatrix} = \begin{bmatrix} 0_3 & \frac{1}{C}I_3 \\ -\frac{1}{L}I_3 & -\frac{r}{L}I_3 \end{bmatrix} \cdot \begin{bmatrix} u_0 \\ i_1 \end{bmatrix} + \begin{bmatrix} 0_3 & -\frac{1}{C}I_3 \\ \frac{1}{L}I_3 & 0 \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ i_0 \end{bmatrix} \tag{4}
$$

$\dot{u}_0 = \begin{bmatrix} u_{0a} & u_{0b} & u_{0c} \end{bmatrix}^T$ is the inverter output phase voltage vector,

$\dot{i}_1 = \begin{bmatrix} i_{1a} & i_{1b} & i_{1c} \end{bmatrix}^T$ is the filter inductor current vector,

$u_1 = N\begin{bmatrix} u_{AB} & u_{BC} & u_{CA} \end{bmatrix}^T$ is the inverter output line voltage vector,

$i_0 = \begin{bmatrix} i_{0a} & i_{0b} & i_{0c} \end{bmatrix}^T$ is the distortion current vector caused by non-linear load,

I_3 is the 3 × 3-dimensional matrix,

0_3 is the 0 × 0-dimensional zero matrix.

$$\begin{bmatrix} \dot{u}_{0a} \\ \dot{u}_{0b} \\ \dot{u}_{0c} \\ \dot{i}_{1a} \\ \dot{i}_{1b} \\ \dot{i}_{1c} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & \frac{1}{C} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{C} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{C} \\ -\frac{1}{L} & 0 & 0 & -\frac{r}{L} & 0 & 0 \\ 0 & -\frac{1}{L} & 0 & 0 & -\frac{r}{L} & 0 \\ 0 & 0 & -\frac{1}{L} & 0 & 0 & -\frac{r}{L} \end{bmatrix} \begin{bmatrix} u_{0a} \\ u_{0b} \\ u_{0c} \\ i_{1a} \\ i_{1b} \\ i_{1c} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & -\frac{1}{C} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{C} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{C} \\ \frac{1}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{L} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Nu_{AB} \\ Nu_{BC} \\ Nu_{CA} \\ i_{0a} \\ i_{0b} \\ i_{0c} \end{bmatrix} \quad (3)$$

From the above model can be seen, the current distortion caused by nonlinear load has a bad influence on the three-phase inverter output voltage, directly affect the output voltage distortion, and produce a large number of low-order harmonics associated with the distortion current, lead to reducing the quality of power supply on non-linear load.

III. THE CONTROL SCHEME OF DOUBLE CLOSED-LOOP

There are two kinds of feedback control of inverter control: the voltage virtual value feedback control and the instantaneous value control. The voltage virtual value feedback control can improve the steady-state output accuracy and accurately tracking control the output voltage virtual value. However, the dynamic performance is not good enough and all kinds of disturbances exist cycle delay. With instantaneous value feedback control, the disturbance response time is less than the voltage virtual value feedback control. But the steady-state error and the output voltage waveform distortion is quite large. In order to improve the effect of instantaneous value feedback control, it can take the voltage and current double closed loop control strategy.

The current inner loop control can be divided into the capacitance current inner loop control and the inductance current inner loop control according to the different feedback quantity. The capacitance current feedback loop including the load disturbance current can quickly respond to the impact of the load and effectively inhibit the disturbance current; the inductor current feedback loop does not including the load disturbance current, the external characteristics of the system is relatively poor. However, the control algorithm can be used to amplitude limiting to achieve current alimiting of the inductor current.

The voltage and current instantaneous value double closed loop control block diagram shown in Fig. 2.

In the in inductor current inner loop voltage instantaneous value control, the basic principle of the voltage outer loop control is comparing the output voltage instantaneous value U_0 of filter inductance with the voltage given value U_f, and get the error signal, then the error signal, which is modulated by the voltage regulator, is the filter capacitor current given value I_r. The inner loop is the current control loop, which is also comparing the capacitance current instantaneous value I_1 with the current given value I_r, and get the current error signal. The intersection of the error signal wave and the triangle carrier are the SPWM switching signals, which can not only adjust the time when is "on" and "off" of the power switch, but also adjust the output voltage of the whole system. The introduction of the inner loop make the filter inductor current into the controlled current source and improve the system stability. According to the vector inverter theory, the variables of the three-phase static coordinate can be transformed to the two-phase α-β

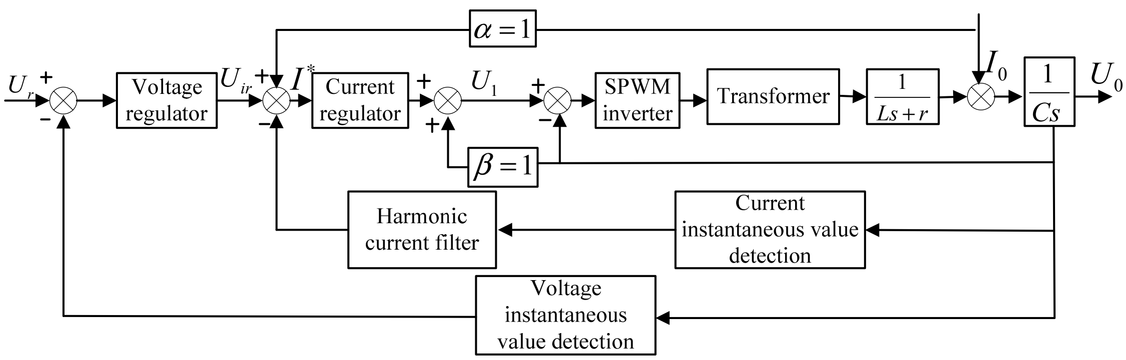


Figure2. Theory frame double closed-loop of voltage and current

coordinate variables. Therefore, through the α-β transformation,the three-phase SPWM inverter space state equation (4) can be written as:

$$\begin{bmatrix}\dot{u}_{0\alpha}\\ \dot{i}_{1\alpha}\end{bmatrix}=\begin{bmatrix}0 & \frac{1}{C}\\ -\frac{1}{L} & -\frac{r}{L}\end{bmatrix}\begin{bmatrix}u_{0\alpha}\\ i_{0\alpha}\end{bmatrix}+\begin{bmatrix}0 & -\frac{1}{C}\\ \frac{1}{L} & 0\end{bmatrix}\begin{bmatrix}u_{\alpha}\\ i_{\alpha}\end{bmatrix} \quad (5)$$

$$\begin{bmatrix}\dot{u}_{0\beta}\\ \dot{i}_{1\beta}\end{bmatrix}=\begin{bmatrix}0 & \frac{1}{C}\\ -\frac{1}{L} & -\frac{r}{L}\end{bmatrix}\begin{bmatrix}u_{0\beta}\\ i_{0\beta}\end{bmatrix}+\begin{bmatrix}0 & -\frac{1}{C}\\ \frac{1}{L} & 0\end{bmatrix}\begin{bmatrix}u_{\beta}\\ i_{\beta}\end{bmatrix} \quad (6)$$

From the above equation, after the three-phase static coordinate transformed into the two-phase α-β coordinate, the three-phase variables can be transformed into two independent variables, which can be equivalent to α phase and β phase inverter, so using this inverter method, the design of the controller becomes much simpler. In order to take consideration to advantages of the inductor current and capacitance current loop control, the inverter adopted feedforward decoupling control strategy, the introduction of the capacitance voltage positive feedback eliminate the effect of capacitance voltage cross feedback. When $\alpha=1$, the control scheme can not only reflect the advantages of capacitance current sampling including the impact of load disturbance, but also achieve software limiting current function; When $\beta=1$, decoupling can be achieved, that is "completely feedforward compensation".

IV. MATHEMATICAL MODEL

The P control has been used in the current inner loop control system to increase the damping coefficient of inverter, and improve the robustness and operation stability of the whole system. The voltage outer loop use PI control, the output voltage waveform transient tracking the given value is the role of the voltage regulator. The dynamic response speed of the current inner loop and voltage outer loop control is very fast, and the static error is small. Assuming the PI control parameters of the outer voltage and the P control parameters of the inner current are:

$$G_1(s)=k_{1p}+\frac{k_{1i}}{s},\quad G_2(s)=k_{2p} \quad (7)$$

The inner current loop transfer function is:

$$G_i(s)=\frac{Ck_{2p}}{LCs^2+\left(r+k_{2p}\right)Cs} \quad (8)$$

The closed loop system transfer function is:

$$G(s)=\frac{\left(k_{1p}+k_{1i}/s\right)k_{2p}}{LCs^2+\left(r+k_{2p}\right)Cs+\left(k_{1p}+k_{1i}/s\right)k_{2p}} \quad (9)$$

As the closed-loop control system use the digital chips for the real-time control, therefore, the above transfer function needs to be discreted. According to the discrete formula, $G(Z)=\xi\left[G(s)\right]$, zero-order hold control method was used for discrete "$\frac{1}{Ls+r}$" link:

$$\left(1-Z^{-1}\right)\xi\left[\frac{1}{s}\cdot\frac{1}{Ls+r}\right]=\frac{Z-1}{rZ}\cdot\xi\left(\frac{r/L}{s\left(s+r/L\right)}\right) \quad (10)$$
$$=\frac{1-e^{-rT/L}}{r\left(Z-e^{-rT/L}\right)}=\frac{0.19988}{Z-0.88011}$$

$$\xi\left(\frac{1}{Cs}\right)=\frac{T}{2C}\cdot\frac{Z+1}{Z-1}=\frac{1.04167(Z+1)}{Z-1} \quad (11)$$

Taking equation (10) and (11) into (8) and (9), we can obtain:

$$G_i(Z)=\frac{0.19988k_{1p}}{Z+0.19988k_{1p}-0.88011} \quad (12)$$

$$G(Z)=\frac{0.20821k_{2p}\cdot\left[(k_{1p}+k_{1i})Z^2+k_{1i}Z-k_{1p}\right]}{F(Z)} \quad (13)$$

F(Z) is the closed-loop transfer function characteristic equation:

$$\begin{aligned}F(Z)&=Z^3+\left[0.19988k_{1i}-2.8801+0.20821k_{1i}(k_{1p}+k_{1i})\right]Z^2\\&+(2.6938-0.39976k_{2p}+0.20821k_{2p}k_{1i})Z\\&+0.19988k_{2p}-0.88011-0.20821k_{1p}k_{2p}\\&=Z^3+AZ^2+BZ+C\end{aligned} \quad (14)$$

Using the pole assignment method to design the controller, the expectation closed-loop dominant pole of the double-loop control system are set as: $s_{1,2}=-\varepsilon\omega_r\pm j\omega_r\sqrt{1-\varepsilon^2}$, the expectations dominant poles of the non-closed-loop is: $s_3=-m\varepsilon\omega_r$. According to the mapping relationship between S plane and Z plane: $Z=e^{sT}$, poles in the discrete domain are:

$$Z_1=e^{-\varepsilon\omega_r T+\omega_r T\sqrt{1-\varepsilon^2}} \quad (15)$$

$$Z_2=e^{-\varepsilon\omega_r T-\omega_r T\sqrt{1-\varepsilon^2}} \quad (16)$$

$$Z_3=e^{-m\varepsilon\omega_r T} \quad (17)$$

The desired characteristic equations for the double closed loop control was:

$$\begin{aligned}D(Z)&=(Z-Z_1)(Z-Z_2)(Z-Z_3)=Z^3-(Z_1+Z_2+Z_3)Z^2\\&+(Z_1Z_2+Z_2Z_3+Z_2Z_3)Z-Z_1Z_2Z_3\end{aligned} \quad (18)$$

According to the mathematical model of the pole assignment, natural oscillation frequency ω_r and damping ratio ε are two important parameters. Fig. 3 and Fig. 4 are bode diagrams of double closed-loop transfer function with different ω_r and ε. The response speed of controller is decided by natural oscillation frequency ω_r at some extent, the larger ω_r is, the quicker response is. The cost and volume of filter are also cut down by ω_r. But ω_r can't be chosed too large, because the inverse process is approximate equivalented as a linear process in the three-phase SPWM inverse system. Control delay is introducted when adjusting the PWM process, and it will reduce the stability of system. The response speed of current inner loop is quicker in this system, so this reduction is more obvious. But if ω_r is too small, dynamic instruction tracking response will easily be unstable. So the influence of PWM process should be considered between stability and response speed when designing the controller. Because system damping will be larger when loaded, damping ratio ε should be some smaller for allowance, between 0.5~0.8 is suitable. The parameters m of expectations dominant poles of the non-closed-loop is between [5,10].

There are a lot of parameters of inner and outer loop, because the system uses current-voltage double closed-loop control to suppress the output harmonic of inverter, in this study using theory to adjust PID parameter. However, because the actual impact of various complex factors, setting parameters can be determined after continuous experimental test and optimization, especially on the first the current sampling digital filter, and then the closed-loop control, so that there are many ideal factors of the model. So taking the integration of theory with practice to adjust PID parameters.

Choosing experimental parameters, filter inductor *L=700uH*, filter capacitor *C=80uF*, equivalent resistance *r=0.6Ω* and switching frequency *f=6kHz*. Natural oscillation frequency $\omega_r = 3768 rad/s$, $\varepsilon = 0.5$, $m = 5$.

Put the above parameters into formula (9) and (10), define PID parameters through comparing coefficients between formula (14) and (18). After arrangemented we can get:

$$k_{1p} = 0.3886 \quad k_{1i} = 0.07935 \quad k_{2p} = 4.4326$$

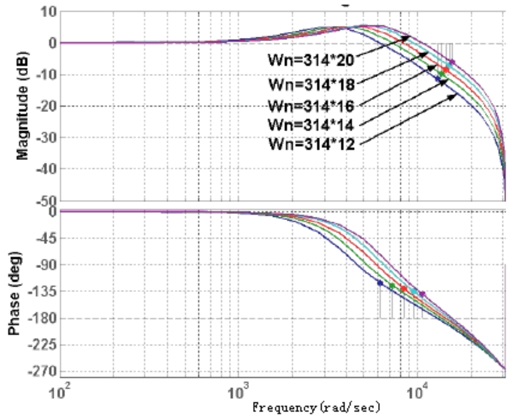


Figure.3 Transfer function Bode diagram double closed-loop under different ω

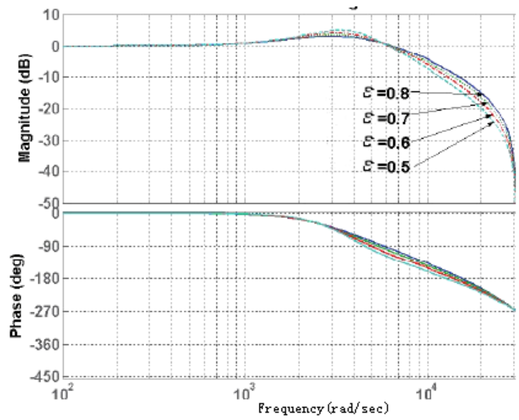
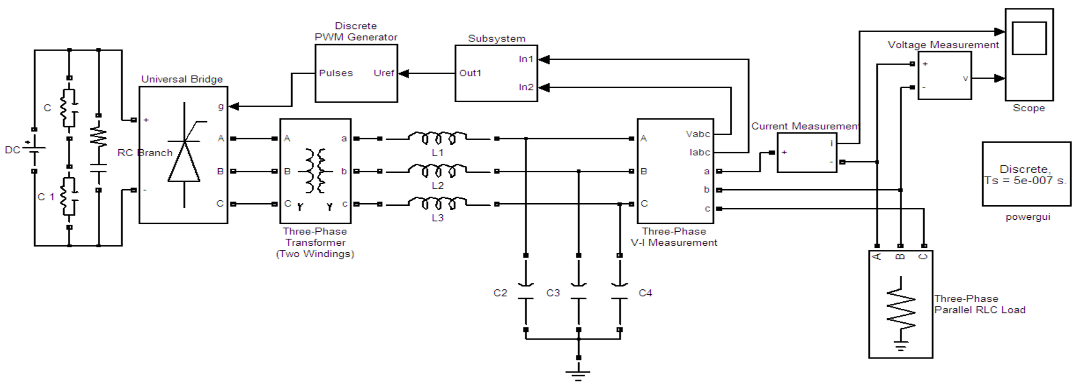
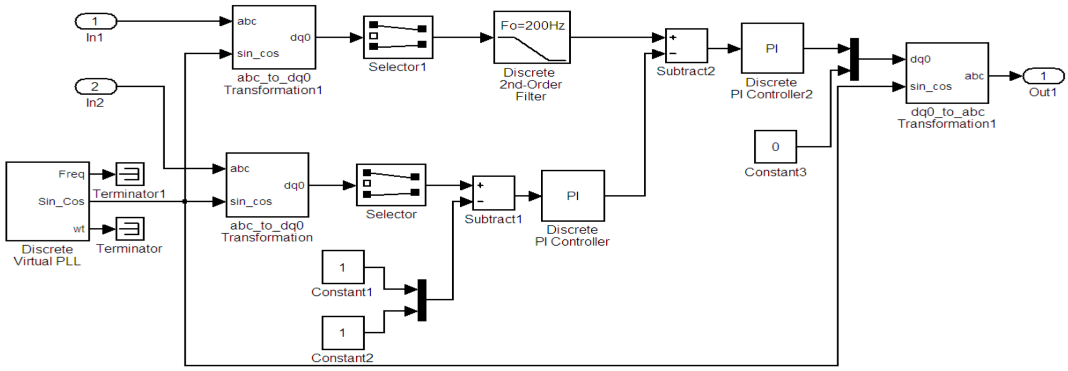


Figure.4 Transfer function Bode diagram double closed-loop under different ε



(a) Simulation diagram of three-phase SPWM inverter with feedback system



(b)The subsystem model of digit PID control

Figure5. Simulation diagram of voltage outside loop and current inside loop control

V. SIMULATION AND ANALYSIS

The three-phase SPWM inverter system model with feedback control was built based on PSB library of Matlab/Simulink. The key component of the model is voltage regulator, shows in Fig. 5, which transform three-phase voltage and current into two-phase through coordinate transformation. Seting the sine and cosine frequency of the model to zero, the conversion from d-q to α-β coordinate can be realized. After the digital filtering of current, double closed-loop PI control of voltage and current is conducted, the given value of current PI control is determined after the voltage adjusted.

According to the established simulation model, simulation computation is conducted in the condition of linear load, resistance-inductance nonlinear load, nonlinear load with linear load and nonlinear load with mixed load. As Fig. 6 shows, under the linear load , the voltage harmonics is very low and can be controlled in 1%. Fig. 7 is the spectrogram of output voltage of double closed-loop control under resistance-inductance nonlinear load, THD value is 2.25%; Fig. 8 shows the three-phase SPWM inverter output voltage and current waveform and its spectrum distribution under non-linear load with linear load and mixed load respectively, the output waveform quality is poor and has a certain degree of distortion, THD value and harmonic content is higher. Fig. 9 shows the situation that nonlinear load with linear load and mixed load respectively by double closed-loop control ,

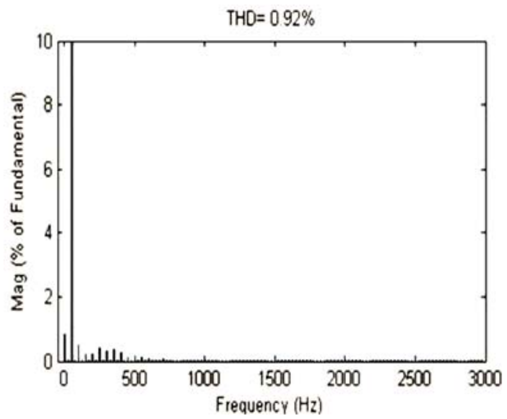


Figure 6. Spectrum distribution under linear load by double closed-loop

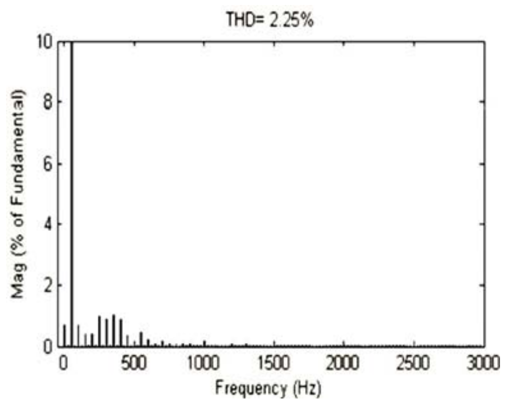
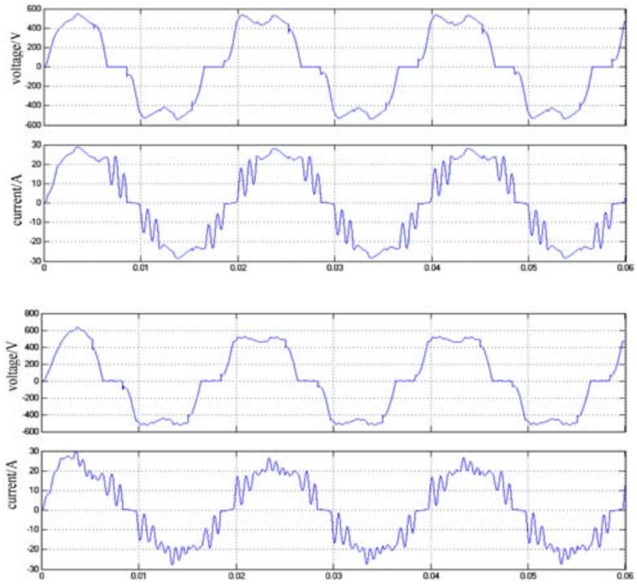
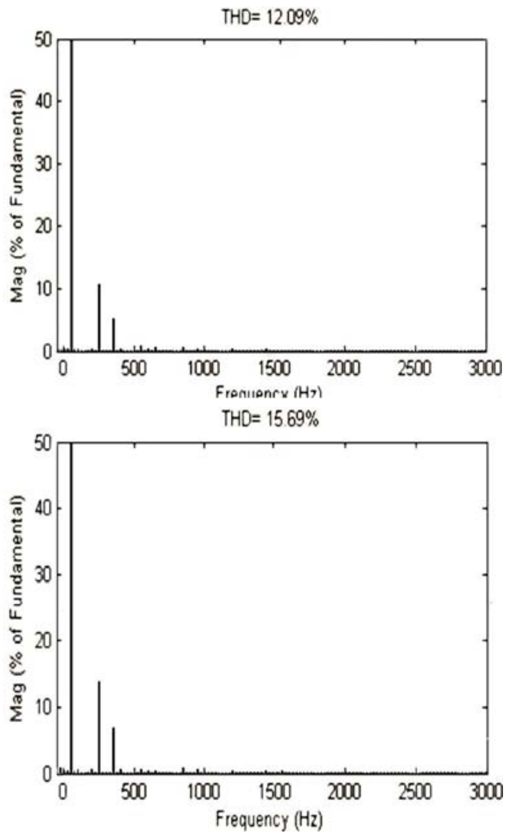


Figure 7. Spectrum distribution under RL nolinear load by double closed-loop



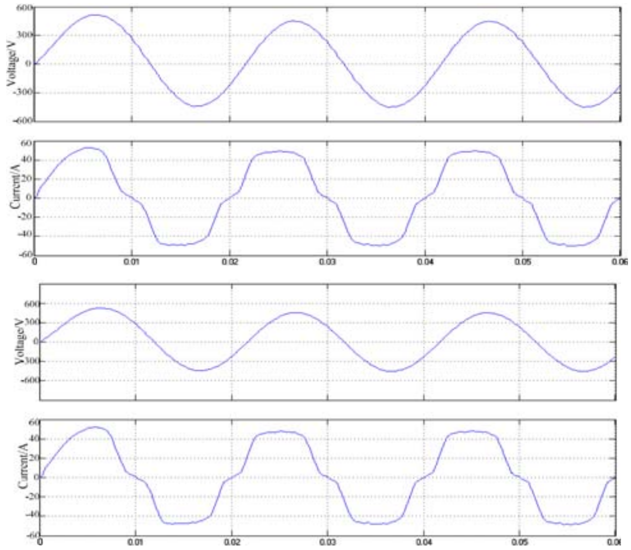
(a)Voltage and current waveforms



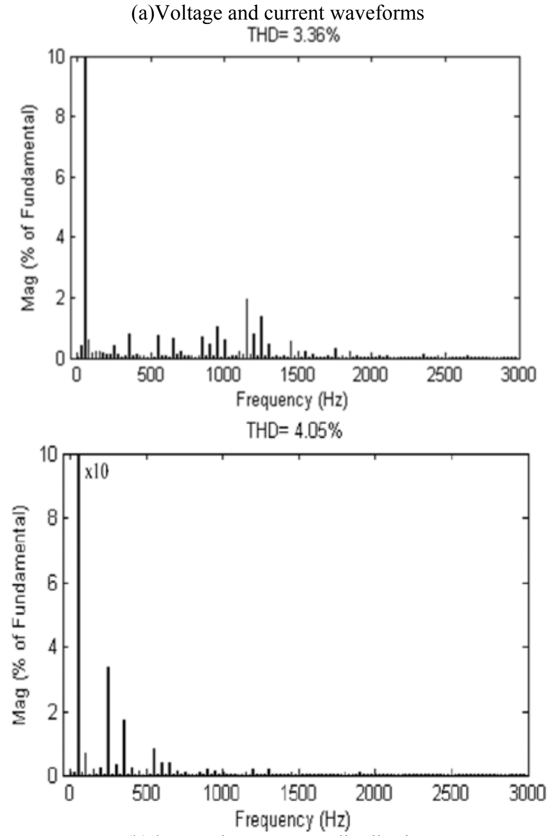
(b) harmonics spectrum distribution

Figure 8. nonlinear load with linear load and mixed load respectively

the output voltage harmonics is much lower than that Fig. 8. The double closed-loop control can meet the requirement that harmonic standard THD in 5%. It can be seen from the simulation above, under the feedback control of the instantaneous value voltage outer loop and inner current loop, the output voltage waveform of three-phase SPWM inverter under nonlinear loads have been greatly improved.



(a)Voltage and current waveforms



(b) harmonics spectrum distribution

Figure9. nonlinear load with linear load and mixed load respectively by double closed-loop control

VI. CONCLUSIONS

According to the process of inverter driving the mine hoist, the output voltage waveform of inverter is distorted. In order to reduce the harmonic, the control system was realized by the the filter inductor current inner loop and voltage instantaneous value feedback control strategy. Established the precise transfer function model of three-phase SPWM inverter system by the current inner loop P control and voltage outer loop PI control strategy, determined inner and outer loop controller parameters by pole assignment method, adjusted cintrol parameters by taking the integration of theory with practice, in order to obtain the optimal controller parameters. Good output waveforms and below 5% harmonics of voltage are obtained on the condition that linear and nonlinear loads by the simulation.

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