H_2/H_∞Robust Controller of the Arc Welding Inverter Power

YAN Jun-rong[1], LIU Hai-kuan[1] ,LIAO Ping[2] ,GAN Liang-zhi[1],LIU Li-jun[1]
1.College of Electrical Engineering and Automation of Xuzhou Normal University,China,221116
2. College of Material Science and Engineering, Jiamusi University,Jiamusi ,China ,154007,
yanjunrongmy@163.com

***Abstract*—There are a lot of interference sources in the system of the arc welding inverter power. In this paper, a small-signal model which was built by the method of state-space average was quoted. A control system which comprised an interference of load resistance and an interference of power supply fluctuation was built. A H_2/H_∞ state -feedback controller was designed in the method of LMI. The simulation indicated the result, which the interference of power was measured by H_2 norm so that the output of the system was influenced weakly, and the interference of arc load was measured by H_∞ norm so that the system was robust.**

***Index Terms*—Arc welding inverter power; H_2/H_∞controller; LMI**

I. INTRODUCTION

The arc welding inverter power is a new power source, it is integrated by electric power and electronic. Arc welding machines are widely used in welding industries. With the development of power electronic technology, inverter arc welding machines are gradually becoming the maim stream products due to their inherent advantages such as small volume, light weight, high efficiency, fast dynamic respond and excellent welding performance, as in [1][2]. Dynamic characteristics of an inverter arc welding power supply are its output voltage and current's response process when its arc load's status has a sudden change, as in [3]. The parameters of the dynamic characteristics can reflect its adaptation ability to arc load's change, which has important influences on arc ignition, welding process' stability and spatter. The dynamic characteristics' studies of inverter arc welding power supply were usually based on experiments, as in [4], which is just the verifications of dynamic characteristics and is lack of guidance on the inverter arc welding power supply design process.

Half-bridge circuit is adopted in our study on the inverter arc welding power supply. Small-signal model of the half-bridge arc welding inverter shown as Fig.2 was established in reference, as in [5], and its double-loop control system was designed based on the small-signal model in reference, as in [6]. The small-signal model can reflect the stability of the welding process, as in [7]

Modern control theories were not only studied and developed in control theory field, but also they were applied successfully in control engineering. The arc welding inverter power is a new power source, it is integrated by electric power and electronic. At present, some control theories were applied in the inverter, such as output feedback of single closed-loop, state feedback of double closed-loop control, multivariable state feedback control, deadbeat control, sliding mode variable structure control, repetitive control, neural net control, internal mold model control and expert control[7~13]. The matter with model uncertainty was solved in some degree. Steady-state capability of system was aimed with the method of H_∞ robust control in [13], but it was limited because the dynamic change of system was not considered. The dynamic performance was considered in LQG controller, and performance index of system were speedy and the smallest energy. Therefore, the H_2/H_∞ controller of control system was applied widely and developed rapidly.

In this paper, the two disturbances in the arc welding inverter power were considered. The H_2/H_∞ robust controller was designed with LMI. The disturbance from power was measured by H_2 norm, the other disturbance from arc load change was measured by H_∞ norm. The system was robust.

II.THE ARC WELDING INVERTER POWER AND ITS MODEL

A. Introduction of Arc Welding Inverter Power System

The fundamental structure block diagram of the arc welding inverter power is followed in figure1..

Inverter power supply system mainly consists of power systems and electronic control system. Power system which also is the main circuit consist of the input circuits, the inverter circuit and the output circuit, etc. The input circuits include the input rectifier and the filter , The rectifier is bridge rectifier. The filter is the capacitor. The inverter circuit which consists of electronic power switching device and inverter step-down transformer, etc

---

corresponding author: tel:86 15152186722,
Email: yanjunrongmy@163.com

doi:10.4304/jcp.6.4.705-710

is the core of the arc welding inverter power，The output circuits include the rectifier and the filter circuits。The electronic control system include the detection circuit, the controller and the drive circuit. The detection circuit measure the control quality of controlled object, for example the voltage and current of the arc load. The error is obtained after the determination value and the given signal comparison. The controller complete some control algorithm and output the control signal. The driving circuit output the driver pulse and control the electronic power switch .

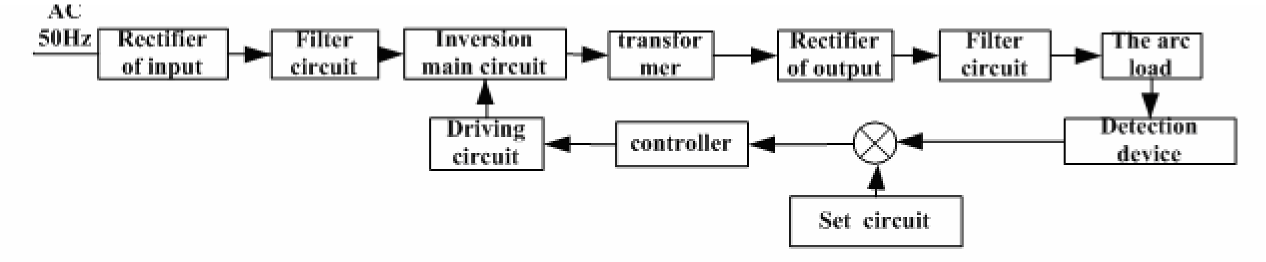


Figure 1. the fundamental structure block diagram of the arc welding inverter power

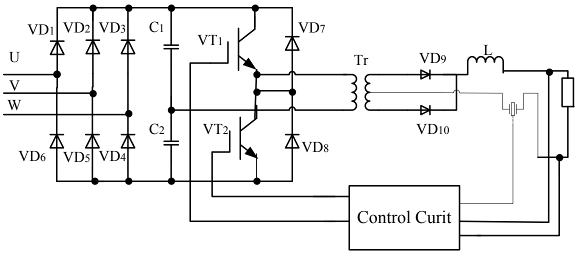


Figure2. Circuit of the arc welding inverter

The circuit of the arc welding inverter is followed in figure2.Simple model of the main circuit is followed in figure3.The main circuit is the full bridge rectification, the DC U_d is from rectifier circuit of input. It is inverted by a half bridge inverter, and it is reduced by a high frequency impulse transformer, and it is rectified by the quick-acting diode, and it is filtered by output inductor. At last, the output is the welding voltage. R_a is resistance of arc load.

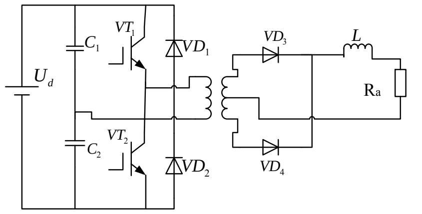


Figure3 Simple model of the main circuit

B. Established Arc Welding Inverter Power System Model

The arc welding inverter power system model is established in method of the state space average. [7].

The conduction time of switch tube is assumed as ‘t_{on}’, ‘T’ is the cycle of pulse which is from the output voltage of inverter, and the duty ratio is described by: $D = t_{on}/T$， $0 \le D \le 0.5$ ，The process of the circuit work in one cycle includes four stages:

When $0 < t < DT$ ，VT1 is turned on，VT2 is turned off:

$$\frac{u_d(t)}{2n} = L\frac{di_a(t)}{dt} + R_a(t)i(t) \qquad (1)$$

When $DT < t < T/2$ ，VT1 and VT2 are turned off:

$$0 = L\frac{di_a(t)}{dt} + R_a(t)i(t) \qquad (2)$$

When $T/2 < t < T/2 + DT$ ，VT2 is turned on，VT1 is turned off:

$$\frac{u_d(t)}{2n} = L\frac{di_a(t)}{dt} + R_a(t)i(t) \qquad (3)$$

When $T/2 + DT < t < T$ ，VT1 and VT2 are turned off.:

$$0 = L\frac{di_a(t)}{dt} + R_a(t)i(t) \qquad (4)$$

Equation(1)、(2)、(3) and (4) is averaged in one cycle, and the averaged model is established. as:

$$L\frac{d < i_a(t) >_T}{dt} = \frac{< u_d(t) >_T}{n} d(t) - < R_a(t) >_T < i_a(t) >_T \qquad (5)$$

In equation (5)，$d(t)$ is variable of duty ratio.

Equation (5) is added to the relative disturbances, namely order:

$$i_a(t) = I_a + \hat{i}_a(t)$$

$$u_d(t) = U_d + \hat{u}_d(t)$$

$$r_a(t) = R_a + \hat{r}_a(t)$$

These equations are substituted into equation(5), Ignoring the higher-order and small-signal items, a low-frequency and small-signal model is built in time domain:

$$L\frac{d\hat{i}_a(t)}{dt} = \frac{D}{n}\hat{u}_d(t) + \frac{U_d}{n}\hat{d}(t) - R_a\hat{i}_a(t) - I_a\hat{r}_a(t) \qquad (6)$$

Equation(6) is transformed in LaplaceA low-frequency and small-signal model is built[1]:

$$\hat{i}_a(s) = \frac{\frac{D}{n}\hat{u}_d(s) + \frac{U_d}{n}\hat{d}(s) - I_a\hat{r}_a(s)}{sL + R_a} \qquad (7)$$

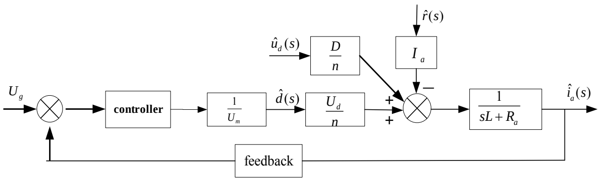


Figure4 Block diagram of system model

According to Eq.(7), Block diagram of system model is showed in figure4.C. The Output Characteristics of Arc Welding Inverter Power in original

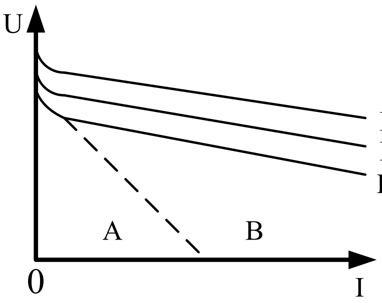


Figure 5 The output characteristics of arc welding inverter power in original

Controlling output characteristics and dynamic characteristics is based on the characteristics in original. So that it is necessary for us to research the output characteristics in original of Arc Welding Inverter Power. The characteristics in original is output characteristics of power source in condition that the time ratio of on-off electronic power switch is unchanged and system have not feedback control. The output characteristics of arc welding inverter power in original are showed in figure5. In figure 5, three lines are different in duty ratio. The relationship of these duty ratio is described as :Dl>D2>D3， They are corresponding with the characteristic lines each. Duty ratio is bigger, the characteristic line is higher, and the value of $\int Udi$ is bigger, and the output energy of power is bigger.

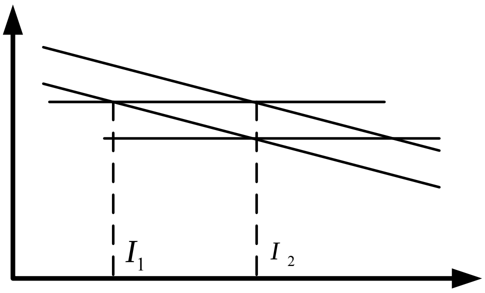


Figure 6 the constant current external characteristic of arc welding inverter power

The output characteristics are nature of arc welding inverter power. They are dependent on the impedance of power in internal and level of production of power. In figure5, the voltage drops down quickly with the current increase in area A where the current is small. The reason lies in that the current is small and fluctuation of current is bigger and when duty ratio is small. The voltage drop in power internal is bigger; the voltage of output is less. Because the power system works unstable in area A, we must apply it avoiding the area. The current is bigger and more stable in area B. Fluctuation of current is smaller, the voltage drop in power internal is smaller. The slopes of every characteristic line are equal. The slope of output voltage drop is dependant on the equivalent resistance in power internal. In usual conditions, the work process of arc welding inverter power includes generating of arc, arcing and no-load which are in the area B.

D. External Characteristic Control

External characteristic which also is the output characteristic in fact of arc welding inverter power with feedback control is obtained in application of pulse-width modulation. External characteristic of arc welding inverter power is different in welding method and control method. In this paper, the shielded metal arc welding (SMAW) is discussed. Its external characteristic is constant current source. The constant current external characteristic of arc welding inverter power is showed in figure 6. In figure 6, Lines I,II are the curves of static output characteristic of arc welding inverter power .Lines 1,2 are the curves of natural output characteristic of arc welding inverter power. Point A which is the intersection of static characteristic and natural characteristic is assumed as the start work point of arc welding inverter power system. Its welding current is I_2 .Because of influence of some factor, length of arc is enlarged. The static characteristic of power will become the curve II. If the duty ratio is unchanged, and the power still works in the curve 1 of natural characteristic, the work point of arc welding inverter power will be the point B. The welding current is described as:$I_1<I_2$， Apparently, it can not be compliant with requirement of the constant current. The current feedback control is adopted in the control of arc welding inverter power, PWM is adjusted in according to the changes of the welding current, and the duty ratio can be adjust in real-time. So that the power will work in the curve 2. The point of intersection of the cure2 and the static characteristic curve II will become the point of A’, and the welding current will be still I_2， and the constant-current control will be realized.

III. CONTROLLER OF THE ARC WELDING INVERTER POWER SYSTEM DESIGNED

A. Descriptive Problem

In figure7, *P*(s) is the control system, *K*(s) is state variables feedback, *w* is the disturbance, *z* is output which will be regulated. State equation of\control system *P*(s) is expressed as[14]:

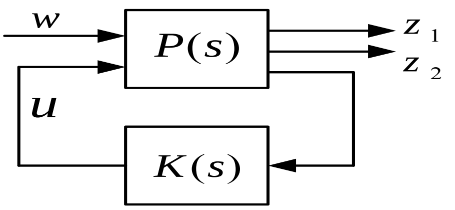


Figure7 H_2/H_∞ control

$$\begin{aligned} \dot{x} &= Ax + Bu + B_1 w_1 + B_2 w_2 \\ z_1 &= C_1 x + D_{10} u + D_{11} w_1 \\ z_2 &= C_2 x + D_{20} u + D_{22} w_2 \end{aligned} \qquad (8)$$

Target of controller is objected to design a state feedback controller $u = Kx$, which can stabilize close-loop system asymptotically. Norm H_∞ of close-loop transfer function which is from w_1 to z_1 is limited to a given upper. Uncertainty of system which is from w_1 is robust. Norm H_2 of close-loop transfer function which is from w_2 to z_2 is the smallest, so that energy of the controlled output z_2 is small.

Lemma[8]： System (8) and a given scalar $\gamma_1 > 0$ are considered ,if $D_{22} = 0$, a optimization is showed:

$$\min \gamma_2 \qquad (9)$$

$$s.t \begin{bmatrix} AX + BW + (AX + BW)^T & B_1 & (C_1 X + D_{10} W)^T \\ B_1^T & -\gamma_1 I & D_{11}^T \\ C_1 X + D_{10} W & D_{11} & -\gamma_1 I \end{bmatrix} < 0$$

$$AX + BW + (AX + BW)^T + B_2 B_2^T < 0$$

$$\begin{bmatrix} -Z & C_2 X + D_{20} W \\ (C_2 X + D_{20} W)^T & -X \end{bmatrix} < 0$$

$$Trace(Z) < \gamma_2$$

If the LMIs have the best solution X, W ， the state-feedback H_2/H_∞control will be feasible. $u = WX^{-1} x$ is a state-feedback H_2/H_∞ controller of system(8).

Question(9) are the LMI constraints, and they are also the convex optimization of a linear objective function. They can be solved by optimizer mincx in LMI toolbox.

B. H_2/H_∞ Controller Designed and Simulation

Parameter of the arc welding power is selected: U_d is output voltage which is from three phase rectifier, $U_d = 1.35 \times 380 = 513V$ ， $n = 8$ ， To the shielded metal arc welding, the relation of load voltage and load current is described ： $U = 20 + 0.04I$ ， when $I_a = 100A$， $U_a = 24V$， the arc load is equal to resistor R_a, $R_a = 0.24\Omega$， the duty-cycle $D = 0.375$， U_m is peak value of carrier signal in PWM, $U_m = 3V$. Inductor of output filter was designed in[9]: $L = 40\mu H$.

According to system block in figure 3, the model of the arc welding power is arrived in Eq(4):

$$\begin{aligned} \dot{x} &= Ax + Bu + B_1 \hat{r}_a + B_2 \hat{u}_d \\ z_1 &= Cx + D_1 \hat{r}_a \\ z_2 &= Cx \end{aligned} \qquad (10)$$

In Eq(4),A=[-6000]， B=[534000]， B1=[2500000]， B2=[1170]，C=[1]，D1=[0]。

MATLAB program 1 of design H_2/H_∞controller is followed as:

```
A=[-6000];B=[534000];C=[1];
B2=[1170];B1=[2500000];D1=[0];r1=102;
setlmis([])
X=lmivar(1,[1,1]);
W=lmivar(2,[1,1]);
Z=lmivar(1,[1,1]);
lmiterm([1 1 1 X],1,A,'s')
lmiterm([1 1 1 W],1,B,'s')
lmiterm([1 1 2 0],B2)
lmiterm([1 2 2 0],-1)
lmiterm([2 1 1 Z],-1,1)
lmiterm([2 1 2 X],C,1)
lmiterm([2 2 2 X],-1,1)
LMIs=getlmis;
[twin,xfeas]=feasp(LMIs)
twin =
  -0.2252
```

In operation results, twin<0， it shows that the conditions of LMI are feasible. Further, state feedback is described as : K=0.0112.

MATLAB program 2 of design H_2/H_∞ controller is followed as:

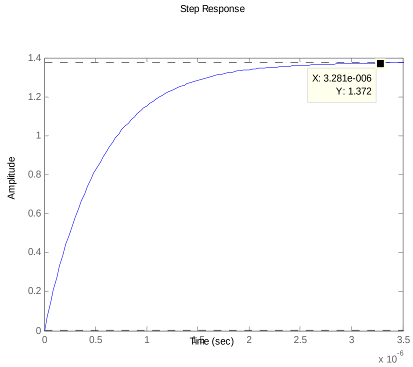
```
num=[21.375];den=[0.000167,1];
G=tf(num,den);
wn=[1,10,50,100];t=0:.01:1;
[a,b,c,d]=tf2ss(num,den);
p1=-0.1;a_shift=a-p1*eye(size(a));
S_shift=mksys(a_shift,b,c,d);
for i=1:length(wn)
  G1=std_tf(1,wn(i),2);G2=1-G1;
w1=[G2.den{1};G2.num{1}];w1(2,3)=0.001;
  TSS_=augtf(S_shift,w1,[1e-5;1],[]);

[gg,ss_F]=hinfopt(TSS_);[af_shift,bf,cf,df]=branch(ss_F);
  af=af_shift+p1*eye(size(af_shift));
  Gc=ss(af,bf,cf,df);G_c=feedback(G*Gc,1);
  step(G_c),hold on;
end
```

The transfer function of controller is showed as:

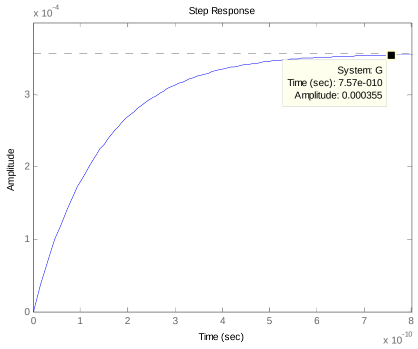
$$G_c = \frac{0.087(s + 5988)}{(s + 141.1)(s + 0.1)} \qquad (11)$$

In the arc welding power system, voltage fluctuation of electric network can lead to variation of input voltage U_d, The variation is named disturbance $\hat{u}_d$, which is demanded that it will take effects on the output energy least., the influence is measured by norm H_2. The variable

$\hat{r}_a$ of arc load is the most important disturbance source, its influence to system is asymptotically stable, the influence is measured by norm H∞.

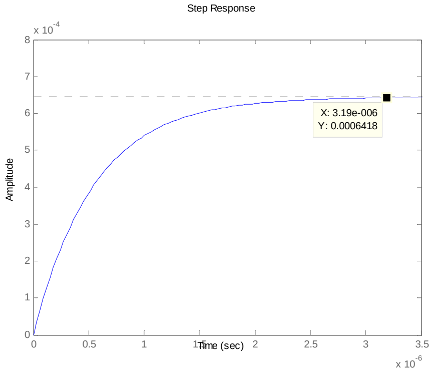


(a) H_2/H∞ controller

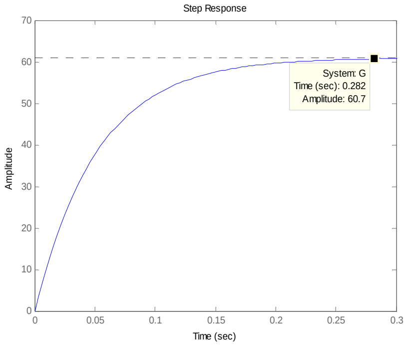


（b）H∞ controller

Figure 7 Step response of disturbance $\hat{r}_a$



(a) H2/H∞ controller



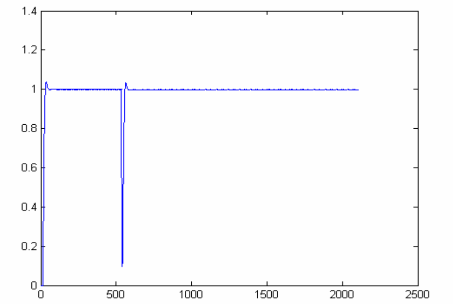
（b）H_2 controller

Figure 8 Step response of disturbance $\hat{u}_d$

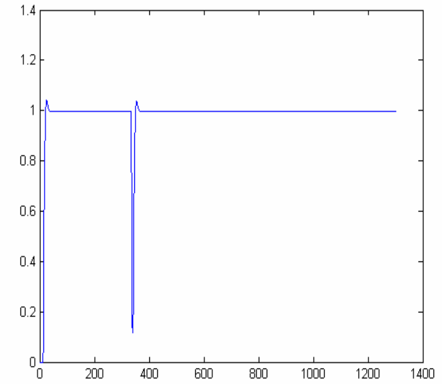
Step response of disturbance $\hat{r}_a$ is as shown in figure 7, Output of system will be steady before $3.2\times10^{-6}s$, it proves that system for arc load change is robust. By contrast of figure(a) and figure(b), we find that system takes into account both performance of H_2 and H∞, but it will lose the performance of robust.

Step response of disturbance $\hat{u}_d$ is as shown in figure 8. The output variable of H_2/H∞ controller is 0.0006418, so it is better than H_2 controller. When system is added to the disturbance of the input voltage, its output energy will be the least.

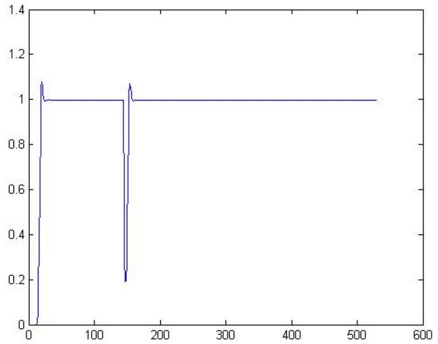
Simulation system is built in application of Toolbox of MATLAB /Simulink. Reference input is assumed as unit-step function. The distance of input voltage is 20V, and $R_a = 0.24\Omega$ (nominal value) $R_a = 0.16\Omega$, $R_a = 0.32\Omega$,that the range ofis $\pm33.3\%$, The step response of different R_a is showed in figure9.



(a) $R_a = 0.24\Omega$



（b）$R_a = 0.16\Omega$



（c）$R_a = 0.32\Omega$

Figure 9 Curve of step response in different Ra

Simulations show that response speed of H_2/H_∞ controller is quick and overshoot of H_2/H_∞ controller is small（Max: $\sigma_p\% = 2.6\%$），Power system can restrain the distance of input and the change of parameter.

C. Simulation of the characteristics

Based on equation (5), Block of Simulink is built in figure 10., The output voltage of system is showed in figure 11, and the output current of system is showed in figure 12.

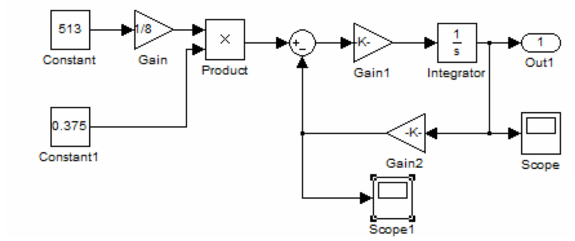


Figure 10 Simulink block of the arc welding power

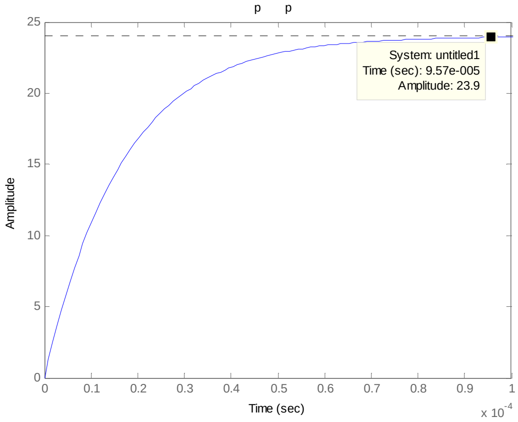


Figure 11 Wave shape of the output voltage

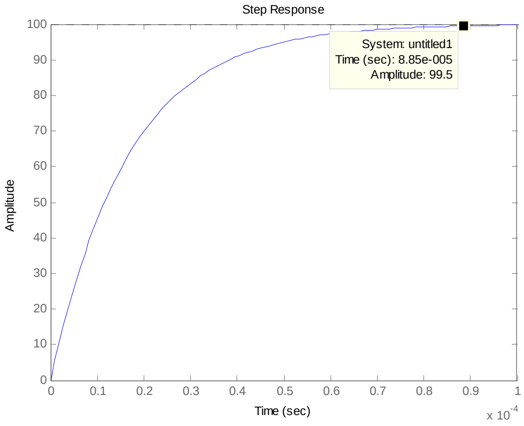


Figure 12 Wave shape of the output current

IV. CONCLUSION

Load variation and power disturbance are the important disturbance source in the arc welding inverter power system. In section III, H_2/H_∞ state feedback controller is designed by LMI method .MATLAB simulation illustrate that output of system is interfered least by disturbance of power, and it is robust for disturbance of load variation.

REFERENCES

[1] Y.-M. Chae, J.-S. Gho, G.-H.Choe, W.-S.Shin, J.-Y.Choi, “PWM Converter-Inverter Arc Welding Machine Using New Type N.C.T.”, IEEE PESC 98 Record, vol.2, pp. 1636-1641, May 1998..

[2] Huang Ji-Qiang, Chen Shu-Jun, Yin Shu-Yun, Wang Dong-Ping, Zeng Hua, “A Novel Three-phase Welding Inverter Power Supply With High Power Factor”, IEEE International Conference on Industrial Technology, Vol.2, pp.1113-1118, Dec.2003.

[3] Lu Peitao, Xie Yan, Huang Shisheng, Li Yang, Wu Kaiyuan. “Situation on measuring method of dynamic characteristic of arc welding power source,” ELECTRIC WELDING MACHINE, 2003,33(02).

[4] Zhang Xiaonan, Li Junyue, Li Guohua, Huang Shisheng, Xue Jiaxiang. “ Experimental analysis of dynamic characteristic evaluating criterions of CO2 arc welding power source,” ELECTRIC WELDING MACHINE , 2001,31(12).

[5] Luo Shoubin, Wang Chunfang, Li Qiang. “Design on Small Signal Model and double closed loop control system of Half-bridge Circuit,” SCIENCE & TECHNOLOGY INFORMATION , 2007, (05),pp.21~25.

[6] Li Qiang, Wang Chunfang, Luo Shoubin. “The design and modeling of the double closed loop control system based on half bridge circuit,” Marine Electric & Electronic Technology, 2007, 27(2).

[7] GUO Li-ping, ZHOU Luo-wei, SU Xiang-feng Small signal model of arc welding inverter power source.. Electric Welding Machine,2003,33(2):22-25.

[8] LIU Hai-kuan, LIAO Ping. Two degree-of-freedom control system of three level arc welding power. Electric Welding Machine,2010,40(3):52-55.

[9] Tzou yingyu, Hb Lienhsun, Ou Rongshyang. Fuzzy control of a closed-loop regulated PWM inverter under large load variations[C]. IEEE IECON Proceedings, 1993.

[10] Chen Hong, HU YV-Wen .Design of Repetitive Controller for Inverter. Power Electronics.,2002,36(5):68-71.

[11] WANG Yv-hua, GUI Chi-bin..Emulation analysis of digital arc welding inverter with combined control Transactions of the China Welding Insitittion,2007,28(1):109-112.

[12] WU Kai-yuan,HUANG Shi-sheng. Double-model fuzzy logic control strategy of arc in pulsed metal inertia gas welding [J].Control Theory and Application,2006,23(1):74-78.

[13] YAN Jun-rong, LIU Hai-kuan.. H_∞ Robust Controller of a Sort of Arc Welding Inverter Power Journal of Heilongjiang Hydraulic Engineering. 2009.36(2):89-91.

[14] YU Li. Robust Control—Linear Matrix Inequalation . Publishing House of Tsinghua University. Beijing,2002.12.

YAN Jun-rong comes from Jiangsu Xuzhou of China. She was born in 1972. She graduated from China University of Mining and Technology at Jiangsu Xuzhou, and attained the graduated degree of automatics in 1997, and attained the degree of Master of control theories and control engineering in 2005. Her major field of research is in robust control and fault diagnosis in induction motor.