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POWER QUALITY IMPROVEMENT BASED ON AN IMPROVED MODEL OF ELECTRIC ARC FURNACE AND A NONLINEAR ROBUST H-INFINITY CONTROL OF STATCOM

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Abstract. *For the problem that the electric arc furnaces (EAFs) can deteriorate the power quality of the distribution system, firstly, a new EAFs model based on the law of energy conservation and physical mechanism of EAFs is built in this paper. By superimposing the band-pass white noise on the ideal electric arc length, the functional relation among conductance, current and the electric arc length is described by the nonlinear differential equation. Then a nonlinear robust H-infinity controller for static synchronous compensator (STATCOM) is developed, in which the voltage of EAFs is seen as a new state variable and the linearization of the model is based on the differential geometry theory. The proposed controller for STATCOM is applied in one distribution system with EAFs load. Simulation results show that the proposed controller can improve effectively the power quality in the solution of voltage fluctuations, voltage distortion, unbalance of three phase voltages and voltage drop.*

Keywords: Electric arc furnaces (EAFs), Variation of arc length, Static synchronous compensator (STATCOM), Robust H-infinity control, Power quality

1. Introduction.

AC EAFs are mainly used in steel smelting, which have the characteristics of imbalanced three phase load, high reactive power, severe fluctuating, producing a large number of harmonics, low power factor, and so on. Then EAFs will make the power quality deteriorate, and endanger the transmission, distribution system and a large number of power users [1]. To improve the power quality, reactive power compensation is always needed in the power system. Static synchronous compensator (STATCOM), as a new type of compensator with fast response and flexible control, has been widely studied and used in recent years.

The operation of EAFs has the characteristics of high complexity and randomness, so it is very important to establish an accurate stochastic model to reflect the harmful affections on power grid from the EAFs load. For the random model of the EAFs in some existing literature, the white noise signal is usually superimposed on one characteristic parameter of the arc furnace, see [2, 3] and the references therein. In [4], based on the energy conservation law, the accurate model of EAFs is established by selecting the arc length and arc instantaneous current as inputs, conductance as the state, and considering the thermal inertia. However, this model cannot be used directly to study the dynamic characteristics of EAFs. Because the active and reactive power fluctuation caused by EAFs is not sharp, which leads to the mismatch of access point voltage fluctuations and the actual situation. Based on [4], the modified EAFs stochastic model is proposed in this paper, and the arc voltage waveform from this improved arc furnace model is highly consistent with the real arc voltage. Therefore, this stochastic model is very important for the study of electric energy quality problems.

For the problems of electric energy quality deteriorated by the EAFs, STATCOM can be used to compensate the reactive power, and the reactive current is controlled by linear PI or PID control in most of the literature. These methods can be competent when the disturbance is not severe, but the control effectiveness will be greatly reduced when the working environment of the system is relatively poor and the initial operating point is far away. Though the initial operating point of the system can be expanded and linearized approximately by using Taylor series, then the optimal control method is adopted, the demands of system stability still cannot be met. In addition, there are some disturbances and uncertainties in the process of running and modeling of STATCOM, which belong to the limited set of signal energy [5]. In view of the above two questions, based on the proposed arc furnace random model, the nonlinear robust H-infinity controller of STATCOM is designed. Simulation results show the designed robust H-infinity controller is superior to the traditional PI control in solving electric power quality problems, such as the sharp fluctuations of the electric grid voltage, reduction of the voltage level, and the unbalanced three-phase voltage.

The rest of this paper is organized as follows. Section 2 is devoted to the random model of EAFs. The details modeling and control of STATCOM are described in Section 3. The simulation studies are given in Section 4, and followed by Section 5 which concludes the work.

2. The Random Model of EAFs.

Taking into account that the arc length variation is an essential factor of voltage fluctuation caused by EAFs, this paper presents an improved model of EAFs based on the energy conservation in [4]. In order to simulate the irregular variation of the arc length of the EAFs, the white noise was superimposed on a given arc length, and then the random model of the EAFs was obtained.

The random arc length with the superimposed band-pass white noise is:

$$L\left(t\right) = L_0 + r\left(t\right) \tag{1}$$

where $L\left(t\right)$ is the random arc length, L_0 is the given arc length, generally no more than 20cm, and $r\left(t\right)$ is the band-pass white noise. The frequency range of $r\left(t\right)$ is selected in 1∼15Hz.

Energy expression for EAFs is:

$$dQ/dt = p - p_0 \tag{2}$$

where Q is the energy accumulated in the EAFs, p is the arc input power, p_0 is the dissipation power of the EAFs, and t is the time.

p and p_0 are related to the arc conductance:

$$p = i^2/g \tag{3}$$

$$p_0 = kg^{-m-1}L\left(t\right) \tag{4}$$

where g is the arc conductance, i is the instantaneous current flowing through the electric arc, k and m are the parameters which are related to the actual melting stage and transformer of EAFs, $k = 2304.7\mathrm{W}\Omega^{-2.9}\mathrm{cm}^{-1}$, $m = -0.99$.

Arc conductivity equation is:

$$\sigma = \sigma_0 e^{\alpha/T_0} \tag{5}$$

where σ is the arc conductivity, and σ_0 and α are the constants.

The arc energy in per unit volume is:

$$q = 0.345p\left(1 - T_1/T_0\right) \tag{6}$$

where q is the arc accumulated energy in per unit volume, T_1 is the temperature around the arc, and T_0 is the temperature of the arc column.

Then we have from (5) and (6):

$$g = \pi r^2 \sigma / L(t) \tag{7}$$

$$Q = q \pi r^2 L(t) \tag{8}$$

where r is the radius of arc.

The accurate stochastic model of the EAFs described by the nonlinear differential equation can be obtained from (1)-(8):

$$dg/dt = \left(\alpha / \left(0.354 p T_1 \pi r^2 L(t)\right)\right) i^2 - k g^{-m} \tag{9}$$

3. **The Modeling and Control of STATCOM.**

3.1. **The modeling of STATCOM.** In power system, the STATCOM can be equivalent to a controllable voltage source with impedance, as shown in Figure 1.

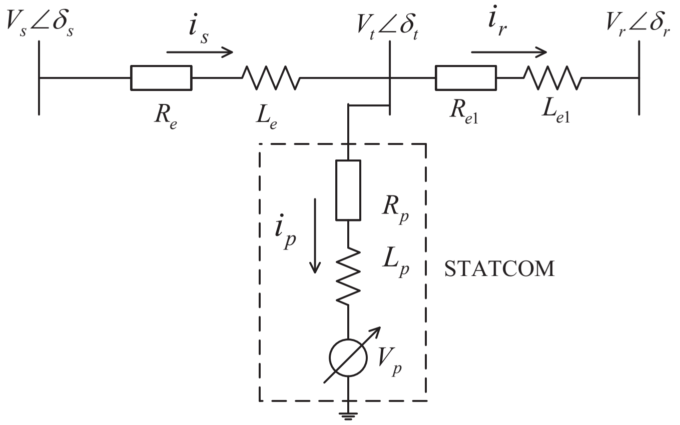


Figure 1. STATCOM equivalent circuit in system

In Figure 1, $V_s\angle\delta_s$ is the transmission side voltage, $V_r\angle\delta_r$ is the receiving end voltage, V_p is the STATCOM output voltage, R_e, R_{e1}, L_e and L_{e1} are the resistance and inductance of the transmission line, R_p and L_p are the resistance and impedance of the connection line between STATCOM and the system.

Under the new d-q-0 coordinates, define the state $x = [x_1\ \ x_2\ \ x_3\ \ x_4]^T = [i_{pd'}\ \ i_{pq'}\ \ V_{dc}\ \ V_r]^T$, input $u = [u_1\ \ u_2]^T = [V_{pd}\ \ V_{pq}]^T$, and the output $y = h(x) = [h_1(x)\ \ h_2(x)]^T = [V_{dc}\ \ V_r]^T$, where $i_{pd'}$, $i_{pq'}$ are the transformations of the d axis and the q axis current component i_{pd} and i_{pq}, respectively, V_{dc} is the DC voltage of capacitor, V_{pd}, V_{pq} are the d axis and the q axis voltage component of V_p, respectively. Because there is a certain loss when the DC capacitor is charged and discharged, then the uncertainty of it is set as w_1, and the impedance of the line is also in the presence of aging and other uncertainties, the uncertainty is set as w_2, and w_1, w_2 belong to the limited energy collection. So the affine system can be derived:

$$\dot{x} = f(x) + g_1 u_1 + g_2 u_2 + g_3 w_1 + g_4 w_2 \tag{10}$$

$$y = h(x) \tag{11}$$

where:

$$f(x) = \begin{bmatrix} f_1 x_1 + \omega x_2 + f_2 x_4 \\ -\omega x_1 + f_1 x_2 \\ f_3\left(x_1 x_4 - R_p\left(x_1^2 + x_2^2\right)\right) - f_4 x_3 \\ f_5 x_1 - f_6 x_2 - f_7 x_4 \end{bmatrix}$$

$$f_1 = -R_p / L_p,\ \ f_2 = 1 / L_p,\ \ f_3 = 3/2C,\ \ f_4 = 1/C R_{dc}$$

$$f_5 = -\omega^2 L_e + R_p R_e / L_P,\ f_6 = \omega R_e + \omega R_p R_e / L_p,\ f_7 = R_e / L_p$$

$$y_1 = h_1(x) = V_{dc},\ y_2 = h_2(x) = V_r$$

$$g_1 = \begin{bmatrix} -1/L_p \\ 0 \\ 0 \\ R_e/L_p \end{bmatrix},\ g_2 = \begin{bmatrix} 0 \\ -1/L_p \\ 0 \\ 0 \end{bmatrix},\ g_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix},\ g_4 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Let $z_1 = h_1(x) = x_3$, $z_2 = \dot{z}_1$, $z_3 = h_2(x) = x_4$, $z_4 = \dot{z}_3$, and the model can be linearized with exact feedback based on differential geometric control theory, and then we can get after some calculations:

$$\dot{z} = Az + B_1 v + B_2 w' \tag{12}$$

$$y = Cz \tag{13}$$

where $A = \begin{bmatrix} 0&1&0&0 \\ 0&0&0&0 \\ 0&0&0&1 \\ 0&0&0&0 \end{bmatrix}$, $B_1 = B_2 = \begin{bmatrix} 0&0 \\ 1&0 \\ 0&0 \\ 0&1 \end{bmatrix}$, $C = \begin{bmatrix} 1&0&0&0 \\ 0&0&1&0 \end{bmatrix}$, $z = [z_1\ \ z_2\ \ z_3\ \ z_4]^T$, $v = [v_1\ \ v_2]^T$, $w' = [w_1'\ \ w_2']^T$.

3.2. **The design of controller.**

The standard feedback control block diagram can be transformed as Figure 2.

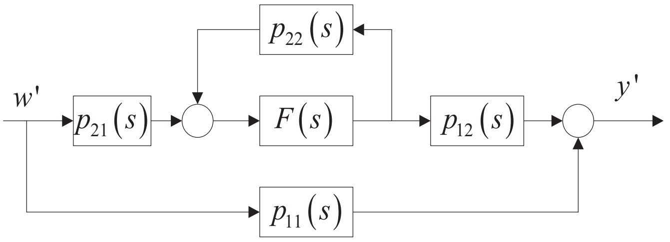


FIGURE 2. Deformation of standard feedback

The transfer function of the closed-loop system from w' to y' is written as:

$$T_{y'w'}(s) = p_{11}(s) + p_{12}(s)\left[I - F(s)\,p_{22}(s)\right]^{-1} F(s)\,p_{21}(s) \tag{14}$$

The control objective of the robust H-infinity is to design a controller $v = F(s)\,y(s)$ and make the following equation be satisfied:

$$\left\|T_{y'w'}(s)\right\|_\infty < 1 \tag{15}$$

Riccati equation is constructed as:

$$PA + A^TP + P\left(\gamma^{-2}B_1B_1^T - \varepsilon^{-2}B_2B_2^T\right)P + C_1^TC_1 + Q = 0 \tag{16}$$

where $\varepsilon > 0$, $0 < \gamma < 1$, Q is the positive definite symmetric matrix, and there is a positive definite solution P. According to the H_∞ control theory of uncertain systems, when (15) is met, the most serious interference which can be withstood in system is:

$$w_*' = B_1^T pz/2\varepsilon^2 \tag{17}$$

Considering the most serious interference, we have by the coordinate transformation:

$$z = \left(I - B_1B^Tp/2\varepsilon^2\right)^{-1}\left[h_1(x)\ \ L_fh_1(x)\ \ h_2(x)\ \ L_fh_2(x)\right]^T \tag{18}$$

The H_∞ controller is as follows.

$$v_* = -B_2^TP\left(I - B_1B_1^TP/2\varepsilon^2\right)^{-1}\left[h_1(x)\ L_fh_1(x)\ h_2(x)\ L_fh_2(x)\right]^T \Big/ 2\varepsilon^2 \tag{19}$$

Finally, the robust controller for STATCOM is:

$$v = E_1^{-1}(x)\left[-L_fh_1(x) - L_fh_2(x)\right]^T + E_1^{-1}(x)\,v_* \tag{20}$$

4. **The Simulation Results.** In this paper, the simulation system is built according to the proposed EAFs model and the STATCOM model. Some parameters in Figure 1 are set as follows. $R_e = 0.06$pu, $X_e = \omega L_e = 0.4$pu, $R_{e1} = 0.016$pu, $X_{e1} = \omega L_{e1} = 0.1$pu, $R_p = 0.023$pu, $X_p = \omega L_p = 0.15$pu. Besides, the DC capacitor of STATCOM $C_{dc} = 10000$uF. R_d is the short net resistor of the EAFs connected to system, $R_d = 0.4\text{m}\Omega$, X_d is the short net reactance, $X_d = 2.5\text{m}\Omega$. The Y/Y connection transformer T from system to the EAFs is 22MVA and 35KV/420V.

Simulation results are shown in Figures 3-6. Figure 3 is the voltage simulation result of the random model of EAFs. It can be seen that the voltage in the random model is similar to the actual waveform, that is, the size of the arc voltage is almost equal, and the top and bottom of each arc voltage are irregular, but the top and bottom of the arc voltage waveforms in the past references are smooth curve.

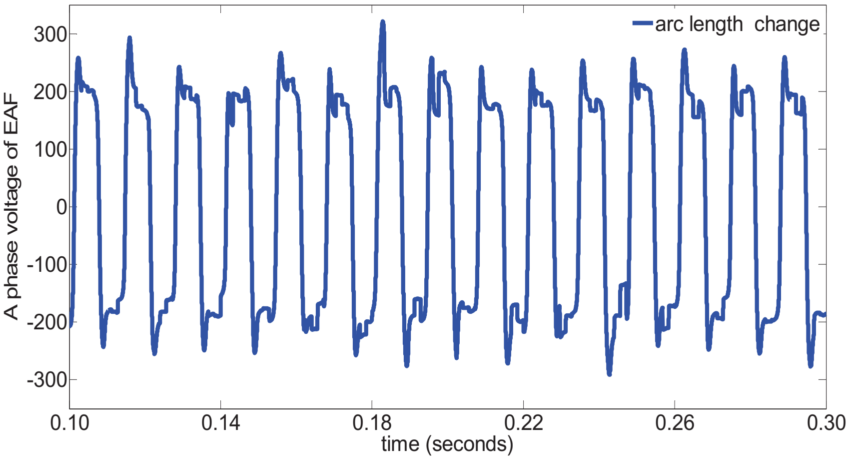


Figure 3. The voltage waveform of the random model of EAFs

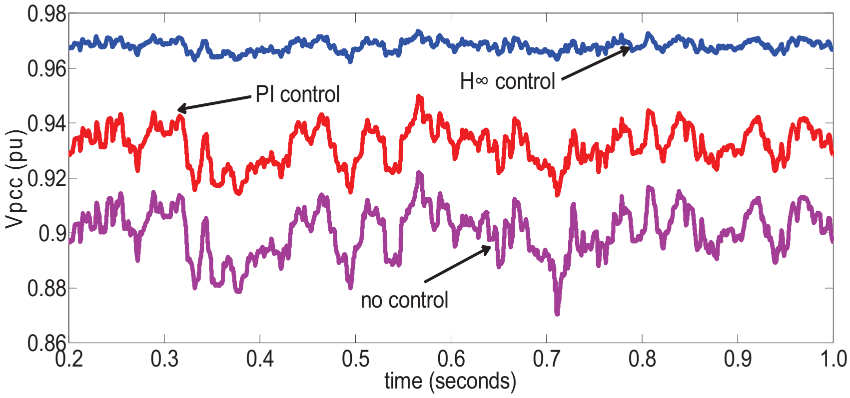
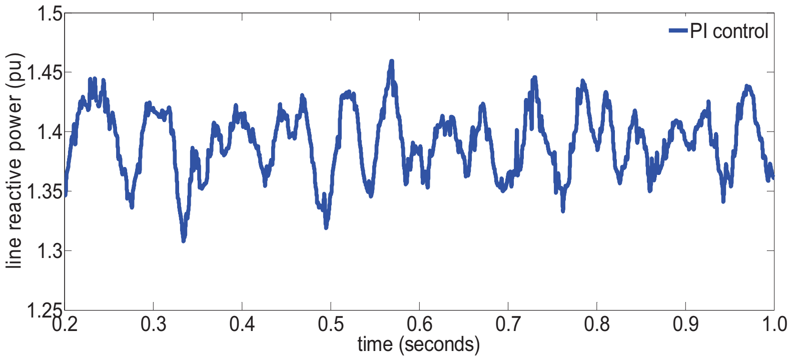
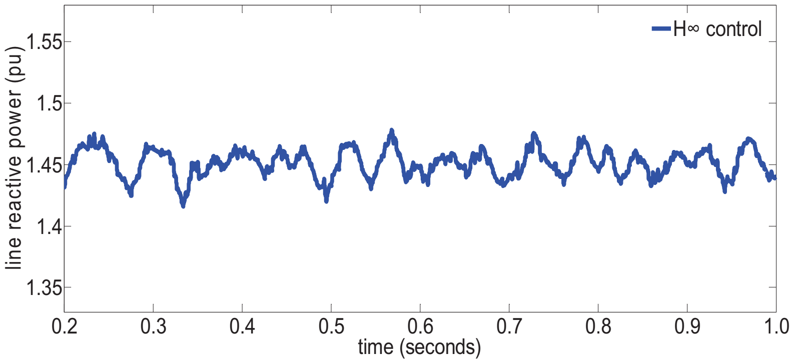


Figure 4. The bus voltage in arc furnace access point

Figure 4 shows the RMS value fluctuation of the bus voltage in arc furnace access point. It can be seen that in the absence of STATCOM, the bus voltage fluctuation range is more than 5%, but STATCOM under PI control and the nonlinear robust H-infinity control can stabilize the bus voltage, the amplitude of the fluctuation of the DC bus voltage under nonlinear robust H-infinity control is within 1%, so the problem of bus voltage flick caused by the severe voltage fluctuation can be effectively solved. In addition, under the robust H-infinity control, the bus voltage is close to 0.97, PI control is near to 0.93, which indicates the ability of improving power factor of STATCOM under robust H-infinity control is better than that of PI control.

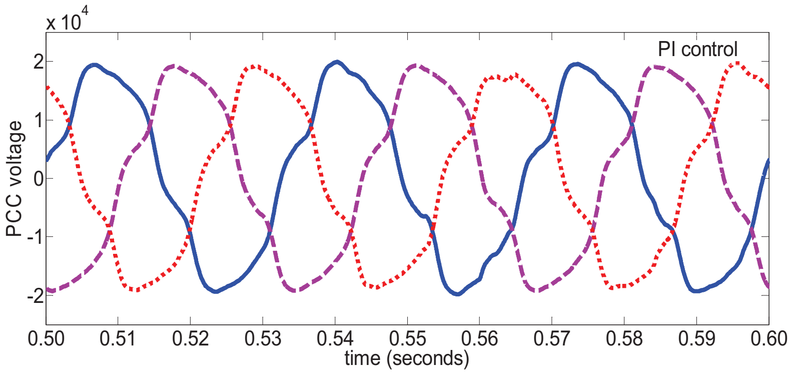


(a) PI control

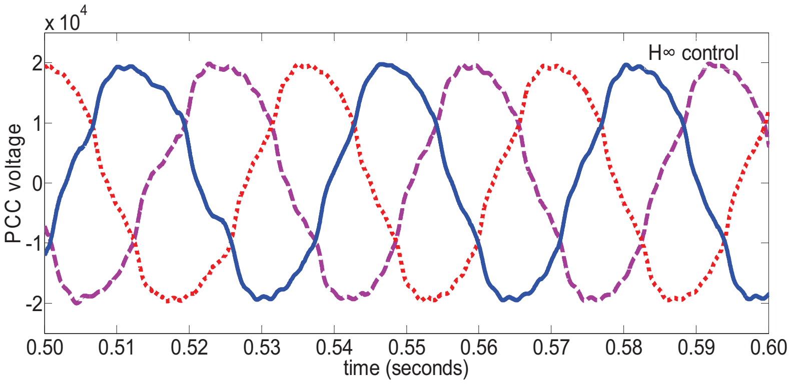


(b) H_∞ control

FIGURE 5. The reactive power waveforms under two controllers



(a) PI control



(b) H_∞ control

FIGURE 6. The waveforms of three-phase voltage

The fluctuation of reactive power in the EAFs access point is given in Figure 5. Under robust H_∞ control, the reactive power fluctuation in the STATCOM access point is 4.1%, while the reactive power fluctuation range under the PI control is 11.4%. Therefore, the reactive power balance ability of STATCOM in access points under robust H_∞ control is far better than that of PI control. The stability of voltage and reactive power are closely related, because the stable reactive power can ensure that the voltage fluctuation is small. Figure 5 reveals the essential reason why the bus voltage fluctuation under the robust H_∞ control is far less than that of PI control in Figure 4.

Figure 6 gives the three-phase voltage waveforms of the STATCOM access point under PI control and robust H_∞ control. The results show that the solution ability of STATCOM for the unbalanced three-phase voltage under the robust H_∞ control is better than that of PI control.

5. **Conclusions.** In this paper, the model of three-phase AC EAFs is built first. The model takes into account the physical mechanism of the EAFs, and the arc length is seen as the random parameter. The simulation results show that the model can reflect the voltage dynamics of EAFs more accurately and can be used to study the effect of EAFs on the distribution network. By selecting the arc furnace load side voltage as a new state variable, the STATCOM modeling and design of the robust H-infinity controller are conducted. From the simulations, we can see that the solving problem ability of STATCOM under nonlinear robust H-infinity control is far superior to that of the traditional PI control. The next direction of possible study is how to design the coordinated controller of the hybrid operation of SVC and STATCOM to improve the power quality further [6].

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