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Effect of static synchronous compensator on stability of electric power systems

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Abstract: The region of attraction of one-machine infinite-bus power system with static synchronous compensator (STATCOM) was estimated. The mathematical model of the system was given and the energy function was derived with first integral based on the model. The conservation of the model to reflect damping effect was discussed. To tide over the conservation, a damping-reflected energy function was derived. Based on the energy function, the region of attraction of the system was studied and a simulation example was given.

Key words: STATCOM; one-machine infinite-bus power system; region of attraction; Lyapunov function

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静止同步补偿器对电力系统稳定性的影响

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摘要: 研究了包含静止无功发生器(STATCOM)的单机-无穷大电力系统的吸引域.首先给出了系统数学模型,用首次积分法导出系统能量函数.讨论了用此方法所得能量函数在系统稳定域估计中不能反映阻尼效应的局限性.为克服由此造成的在系统稳定域估计中的保守性.导出了一种能反映系统阻尼效应的能量函数.此种能量函数可作为估计系统稳定域的李雅普诺夫函数.利用这一函数对系统稳定域进行了估计,并给出了仿真结果.

关键词: 静止无功发生器; 单机-无穷大系统; 吸引域; 李雅普诺夫函数

1 Introduction

The concept of flexible AC transmission system (FACTS) raised by scholars of the United States and the application of the technology afford a new important means to the control of power system stability. Static synchronous compensator (STATCOM) is a member of FACTS. Several such apparatus are in operation at home and abroad. Extensive and Intensive research on the effect of STATCOM that is exerted on power system have been carried out. Based on the theory of controlled Harmilton systems, Reference [1] analyses the issue. References [2,3] and [4] study the nonlinear control for STATCOM and the improvement on the voltage stability, system damping characteristics and transient stability. Based on the Lyapunov direct method[5,6], the region of attraction of one-machine infinite-bus power system with STATCOM is studied in the paper to investigate the effect of STATCOM on the stability of the systems. Compared with the studies ever, the paper extensively verified the effect of STATCOM on the stability of power systems.

2 Mathematical model of one-machine infinite-bus power system and energy function

Figure 1 shows a one-machine infinite-bus power system with STATCOM, which is equivalent to a varcurr-

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ent source, connected in parallel to the electric midpoint of transmission line[7]. In the case of the voltage of the point as phase reference, the node voltage equation can be written as

$$\frac{1}{\mathrm{j}X_L/2}(V-E_q\mathrm{e}^{\mathrm{j}\delta/2})+\frac{1}{\mathrm{j}X_L/2}(V-V_s\mathrm{e}^{-\mathrm{j}\delta/2}) = -\mathrm{j}I_{CR}. \tag{1}$$

Setting $V_s = E_q$, we obtain

$$V = E_q\cos\delta/2 + \frac{X_L}{4}I_{CR} \tag{2}$$

such that the electric power output of the generator (G) is

$$P_e = E_q\frac{2}{X_L}(E_q\cos\frac{\delta}{2} + \frac{X_L}{4}I_{CR})\sin\frac{\delta}{2} = \frac{E_q^2}{X_L}\sin\delta + \frac{1}{2}E_qI_{CR}\sin\frac{\delta}{2}. \tag{3}$$

Using the second order model (swinging equation) of the generator, we get the mathematical model of one-machine infinite-bus power system with STATCOM as follows

$$\dot\delta = \omega, \tag{4}$$

$$M\dot\omega + D\omega = P_m - \frac{E_q^2}{X_L}\sin\delta - \frac{1}{2}E_qI_{CR}\sin\frac{\delta}{2}. \tag{5}$$

The meaning of the terms in the equations above can be found from [7]. From equation (3), it can be seen that the STATCOM can change the electric power output of the generator and in the case of (4) and (5) the use of STATCOM correspons to increasing the damping of the system. During the analysis of system stability, the input machine power P_m and the output voltage of the generator without any load are assumed to be constant. In that case, ignoring the effect of damping, we obtain the energy function by the first integral[7]. Based on equations (4) and (5), we obtain

$$\frac{\mathrm{d}\delta}{M\mathrm{d}\omega} = \frac{\omega}{p_m - \frac{E_q^2}{X_L}\sin\delta - \frac{1}{2}E_qI_{CR}\sin\frac{\delta}{2}}. \tag{6}$$

Multiplying crosswise and integrating, we give energy function

$$E = \frac{1}{2}M\omega^2 + \frac{E_q^2}{X_L}(\cos\delta_0 - \cos\delta) + E_qI_{CR}(\cos\frac{\delta_0}{2} - \cos\frac{\delta}{2}) - P_m(\delta - \delta_0) \tag{7}$$

where δ_0 is the singular point of the swinging equation, i.e.,

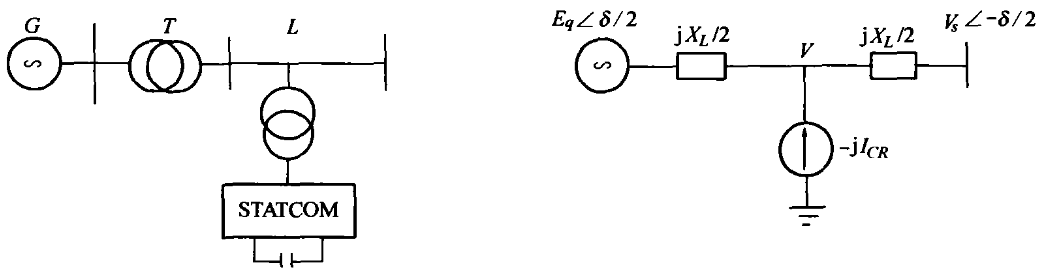
$$P_m - \frac{E_q^2}{X_L}\sin\delta_0 - \frac{1}{2}E_qI_{CR}\sin\frac{\delta_0}{2} = 0. \tag{8}$$

Based on this, we get the energy conservation law of the system

$$\frac{1}{2}M\omega^2 + \frac{E_q^2}{X_L}(\cos\delta_0 - \cos\delta) + E_qI_{CR}(\cos\frac{\delta_0}{2} - \cos\frac{\delta}{2}) - P_m(\delta - \delta_0) = E_0 \tag{9}$$

where E_0 is the original energy of the system.

A stable region of the system operation can be derived by means of the energy function above. But the estimation is too conservative due to the fact that the energy function E of the system obtained via the first-integral does not reflect the damping effect. If the damping coefficient of the system is large enough, the stable region will be extended. The following will give a kind of energy function reflecting the damping effect of the system.



(a) one-machine infinite-bus power system with STATCOM (b) equivalent circuit

Fig. 1 One-machine infinite-bus power system with STATCOM and its equivalent circuit

3 Lyapunov function of system

The terms related to the damping will be added into equation (9) in order to reflect the damping effect[6].

When there exists damping in the system, the time derivative of the energy function E is given by

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -D\omega^2. \tag{10}$$

Equation (9) changes as

$$\frac{1}{2}M\omega^2 + \frac{E_q^2}{X_L}(\cos\delta_0 - \cos\delta + E_qI_{CR}(\cos\frac{\delta_0}{2} - \cos\frac{\delta}{2}) - P_m(\delta - \delta_0) + \int_0^t D\omega^2 dt = E_0. \tag{9'}$$

Multiplying both sides of equation (5) by $(\Delta\delta)$ and integrating it in the time interval $[0, t]$, one obtains

$$\int_0^t M\dot{\omega}(\Delta\delta)dt + \int_0^t D\omega(\Delta\delta)dt = \int_0^t (P_m - P_e)(\Delta\delta)dt \tag{11}$$

where, $\Delta\delta = \delta - \delta_0, P_e = \frac{E_q^2}{X_L}\sin\delta + \frac{1}{2}E_qI_{CR}\sin\frac{\delta}{2}$.

Considering $\omega = \frac{d\delta}{dt} = \frac{d(\Delta\delta)}{dt}$, with the integration of part integral, we can write the first term of the equation above as

$$\int_0^t M(\dot{\omega})(\Delta\delta)dt = M\omega(\Delta\delta) - M\int_0^t \omega^2 dt.$$

The second one can be integrated directly. By operation equation (11) can be written as

$$\int_0^t \omega^2 dt = \omega(\Delta\delta) + \frac{1}{2}\frac{D}{M}(\Delta\delta)^2 - \frac{1}{M}\int_0^t (P_m - P_e)(\Delta\delta)dt. \tag{12}$$

From equation (12), the final term of the equation (9′) can be written as

$$\int_0^t D\omega^2 dt = D\omega(\Delta\delta) + \frac{1}{2}\frac{D^2}{M}(\Delta\delta)^2 - \frac{D}{M}\int_0^t (P_m - P_e)(\Delta\delta)dt.$$

By splitting the damping loss and from the equation (9), the energy of the system can be obtained as

$$E_{\lambda,I_{CR}}(\omega,\delta) = \frac{1}{2}M\omega^2 + \frac{E_q^2}{X_L}(\cos\delta_0 - \cos\delta) + E_qI_{CR}(\cos\frac{\delta_0}{2} - \cos\frac{\delta}{2}) - P_m(\delta - \delta_0) + D\lambda\omega(\Delta\delta) + \frac{1}{2}\frac{D^2}{M}\lambda(\Delta\delta)^2. \tag{13}$$

The energy function is related to two parameters, one of which is the controlling variable I_{CR} with which the electric power output of the generator can be controlled. The other parameter, λ, reflects the affecting level of the damping effect on the energy function. The following shows that the function $E_{\lambda,I_{CR}}(\omega,\delta)$ can be as the Lyapunov function of the system and by changing λ, different regions of the stable operation can be obtained.

At first, the function $E_{\lambda,I_{CR}}(\omega,\delta)$ is defined positive. As a matter of fact, around the stable equilibrium point, $\delta = \delta_0, P_m = \frac{E_q^2}{X_L}\sin\delta + \frac{1}{2}E_qI_{CR}\sin\frac{\delta}{2}$, the second and third terms of equation (13) is written as

$$f(\delta) = \frac{E_q^2}{X_L}(\cos\delta_0 - \cos\delta) + E_qI_{CR}(\cos\frac{\delta_0}{2} - \cos\frac{\delta}{2}).$$

$f(\delta)$ can be expanded as Taylor series and the first three terms are reserved such that $E_{\lambda,I_{CR}}(\omega,\delta)$ can be approximated as

$$E_{\lambda,I_{CR}} \approx \frac{1}{2}M\omega^2 + D\lambda\omega(\Delta\delta) + \frac{1}{2}\frac{E_q^2\cos\delta_0}{X_L} + \frac{1}{4}E_qI_{CR}\cos\frac{\delta_0}{2} + \frac{1}{2}\frac{D^2}{M}\lambda(\Delta\delta)^2. \tag{14}$$

From the above equation, it can be seen that $E_{\lambda,I_{CR}}$ is larger than zero ($E_{\lambda,I_{CR}} > 0$). Furthermore, the time derivative of the function $E_{\lambda,I_{CR}}(\omega,\delta)$ is

$$\frac{dE_{\lambda,I_{CR}}}{dt} = -(1-\lambda)D\omega^2 + \frac{\lambda}{M}(P_m - P_e)(\Delta\delta). \tag{15}$$

When δ is at a neighbor around δ_0, $(P_m - P_e)(\Delta\delta) < 0$, such that $\frac{dE_{\lambda,I_{CR}}}{dt} < 0$. For all $\lambda \in [0,1]$, the time derivative of the energy function $E_{\lambda,I_{CR}}$ is defined negative.

It follows from the above-mentioned the energy function $E_{\lambda,I_{CR}}$ proposed can be served as the Lyapurov function of the system.

4 Estimating region of attraction

Equation (13) can be seen as the first integral of another form of the system dynamic equation. By setting $E_{\lambda,I_{CR}} = E_c$ (constant), its equal-valued line can be obtained. When the constant is different, a set of trajectory can be got on the phase plane.

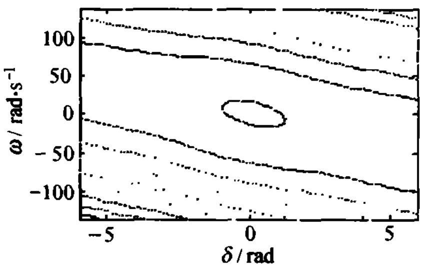
There are three types of the trajectory, the first of which is closed curves of $E_{\lambda,I_{CR}} > E_s$ where E_s is the energy value corresponding the saddle point of $E_{\lambda,I_{CR}}$, which will be discussed lately. Due to the damping effect the curve above will tend to the origin point of phase plane as the time passes. The second one is non-closed curve of $E_{\lambda, I_{CR}} > E_s$, which can not tend to the origin point. The final one of $E_{\lambda, I_{CR}} = E_s$ is the demarcation line between the regions above, called critical line which is also a closed curve. The domain within the critical line is the stable region of the system operation. By letting λ equal to all different values on the interval $[0,1]$, we can obtain different stable region of the system. By taking the union of the stable regions above the largest region of the asymptotic stability, the region of attraction can be got. As a controlling variable reflecting the effect of STATCOM, the value of the var current can be adjusted to change the stable region of the system under different λ so that the region of attraction of the system is expanded. From the above, to ask for the stable region of the system under certain I_{CR} is to calculate the closed trajectory $E_{\lambda, I_{CR}}(\omega, \delta) = E_s$ on the phase plane while E_s depends upon the saddle point (δ_s, ω_s), calculated as

$$\begin{cases} \dfrac{\partial E_{\lambda, I_{CR}}}{\partial \omega_s} = 0, \\ \dfrac{\partial E_{\lambda, I_{CR}}}{\partial \delta_s} = 0. \end{cases} \tag{16}$$

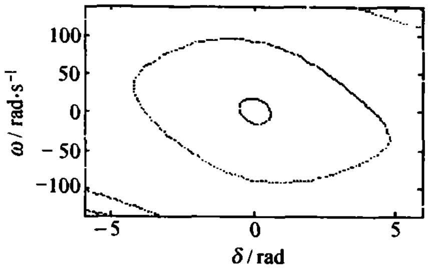
The stable region of the system is the domain encircled within the closed curve

$$E_{\lambda, I_{CR}} = E_{\lambda, I_{CR}}(\omega, \delta) = E_s.$$

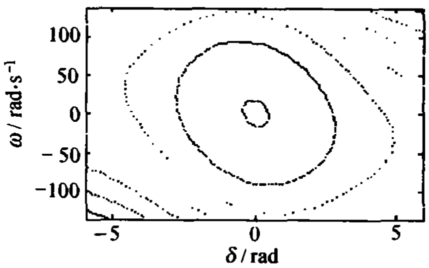
An example is studied in order to investigate the effect of the var current denoting compensating level on the region of attraction of the system. In the example, we set $E_q = 1.1, P_m = 1.0, M = 0.0255, \delta_0 = 0.237$ rad, $D = 0.4, X_L = 0.30$. The equivalent var current of STATCOM is 0, 2, and 4 pu separately, for each of which, the parameter λ is taken 0.6 for simulating calculation so that three different stable regions of the system are obtained. Fig.2 shows the simulation result from which one can see that under certain parameter λ, as the var current I_{CR} of the STATCOM increases, the stable region of the system will extend.



(a) $I_{CR} = 0.0$ pu



(b) $I_{CR} = 2.0$ pu



(c) $I_{CR} = 4.0$ pu

Fig. 2 Region of attraction: $\lambda = 0.6$

5 Conclusion

The paper studies the one-machine infinite-bus power systems with STATCOM, derives Lyapunov function for stability analysis and discusses the estimating approach for the region of attraction based on the function above. The simulation curve shows that the approach proposed is appropriate.

The simulation result reveals the changing tendency of the stable region of the system as the equivalent var current of STATCOM increases, which indicates STATCOM is beneficial for stable operation of the system and efficiently expands the asymptotic stable region (region of attraction) of the system.

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