STATCOM을 위한 Passivity-Based Controller 설계

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Passivity-Based Controller Design for STATCOM

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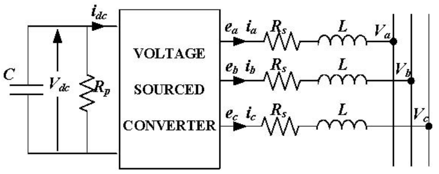
1. Introduction

Static Synchronous Compensator (STATCOM) based on a Voltage-Sourced Converter (VSC) has been used for enhancing controllability and increasing power transfer capability of the network. Under the classification of the number of the control degree, there are two types of the STATCOM. Because of simple structure and cost savings, both in initial manufacture and operational costs [1], we consider type 2 STATCOM in this study. For STATCOM system, various kinds of controllers have been researched [1,2]. Passivity-based control (PBC) enhances robustness of system and can be simplified realization in controller implementation as compared to the feedback linearizing control law [3]. In this paper, we propose the PBC controller based on error dynamics for the type 2 STATCOM system. The main purpose of the control design for type 2 STATCOM system is tracking the reactive current's reference. Unlike type 1 system, type 2 system has only one degree of control, thus the PBC controller designed in [4] cannot be applied to type 2 system. We design two kinds of the PBC controllers with a new control input considering the performance of all states. We design the controllers based on Lyapunov function, thus asymptotically stability of equilibrium point of the system is guaranteed.

2. STATCOM Model



<Fig. 1> Equivalent circuit of STATCOM.

Fig. 1 shows the equivalent circuit of a STATCOM connected to the line through an inductances L's in series which is represented the leakage of the actual power transformers. The resistances R_s's represents conduction losses between the inverter and the transformer, and the resistance R_p represents switching losses in the system. STATCOM system's mathematically averaged model in state-space on d-q frame can be described as follows [1]:

$$\dot{x}=f(x,\alpha)$$

$$=\begin{bmatrix} -\frac{R_s'\omega_b}{L'}x_1+\omega x_2+\frac{k\omega_b}{L'}x_3\cos\alpha-\frac{\omega_b}{L'}|V'| \\ \omega x_1+-\frac{R_s'\omega_b}{L'}x_2+\frac{k\omega_b}{L'}x_3\sin\alpha \\ -\frac{3}{2}kC'\omega_b x_1\cos\alpha-\frac{3}{2}kC'\omega_b x_1\sin\alpha-\frac{\omega_b C'}{L'}x_3 \end{bmatrix} \quad (1)$$

$$y=x_2,$$

where $[x_1\ x_2\ x_3]^T=[I'_d\ I'_q\ V'_{dc}]^T$.

The parameters and state variables with an apostrophe represent the per-unit value. I_d', I_q' and V_{dc}' represent active current, reactive current and voltage of capacitor, respectively. The factor k is a constant and α is the phase shift angle as control input of the system. Here, $f: R^3\times R^1 \rightarrow R^3$ is sufficiently smooth function, and the phase angle $\alpha \in R^1$ is the control input. Since the function $f(x,\alpha)$ in (1) is satisfied that $\frac{\partial}{\partial x}f(x,\alpha)$ is nonsingular, it is satisfied the *implicit function theorem.*

3. Design a Passivity-Based Controller

In order to design PBC, we represent the system dynamics with Euler-Lagrange (EL) equation of motion, which has been applied to standard Lyapunov methods [3]. The general form of the EL model is

$$\Phi\dot{x}=\Xi x+\Psi x+\Psi_u(u)x+E \quad (2)$$

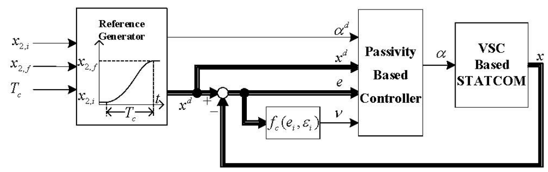
with $\Xi=\Xi^T \le 0,\ \Phi=\Phi^T>0,\ \Psi+\Psi^T=0,\ \Psi_u+\Psi_u^T=0.$

We approximate $\cos\alpha \approx 1$ for the simplification of controller design. Then we can rewrite (1) as general form of EL model.

$$\Phi=\begin{bmatrix}1&0&0\\0&1&0\\0&0&\frac{2}{3C'L'}\end{bmatrix},\ \Psi=\begin{bmatrix}0&\omega&\frac{k\omega}{L'}\\-\omega&0&0\\-\frac{k\omega}{L'}&0&0\end{bmatrix},\ \Psi_u=\begin{bmatrix}0&0&0\\0&0&\frac{k\omega_b}{L'}sin\alpha\\0&-\frac{k\omega_b}{L'}sin\alpha&0\end{bmatrix},$$

$$\Xi=\begin{bmatrix}-\frac{R_s'\omega_b}{L'}&0&0\\0&-\frac{R_s'\omega_b}{L'}&0\\0&0&-\frac{2\omega_b}{3L'R_p'}\end{bmatrix},\ E=\begin{bmatrix}-\frac{\omega_b}{L'}|V'|\\0\\0\end{bmatrix}.$$

3.2 Passivity-based controller



<Fig. 2> Controller block.

Fig. 2 shows the controller structure proposed in this paper. At first, we just select the initial value of x_2, $x_{2,i}$, the final value of x_2, $x_{2,f}$, and the time interval x_2 from $x_{2,i}$ to $x_{2,f}$, T_c. Then the reference generator makes the reference, x_1^d, x_2^d, x_3^d and α^d, using the third-order profile. If the desired dynamics is given by

$$\Phi\dot{x}^d=\Xi x^d+\Psi x^d+\Psi_u(u^d)x^d+E \quad (3)$$

and we define $e=x^d-x$,, then the error dynamics is obtained by subtracting (2) from (3) as follows:

$$\Phi\dot{e}=\Xi e+\Psi e+\Psi_u(u^d)x^d-\Psi_u(u)x.$$

Let' consider

$$V_{ctrl}=\frac{1}{2}e^T\Phi e \quad (4)$$

as a Lyapunov function candidate. The derivative of this function (4) along the trajectories of the error dynamics results in

$$\dot{V}_{ctrl} = e^T \Xi e + \left(\frac{k\omega}{L'} e_2 x_3^d - \frac{k\omega}{L'} e_3 x_2^d\right)\sin\alpha^d - \left(\frac{k\omega}{L'} e_2 x_3 - \frac{k\omega}{L'} e_3 x_2\right)\sin\alpha \quad (5)$$

Since $\Xi = \Xi^T < 0$ in the system, our task is to find a control law input to a stabilize the system (5) at equilibrium point. If we take a control input

$$\sin\alpha = \frac{\left(\frac{k\omega}{L'} e_2 x_3^d - \frac{k\omega}{L'} e_3 x_2^d\right)\sin\alpha^d + \nu}{\frac{k\omega}{L'} e_2 x_3 - \frac{k\omega}{L'} e_3 x_2 + \rho_0 \epsilon_0}, \quad \epsilon_0 \simeq 0,\ \epsilon_0 > 0, \quad (6)$$

where

$$\rho_0 = sgn\left(\frac{k\omega}{L'} e_2 x_3 - \frac{k\omega}{L'} e_3 x_2\right),\ \nu = f_c(e_i, \varepsilon_i),$$

then the problem is redefined as finding the feedback control law ν. Here, the signum function is defined as

$$sgn(\eta) = \begin{cases} 1, & \eta > 0 \\ 0, & \eta = 0. \\ -1, & \eta < 0 \end{cases}$$

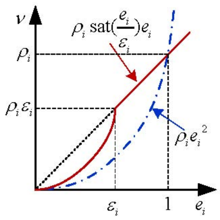
We add $\rho_0 e_0$ to avoid the input saturation. If ν is taken as a positive value, then $\dot{V}_{ctrl}$ is negative definite, i.e., the equilibrium point of the system is asymptotically stable by *Lyapunov theorem* [13]. We propose two kinds of the full state feedback controllers ν as a function of error, $f_c(e_i, \varepsilon_i)$, to improve the transient performance of all states. The control law ν as follows:

1) Controller 1 (square function):

$$\nu_1 = \sum_{i=1}^{3} \rho_i e_i^2,\ \rho_i \geq 0,\ i = 1,2,3\ . \quad (7)$$

In (7). We find that a large weighting ρ_2 is associated to the fast settling time T_s of I_q'. When ρ_2 is taken as the large value, however, the value α arrives at its limit, then the states diverge.

2) Controller 2 (saturation function):



<Fig. 3> Controller 1 and controller 2.

In order to avoid the saturation of α we propose the control law as the following form

$$\nu_2 = \sum_{i=1}^{3} \rho_i sat\left(\frac{e_i}{\varepsilon_i}\right) e_i,\ \rho_i \geq 0,\ i = 1,2,3\ , \quad (8)$$

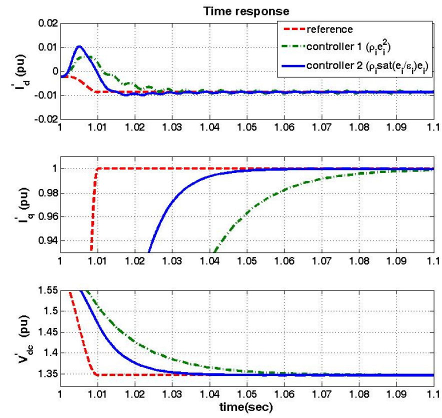
where

$$sat\left(\frac{e_i}{\varepsilon_i}\right) = \begin{cases} \frac{e_i}{\varepsilon_i}, & \text{if } \left|\frac{e_i}{\varepsilon_i}\right| \leq 1 \\ sgn\left(\frac{e_i}{\varepsilon_i}\right), & \text{if } \left|\frac{e_i}{\varepsilon_i}\right| > 1 \end{cases},\ i = 1,2,3$$

and $0 < \varepsilon_i < 1$, $\forall i$. Fig. 3 shows the differences between the controller 1 and controller 2. If ρ_i in both (7) and (8) are the same, ν_2 has smaller value than ν_1 for $e_i > 1$. Thus the controller 2 prevents the control output α from saturating for large magnitude of error. For $e_i < 1$, the controller 2 forces larger control output than the controller 1, thus the transient performances such as the rising time T_r and settling time T_s are improved.

4. Simulation Results

To validate the proposed control strategies, simulations using an averaged model is implemented in MATLAB/Simulink. This model does not include power electronic devices. We simulate in the case that $I_q'^d$ is changed from 0 to 1pu generated in the form of third-order profile during 10ms. At $I_q'^d = 1$pu, the system is lightly damped. Thus our approaches is based on the worst-case performance optimization. Fig. 4 shows that the response of the system with the weighting $\rho_1 = 1$, $\rho_2 = 60$ and $\rho_3 = 40$. The dashed curve is the desired value. With controller 1, T_s of I_q' is about 58ms, which is shown by dashed-dot curve. With controller 2, T_s of I_q' is about 32ms, which is shown by solid curve, smaller than the controller 1. The tendency of the V_{dc}' response is the same as that of the I_q' response. And the overshoot %OS of I_d' is increased by using the controller 2.



<Fig. 4> Time response of STATCOM with controller 1 and controller 2 when $I_q'^d$ is changed from 0 to 1.

5. Conclusion

In this paper, the STATCOM having only one control input degree is considered to design a nonlinear controller. PBC based on a new control input is designed for robustness and asymptotically stable. In order to solve the control output saturation problem, the saturation function is applied for the state feedback and the performance is compared to the square function. It is shown that the saturation function with PBC achieves faster settling time of the system than the square function.

6. Acknowledgement

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