Adaptive PI Control of STATCOM for Voltage Regulation with Fuzzy Interfacing

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Abstract: STATCOM can provide fast and efficient reactive power support to maintain power system voltage stability. This paper proposes a fuzzy control model based on adaptive PI control, which can self-adjust the control gains during a disturbance such that the performance always matches a desired response, regardless of the change of operating condition. Since the adjustment is autonomous, this gives the plug-and-play capability for STATCOM operation. In the simulation test, the adaptive PI control shows consistent excellence under various operating conditions, such as different initial control gains, different load levels, change of transmission network, consecutive disturbances, and a severe disturbance. In contrast, the conventional STATCOM control with tuned, fixed PI gains usually perform fine in the original system, but may not perform as efficient as the proposed control method when there is a change of system conditions.

Keywords: DC–AC Power Conversion, Distributed Power Generation, Grid-Connected Converters, Multilevel Converters, Single-Phase Systems.

I. INTRODUCTION

Voltage stability is a critical consideration in improving the security and reliability of power systems. The static compensator (STATCOM), a popular device for reactive power control based on gate turnoff (GTO) thyristors, has gained much interest in the last decade for improving power system stability [1]. In the past, various control methods have been proposed for STATCOM control. References [2]–[9] mainly focus on the control design rather than exploring how to set proportional-integral (PI) control gains. In many STATCOM models, the control logic is implemented with the PI controllers. The control parameters or gains play a key factor in STATCOM performance. Presently, few studies have been carried out in the control parameter settings. In [10]–[12], the PI controller gains are designed in a case-by-case study or trial-and-error approach with tradeoffs in performance and efficiency. Generally speaking, it is not feasible for utility engineers to perform trial-and-error studies to find suitable parameters when a new STATCOM is connected to a system. Further, even if the control gains have been tuned to fit the projected scenarios, performance may be disappointing when a considerable change of the system conditions occurs, such as when a line is upgraded or retires from service [13], [14]. The situation can be even worse if such transmission topology change is due to a contingency.

Thus, the STATCOM control system may not perform well when mostly needed. A few, but limited previous works in the literature discussed the STATCOM PI controller gains in order to better enhance voltage stability and to avoid time-consuming tuning. For instance, in [15]–[17], linear optimal controls based on the linear quadratic regular (LQR) control are proposed. This control depends on the designer’s experience to obtain optimal parameters. In [18], a new STATCOM state feedback controller still depend on the designer’s choice. In [19]–[21], a fuzzy PI control method is proposed to tune PI controller gains. However, it is still up to the designer to choose the actual, deterministic gains. In [22], the population-based search technique is applied to tune controller gains. However, this method usually needs a long running time to calculate the controller gains. A tradeoff of performance and the variety of operation conditions still has to be made during the designer’s decision-making process. Thus, highly efficient results may not be always achievable under a specific operating condition. Different from these previous works, the motivation of this paper is to propose a control method that can ensure a quick and consistent desired response when the system operation condition varies.

Fig. 1. Equivalent circuit of STATCOM.

In other words, the change of the external condition will not have a negative impact, such as slower response, overshoot, or even instability to the performance. Base on this fundamental motivation, an adaptive PI control of STATCOM for voltage regulation is presented in this paper. With this adaptive PI control method, the PI control parameters can be self-adjusted automatically and
dynamically under different disturbances in a power system. When a disturbance occurs in the system, the PI control parameters for STATCOM can be computed automatically in every sampling time period and can be adjusted in real time to track the reference voltage. Different from other control methods, this method will not be affected by the initial gain settings, changes of system conditions, and the limits of human experience and judgment. This will make the STATCOM a “plug-and-play” device. In addition, this research work demonstrates fast, dynamic performance of the STATCOM in various operating conditions.

II. STATCOM MODEL AND CONTROL

A. System Configuration

The equivalent circuit of the STATCOM is shown in Fig.1. In this power system, the resistance \( R_s \) in series with the voltage source inverter represents the sum of the transformer winding resistance losses and the inverter conduction losses. The inductance \( L_s \) represents the leakage inductance of the transformer. The resistance \( R_c \) in shunt with the capacitor represents the sum of the switching losses of the inverter and the power losses in the capacitor. In Fig. 1, \( V_{as} \), \( V_{bs} \), and \( V_{cs} \) are the three-phase STATCOM output voltages; \( V_{a'b'} \), \( V_{b'b'} \), and \( V_{c'c'} \) are the three-phase bus voltages; and \( I_{as} \), \( I_{bs} \), and \( I_{cs} \) are the three-phase STATCOM output currents [15], [23].

B. STATCOM Dynamic Model

The three-phase mathematical expressions of the STATCOM can be written in the following form [15], [23]:

\[
\begin{align*}
L_s \frac{dI_{as}}{dt} &= -R_s I_{as} + V_{as} - V_{d}t \quad (1) \\
L_s \frac{dI_{bs}}{dt} &= -R_s I_{bs} + V_{bs} - V_{d}t \quad (2) \\
L_s \frac{dI_{cs}}{dt} &= -R_s I_{cs} + V_{cs} - V_{d}t \quad (3)
\end{align*}
\]

By using the transformation, the equations from (1) to (4) can be rewritten as

\[
\frac{d}{dt}\begin{bmatrix}
i_d \\
i_q \\
V_{dc}
\end{bmatrix} =
\begin{bmatrix}
\frac{\omega}{L_s} & -\frac{R_s}{L_s} & -\frac{R_c}{L_s} \\
-\frac{R_s}{L_s} & \frac{\omega}{L_s} & -\frac{R_c}{L_s} \\
-\frac{R_c}{L_s} & -\frac{R_c}{L_s} & -\frac{1}{C}
\end{bmatrix}
\begin{bmatrix}
i_d \\
i_q \\
V_{dc}
\end{bmatrix} \\
-\frac{1}{L_s}
\begin{bmatrix}
V_d \\
V_q \\
0
\end{bmatrix}
\]

(5)

III. ADAPTIVE PI CONTROL FOR STATCOM

A. Concept of the Proposed Adaptive PI Control Method

The STATCOM with fixed PI control parameters may not reach the desired and acceptable response in the power system when the power system operating condition (e.g., loads or transmissions) changes. An adaptive PI control method is presented in this section in order to obtain the desired response and to avoid performing trial-and-error studies to find suitable parameters for PI controllers when a new STATCOM is installed in a power system as shown in Fig.2. With this adaptive PI control method, the dynamical self-adjustment of PI control parameters can be realized.

- The bus voltage \( V_m \) is measured in real time.
- When the measured bus voltage over time \( V_m \) not-equal to \( V_{ss} \) the target steady-state voltage, which is set to 1.0 per unit (p.u.) in the discussion and examples, \( V_m \) is compared with \( V_{ss} \). Based on the desired reference voltage curve, and are dynamically adjusted in order to make the measured voltage match the desired reference voltage, and the-axis reference current can be obtained.
- In the inner loop, \( I_{qref} \) is compared with the \( -a \)-axis current \( i_a \). Using the similar control method like the one for the outer loop, the parameters and can be adjusted based on the error as shown in Fig.3. Then, a suitable angle can be found and eventually the dc voltage in STATCOM can be modified such that STATCOM provides the exact amount of reactive power injected into the system to keep the bus voltage at the desired value.

![Fig.2. Adaptive PI control block for STATCOM.](image1)

![Fig.3. Reference voltage curve.](image2)

B. Derivation of the Key Equations

Since the inner loop control is similar to the outer loop control, the mathematical method to automatically adjust PI controller gains in the outer loop is discussed in this section for illustrative purposes. A similar analysis can be applied to the inner loop. Here, \( V_{dL} \) And \( V_{qL} \) can be computed with the -trans-Formation.

\[
\begin{bmatrix}
V_{dL} \\
V_{qL} \\
V_{vl}
\end{bmatrix} = \begin{bmatrix}
2 & 1 & -\frac{1}{2} \\
0 & 1 & -\frac{3}{2} \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
V_{dl} \\
V_{ql} \\
V_{vl}
\end{bmatrix}
\]

(6)

Then, we have

\[
V_{m(t)} = \sqrt{\frac{V_{dL}^2 + V_{qL}^2}{2}}
\]

(7)

Based on \( V_{m(t)} \), the reference voltage \( V_{ref} \) is set as

\[
V_{ref} = V_{as} - (V_{as} - V_{m(t)})e^{-\frac{t}{\tau}}
\]

(8)
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In (10), $V_{ss}$ is the target steady state voltage, which is set to 1.0 p.u in the discussion and examples; $V_m(t)$ is the measured voltage; $T=0.01$ s. the curve in fig 4 is one example of $V_{ref}(t)$. If the system is operating in the normal condition, then $V_m(t)=1$ p.u and, thus, $V_{ref}(t)=1$ p.u. This means that $K_{p_v}$ and $K_{i_v}$ will not change and the STATCOM will not inject or absorb any reactive power to maintain the voltage disturbance in the power system, based on $V_{ref}(t)=(V_{ss} - V_m(t))e^{-\alpha T}$. $K_{p_v}$ and $K_{i_v}$ will become adjustable and the STATCOM will provide reactive power to increase the voltage. Here, the error between $V_{ref}(t)$ and $V_m(t)$ is denoted by $\Delta V(t)$; when there is a disturbance in the power system. Based on the adaptive voltage control model, at any arbitrary time instant $t$, the following equation can be obtained:

$$\Delta V(t)K_{p_v} + K_{i_v}(t) \int_{t}^{t+T} \Delta V(t) dt = I_{qref}(t + T)$$

(9)

Based on (12), if we can determine in ideal response the ratio and ideal ratio, the desired $K_{p_v}$ and $K_{i_v}$ can be solved.

Fig.4. Adaptive PI control algorithm flowchart.

In this system, the discrete-time integrator block in place of the integrator block is used to create a purely discrete system, and the Forward-Euler method is used in the discrete-time integrator block. Therefore, the resulting expression for the output of the discrete-time integrator block at is

$$y(t) = y(t - T) + K_{i_v}(t - T) \times T \times \Delta V(t - T)$$

(10)

$$\Delta V(t)K_{p_v} + K_{i_v}(t) \int_{t}^{t+T} \Delta V(t) dt = I_{qref}(t + T) - I_{qref}(t)$$

(11)

$$\Delta V(t)K_{p_v} + K_{i_v}(t) \int_{t}^{t+T} \Delta V(t) dt = I_{qref}(t + T) - I_{qref}(t)$$

(12)

IV. SIMULATION RESULTS

A. System Data

In the system simulation diagram shown in Fig. 5, a 100-MVAR STATCOM is implemented with a 48-pulse VSC and connected to a 500-kV bus. This is the standard sample STATCOM system in Matlab/Simulink library, and all machines used in the simulation are dynamical models [10]–[12]. Here, the attention is focused on the STATCOM control performance in bus voltage regulation mode. In the original model, the compensating reactive power injection and the regulation speed are mainly affected by PI controller parameters in the voltage regulator and the current regulator. The original control will be compared with the proposed adaptive PI control model. Assume the steady-state voltage, 1.0 p.u. In Sections IV-B, C, and F, a disturbance is assumed to cause a voltage drop at 0.2 s from 1.0 to 0.989 p.u. at the source (substation A). Here, the 0.989-p.u. voltage at substation A is the lowest voltage that the STATCOM system can support due to its capacity limit. The third simulation study in Subsection IV-D assumes a voltage drop from 1.0 to 0.991 under a changed load. The fourth simulation study in Subsection IV-E assumes a disturbance at 0.2 s, causing a voltage rise from 1.0 to 1.01 p.u. at substation A under a modified transmission network. In Subsection IV-F, a disturbance at 0.2 s causes a voltage decrease from 1.0 to 0.989 p.u. occurring at substation A. After that, line 1 is switched off at 0.25 s. In Subsection IV-G, a severe disturbance is assumed with a voltage sag of 60% of the rated voltage. When the fault clears, the voltage gets back to around 1.0 p.u. In all simulation studies, the STATCOM immediately operates after the disturbance with the expectation of bringing the voltage back to 1.0 p.u. The proposed control and the original PI control are studied and compared.

B. Response of the Original Model

Fig.5. Results of (a) voltages and (b) output reactive power using the same network and loads as in the original system.
C. Change of PI Control Gains

Fig. 6. Results of using the same network and loads as in the original system.

D. Change of Load

Fig. 7. Results of (a) voltages and (b) output reactive power with changed PI control gains.

E. Change of Transmission Network

In this case, the PI controller gains remain unchanged, as in the original model. However, line 1 is switched off at 0.2 s to represent a different network which may correspond to scheduled transmission maintenance. Here, we have

$$k_{\text{pu}}(t) = \frac{15\cdot3240\times \Delta V(t)}{(\Delta V(t) + 8\cdot3240 \times t^{1/2})^{2}}$$

(15)

Based on (39)–(42), the adaptive PI control model can be designed to automatically react to changes in the transmission network. There results are shown in Figs. 6 and 7. Key observations are summarized in Table III. Note that the STATCOM absorbs VAR from the system in this case. Here, the disturbance is assumed to give a voltage rise at (substation A) from 1.0 to 1.01 p.u.; meanwhile, the system has a transmission line removed which tends to lower the voltages. The overall impact leads to a voltage rise to higher than 1.0 at the controlled bus in the steady state if the STATCOM is not activated. Thus, the STATCOM needs to absorb VAR in the final steady state to reach 1.0 p.u. voltage at the controlled bus. Also note that the initial transients immediately after 0.2 s lead to an over absorption by the STATCOM, while the adaptive PI control gives a much smoother and quicker response, as shown in Fig. 7.

F. Two Consecutive Disturbances

In this case, a disturbance at 0.2 s causes a voltage decrease from 1.0 to 0.989 p.u. and it occurs at substation A. After that, line 1 is switched off at 0.25 s. The results are shown in Figs. 8 and 9. From Fig. 9, it is apparent that the adaptive PI control can achieve much quicker response than the original one, which makes the system voltage drop much less than the original control during the second disturbance. Note in Fig. 9(a) that the largest voltage drop during the second disturbance event (starting at 0.25 s) with the original control is 0.012 p.u., while it is 0.006 p.u. with the proposed adaptive control. Therefore, the system is more robust in responding to consecutive disturbances with adaptive PI control.

G. Severe Disturbance

In this case, a severe disturbance at 0.2 s causes a voltage decrease from 1.0 to 0.6 p.u. and it occurs at substation A. After that, the disturbance is cleared at 0.25 s. Due to the limit of STATCOM capacity, the voltage cannot get back to 1 p.u. after the severe voltage drop to 0.6 p.u. After the disturbance is cleared at 0.25 s, the voltage goes back to around 1.0 p.u. As shown in Fig. 12(a) and the two insets, the adaptive PI control can bring the voltage back to 1.0 p.u. much quicker and smoother than the original one. More important, the Q curve in the adaptive control (40 MVar) is much less than the Q in the original control (118 MVar).
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H. Summary of the Simulation Study

Fig. 10. Results of with a change of load.

Fig. 11. Results of (a) voltages and (b) output reactive power with a change of transmission network.

Fig. 12. Results of (a) voltages and (b) output reactive power with two consecutive disturbances.

V. CONCLUSION AND FUTURE WORK

This paper proposes a fuzzy control model based on adaptive PI control, which can self-adjust the control gains dynamically during disturbances so that the performance always matches a desired response, regardless of the change of operating condition. Since the adjustment is autonomous, this gives the “plug-and-play” capability for STATCOM operation. In the simulation study, the proposed adaptive PI control for STATCOM is compared with the conventional STATCOM control with pretuned fixed PI gains to verify the advantages of the proposed method. The results show that the adaptive PI control gives consistently excellent performance under various operating conditions, such as different initial control gains, different load levels, change of the transmission network, consecutive disturbances, and a severe disturbance. Future work may lie in the investigation of multiple STATCOMs since the interaction among different STATCOMs may affect each other. Also, the extension to other power system control problems can be explored.

VI. REFERENCES