

Adaptive PI Control of STATCOM for Voltage Regulation

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Abstract: STATCOM can give quick and productive responsive power backing to keep up power system voltage soundness. Previously, different STATCOM control systems have been talked about including numerous utilizations of relative fundamental (PI) controllers. On the other hand, these past works acquire the PI picks up through an experimentation approach or far reaching studies with a tradeoff of execution and relevance. Consequently, control parameters for the ideal execution at a given working point may not be powerful at an alternate working point. This paper proposes another control model taking into account versatile PI control, which can self-change the control additions amid an unsettling influence such that the execution dependably coordinates a fancied reaction, paying little respect to the change of working condition. Since the change is self-governing, this gives the attachment and-play capacity for STATCOM operation. In the reenactment test, the versatile PI control shows steady fabulousness under different working conditions, for example, distinctive introductory control increases, diverse burden levels, change of transmission system, continuous aggravations, and a serious aggravation. Interestingly, the routine STATCOM control with tuned, altered PI picks up for the most part perform fine in the first framework, yet may not execute as productive as the proposed control strategy when there is a change of framework conditions.

Keywords: Adaptive Control, Plug and Play, Proportional-Integral (PI) Control, Reactive Power Compensation, STATCOM, Voltage Stability.

1. INTRODUCTION

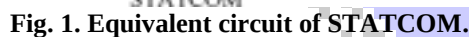
Voltage constancy is a decisive deliberation in improving the security and consistency of power systems. The static compensator (STATCOM), a well-liked device for reactive power control based on gate turnoff (GTO) thyristors, has gained much interest in the last decade for improving power system stability. In the past, a variety of control methods have been proposed for STATCOM control. References mainly focus on the organize 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 the PI controller gains are intended in a case-by-case study or trial-and-error approach with tradeoffs in performance and competence. Generally speaking, it is not possible 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.

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. In Our project, we concentrate on the near

investigation of the control systems or voltage source converter based STATCOM, comprehensively grouped into voltage control STATCOM and current control STATCOM. Under the previous, stage movement control is contrasted and the recent, considering backhanded decoupled current control and regulation of AC transport and DC join voltage with hysteresis current control. The initial two plans have been effectively executed for STATCOM control at the transmission level, for receptive force pay, and voltage bolster and are as of late being used to control a STATCOM utilized at the appropriation end. The accompanying lists are considered for examination – estimation and sign moulding necessity, execution with differing straight/nonlinear burden, absolute consonant bending (THD), DC join voltage variety and exchanging recurrence. The paper quickly portrays the notable highlights of every procedure, with their benefits and negative marks. The paper likewise underscores the decision of current control procedure, as it fundamentally influences the execution of a STATCOM.

A dynamic recreation model of the STATCOM has been produced for different control calculations in MATLAB/ SimPower System environment. Voltage strength is a discriminating thought in enhancing the security and unwavering quality of force frameworks. The static compensator (STATCOM), a famous gadget for receptive force control in light of door side road (GTO) thyristors, has increased much enthusiasm for the most recent decade for

The circumstance can be far and away more terrible if such transmission topology change is because of a possibility. Accordingly, the STATCOM control framework may not perform well when for the most part required. Not quite the same as these past works, the inspiration of this paper is to propose a control system that can guarantee a brisk and steady craved reaction when the framework operation condition differs. At the end of the day, the change of the outer condition won't have a negative effect, for example, slower reaction, overshoot, or even unsteadiness to the execution. Base on this essential inspiration, a versatile PI control of STATCOM for voltage regulation is displayed in this paper. With this versatile PI control strategy, the PI control parameters can act naturally balanced consequently and alterably under distinctive unsettling influences in a force framework.



adaptive PI control methods with the traditional PI control, and presents the simulation results. Finally, Section V concludes this paper.

A. System Configuration

B. STATCOM Dynamic Model

Fig. 2. Traditional STATCOM PI control block diagram.

$$\frac{d}{dt} \begin{bmatrix} i_{ds} \\ i_{qs} \\ V_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & \omega & \frac{K}{L_s} \cos \alpha \\ -\omega & -\frac{R_s}{L_s} & \frac{K}{L_s} \sin \alpha \\ -\frac{3K}{2C} \cos \alpha & -\frac{3K}{2C} \sin \alpha & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ V_{dc} \end{bmatrix} - \frac{1}{L_s} \begin{bmatrix} V_{df} \\ V_{qf} \\ 0 \end{bmatrix} \quad (1)$$

Where, I_{d1} and I_{q1} are the d and q currents corresponding to I_{a1} , I_{b1} and I_{c1} . K is a factor that relates the dc voltage to the peak phase-to-neutral voltage on the ac side; V_{d1} is the dc-side voltage; α is the phase angle at which the STATCOM output voltage leads the bus voltage; W is the synchronously rotating angle speed of the voltage vector; V_{d1} and V_{q1} represent the d and q axis voltage corresponding to V_{a1} , V_{b1} and V_{c1} . Since $V_{q1} = 0$, based on the instantaneous active and reactive power definition, and can be obtained as follows.

$$p_l = \frac{3}{2} V_{dl} i_{ds} \quad (2)$$

Based on the above equations, the traditional control strategy can be obtained, and the STATCOM control block diagram is shown in Fig. 2 [10], [11]. As shown in Fig2, the phase-locked loop (PLL) provides the basic synchronizing signal which is the reference angle to the measurement system. Measured bus line voltage V_{bus} is compared with the

reference voltage V_{ref} , and the voltage regulator provides the required reactive reference current I_{qref} . The droop factor K_d is defined as the allowable voltage error at the rated reactive current flow through the STATCOM. The STATCOM reactive current I_q is compared with I_{qref} , and the output of the current regulator is the angle phase shift of the inverter voltage with regard to the system voltage. The limiter is the limit imposed on the value of control while considering the maximum reactive power capability of the STATCOM.

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. With this adaptive PI control method, the dynamical self adjustment of PI control parameters can be realized. An adaptive PI control block for STATCOM is shown in Fig. 3. In Fig. 3, the measured voltage $V_m(t)$ and the reference voltage $V_{ref}(t)$, and the q -axis reference current I_{qref} and the q -axis current

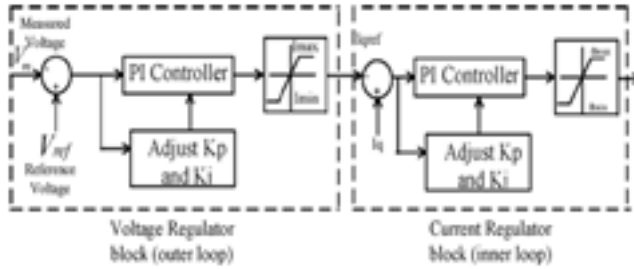


Fig.3. Adaptive PI control block for STATCOM.

The proportional and integral parts of the voltage regulator gains are denoted by K_{p-v} and K_{i-v} respectively. Similarly, the gains K_{p-i} and K_{i-i} represent the proportional and integral parts, respectively, of the current regulator. In this control system, the allowable voltage error K_d is set to 0. The K_{p-v} , K_{i-v} , K_{p-i} and K_{i-i} can be set to an arbitrary initial value such as simply 1.0. One exemplary desired curve is an exponential curve in terms of the voltage growth, shown in Fig. 4, which is set as the reference voltage in the outer loop. Other curves may also be used than the depicted exponential curve as long as the measured voltage returns to the desired steady-state voltage in desired time duration.

The process of the adaptive voltage-control method for STATCOM is described as follows.

1. The bus voltage $V_m(t)$ is measured in real time.
2. When the measured bus voltage over time $V_m(t) \neq V_{ss}$, the target steady-state voltage, which is set to 1.0 per unit (p.u.) in the discussion and examples, $V_m(t)$ is compared with V_{ss} . Based on the desired reference voltage curve, K_{p-v} and K_{i-v} are dynamically adjusted in order to make the measured voltage match the desired

reference voltage, and the q -axis reference current I_{qref} can be obtained.

3. In the inner loop, I_{qref} is compared with the q -axis current I_q . Using the similar control method like the one for the outer loop, the parameters K_{p-i} and K_{i-i} can be adjusted based on the error. 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.

It should be noted that the current I_{max} and I_{min} and the angle α_{max} and α_{min} are the limits imposed with the consideration of the maximum reactive power generation capability of the STATCOM controlled in this manner. If one of the maximum or minimum limits is reached, the maximum capability of the STATCOM to inject reactive power has been reached. Certainly, as long as the STATCOM sizing has been appropriately studied during planning stages for inserting the STATCOM into the power system, the STATCOM should not reach its limit unexpectedly.

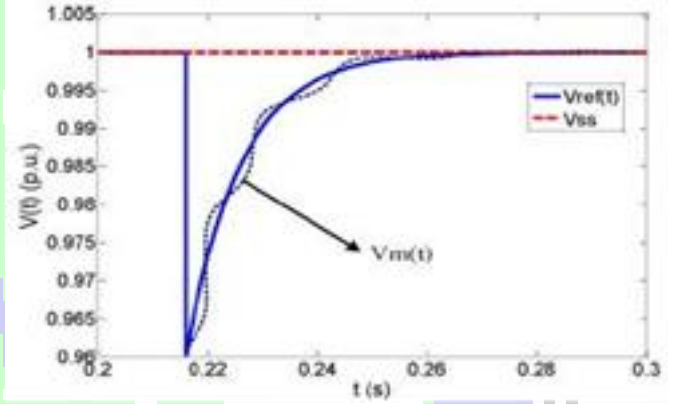


Fig. 4. Reference voltage curve.

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, $V_{d1}(t)$ and $V_{q1}(t)$ can be computed with $d-q$ the $d-q$ -transformation

$$\begin{bmatrix} V_{d1}(t) \\ V_{q1}(t) \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} V_{a1}(t) \\ V_{b1}(t) \\ V_{c1}(t) \end{bmatrix} \quad (4)$$

Then, we have

$$V_m(t) = \sqrt{V_{d1}^2(t) + V_{q1}^2(t)}. \quad (5)$$

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

$$V_{ref}(t) = V_{ss} - (V_{ss} - V_m(t))e^{-\frac{t}{\tau}} \quad (6)$$

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; $\tau=0.01$ s. The curve in Fig. 4 is one examples 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 meeting the reference voltage. However, once there is a voltage disturbance in the power system, based on $V_{ref}(t) = V_m - (V_m - V_m(t))e^{-(t)/(T_s)}$, 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:

$$\Delta V(t)K_{p-V}(t) + K_{i-V}(t) \int_t^{t+T_s} \Delta V(t)dt = I_{qref}(t + T_s) \quad (7)$$

Where, T_s is the sample time, which is set to s here as an example. 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 t is

$$y(t) = y(t - T_s) + K_{i-V}(t - T_s) \times T_s \times \Delta V(t - T_s) \quad (8)$$

Where, $y(t) = K_{i-V}(t) \int_t^{t+T_s} \Delta V(t)dt$; $y(t - T_s) = K_{i-V}(t - T_s) \int_{t-T_s}^t \Delta V(t - T_s)dt$.

Considering $y(t - T_s) = I_{qref}(t)$, we can rewrite (11) as follows:

$$\begin{aligned} \Delta V(t)K_{p-V}(t) + K_{i-V}(t) \int_t^{t+T_s} \Delta V(t)dt \\ - K_{i-V}(t - T_s) \int_{t-T_s}^t \Delta V(t - T_s)dt \\ = I_{qref}(t + T_s) - I_{qref}(t). \end{aligned} \quad (9)$$

Over a very short time duration, we can consider $K_{i-V}(t) = K_{i-V}(t - T_s)$. Hence, (13) can be rewritten as

$$\Delta V(t)K_{p-V}(t) + K_{i-V}(t) \int_t^{t+T_s} \Delta V(t)dt = I_{qref}(t + T_s) - I_{qref}(t) \quad (10)$$

where $\Delta V(t) = V(t) - V_m(t)$. Based on (12), if we can determine in ideal response the ratio $(I_{qref}(t + T_s) - I_{qref}(t))/(\Delta V(t))$ and the ideal ratio $K_{i-V}(t)/K_{p-V}(t)$, the desired $K_{p-V}(t)$ and $K_{i-V}(t)$ can be solved. Assume at the ideal response, we have

$$I_{qref}(t + T_s) - I_{qref}(t) = R \times \Delta V(t) \quad (11)$$

Since the system is expected to be stable, without losing generality, we may assume that the bus voltage will come back to 1 p.u. in 5τ , where 5τ is the delay defined by users as shown in Fig. 4. Since $I_{qref}(t_0) = 0$ based on (15), (11) can be rewritten as

$$\Delta V(t_0)K_{p-V}(t_0) + K_{i-V}(t_0) \int_{t_0}^{t_0+5\tau} \Delta V(t)dt = R \times \Delta V(t_0) \quad (12)$$

Where, t_0 is the time that the system disturbance occurs. Setting $K_{i-V}(t_0) = 0$, we then have

$$K_{p-V}(t_0) = R. \quad (13)$$

Setting $K_{p-V}(t_0) = 0$, we then have

$$K_{i-V}(t_0) = \frac{\Delta V(t_0) \times R}{\int_{t_0}^{t_0+5\tau} \Delta V(t)dt}. \quad (14)$$

Now, the ratio $m_V = (K_{i-V}(t_0))/(K_{p-V}(t_0))$ can be considered as the ideal ratio of the values of and after fault. Thus, (15) can be rewritten as

$$I_{qref}(t + 5\tau) - I_{qref}(t) = k_V \times \Delta V(t_0) \quad (15)$$

Here, k_V can be considered as the steady and ideal ratio $(I_{qref}(t + T_s) - I_{qref}(t))/(\Delta V(t))$. Based on the system bus capacity and the STATCOM rating, ΔI_{max} can be obtained, which means any voltage change greater than ΔI_{max} cannot come back to 1 p.u. Since we have $-1 \leq I_{qref}(t) \leq 1$, we have the following equation:

$$\begin{aligned} \frac{\Delta V(t_0)}{\Delta V_{max}} = k_V \\ \times \frac{\Delta V(t_0)K_{p-V}(t_0) + K_{i-V}(t_0) \int_{t_0}^{t_0+5\tau} \Delta V(t)dt}{R} \end{aligned} \quad (16)$$

Based on (16), (19), and (20), k_V can be calculated by (21), shown at the bottom of the page. In order to exactly calculate the PI controller gains based on (14), we can derive

$$k_V = \frac{R \times \Delta V(t_0)}{K_{p-V}(t_0)\Delta V(t_0) + K_{i-V}(t_0) \int_{t_0}^{t_0+5\tau} \Delta V(t)dt} \times \Delta V_{max} \quad (17)$$

$$\Delta V(t)K_{p-V}(t) + m_V K_{p-V}(t) \int_t^{t+T_s} \Delta V(t)dt = k_V \times \Delta V(t) \quad (18)$$

Therefore, $K_{p-V}(t)$ and $K_{i-V}(t)$ can be computed by the following equations:

$$K_{p-V}(t) = \frac{k_V \times \Delta V(t)}{(\Delta V(t) + m_V \times \int_t^{t+T_s} \Delta V(t)dt)} \quad (19)$$

$$K_{i-V}(t) = m_V \times K_{p-V}(t) \quad (20)$$

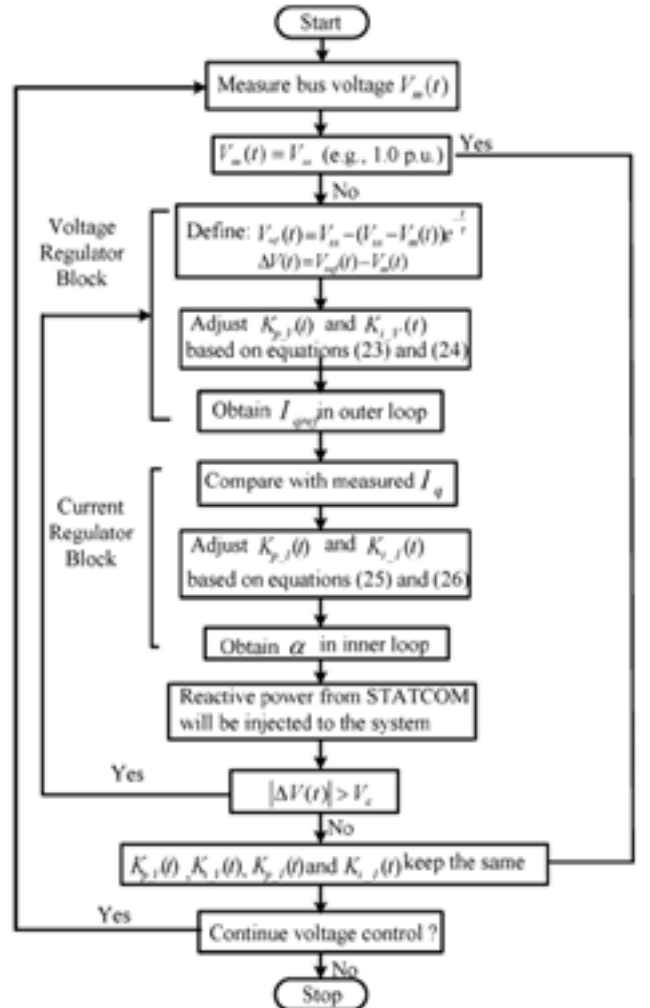


Fig. 5. Adaptive PI control algorithm flowchart.

Therefore, based on (23) and (24), $K_{p-v}(t)$ and $K_{i-v}(t)$ can be adjusted dynamically. Using a similar process, the following expressions for current regulator PI gains can be obtained:

$$K_{p-i}(t) = \frac{k_I \times \Delta I_q(t)}{(\Delta I_q(t) + m_I \times \int_t^{t+T_s} B dt)} \quad (21)$$

$$K_{i-i}(t) = m_I \times K_{p-i}(t) \quad (22)$$

Where, $\Delta I_q(t)$ is the error between I_{qref} and I_q , k_I is the steady and ideal ratio $(\alpha(t+T_s) - \alpha(t)) / (\Delta I_q(t))$, and $\alpha(t)$ is the angle of the phase shift of the inverter voltage with respect to the system voltage at time t ; m_I is the ideal ratio of the values of $K_{i-i}(t)$ and $K_{p-i}(t)$ after fault; and B is equal to $\Delta I_q(t) - \Delta I_q(t - T_s)$. Note that the derivation from (21) is fully reversible so that it ensures that the measured voltage curve can follow the desired ideal response, as defined in (10).

C. Flowcharts of the Adaptive PI Control Procedure

Fig. 5 is an exemplary flowchart of the proposed adaptive PI control for STATCOM for the block diagram of Fig. 3. The adaptive PI control process begins at Start. The bus voltage $V_m(t)$ over time is sampled according to a desired sampling rate. Then, $V_m(t)$ is compared with V_{ref} . If $V_m(t) = V_{ref}$, then there is no reason to change any of the identified parameters $K_{p-v}(t)$, $K_{i-v}(t)$, $K_{i-i}(t)$ and $K_{p-i}(t)$. The power system is running smoothly. On the other hand, if $V_m(t) \neq V_{ref}$, then adaptive PI control begins.

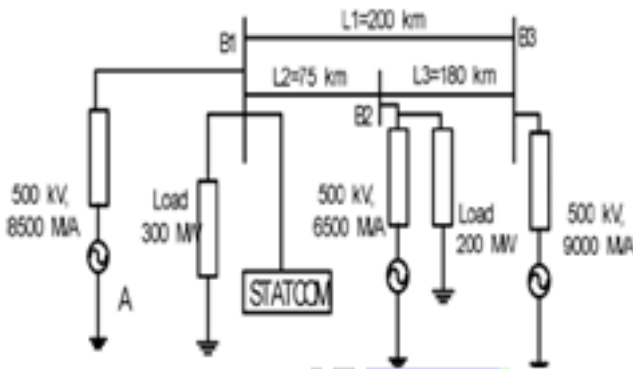


Fig. 6. Studied system.

The measured voltage is compared with $V_{ref}(t)$, the reference voltage defined in (10). Then, K_{p-v} and K_{i-v} are adjusted in the voltage regulator block (outer loop) based on (23) and (24), which leads to an updated I_{ref} via a current limiter as shown in Fig. 3. Then, the I_{ref} is compared with the measured q-current I_q . The control gains are adjusted based on (25) and (26). Then, the phase angle is determined and passed through a limiter for output, which essentially decides the reactive power output from the STATCOM. Next, if $|\Delta V(t)|$ is not within a tolerance threshold V_{ϵ} , which is a very small value such as 0.0001 p.u., the voltage regulator block and current regulator blocks are re-entered until the change is less than the given threshold V_{ϵ} . Thus, the values for $K_{p-v}(t)$, $K_{i-v}(t)$, $K_{i-i}(t)$ and $K_{p-i}(t)$ are maintained. If there is the need to continuously perform the voltage-

control process, which is usually the case, then the process returns to the measured bus voltage. Otherwise, the voltage-control process stops (i.e., the STATCOM control is deactivated).

IV. SIMULATION RESULTS

A. System Data

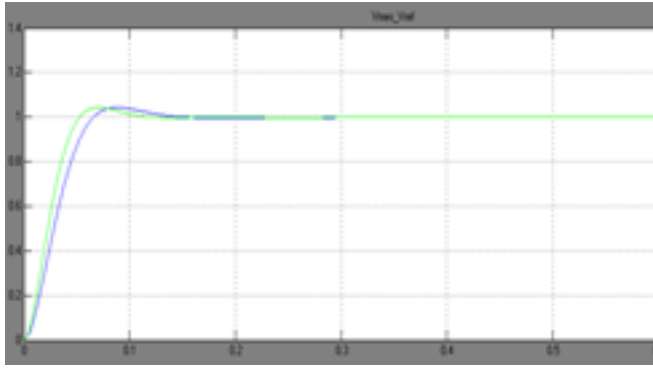
In the system simulation diagram shown in Fig. 6, a 100-MVAR STATCOM is implemented with a 48-pulse VSC and connected to a 500-kV bus. This is the standard sample STATCOM system in Matlab/Simulink library, and all machines used in the simulation are dynamical models [10]–[12]. Here, the attention is 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, $V_{ref}=1.0$ 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

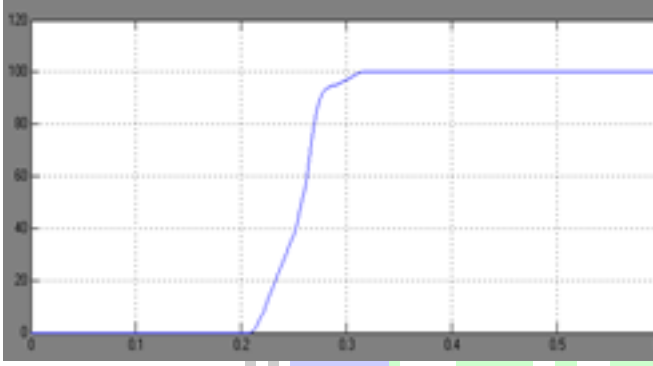
In the original model, $K_{p-v}=12$, $K_{i-v}=3000$, $K_{p-i}=5$ and $K_{i-i}=40$. Here, we keep all of the parameters unchanged. The initial voltage source, shown in Fig. 6, is 1 p.u., with the voltage base being 500 kV. In this case, if we set $R=1$, then we have the initial m_I calculated as $m_I=770.8780$. Since, in this case, $\Delta V(t_0) = \Delta V_{max}$ and $K_I=84.7425$, based on (23)–(26), we have

$$K_{p-v}(t) = \frac{84.7425 \times \Delta V(t)}{(\Delta V(t) + 770.8780 \times \int_t^{t+T_s} A dt)} \quad (23)$$

Based on the adaptive PI control system can be designed, and the results are shown in Figs. 7 and 8, respectively. Observations are summarized in Table I. From the results, it is obvious that the adaptive PI control can achieve quicker response than the original one. The necessary reactive power amount is the same while the adaptive PI approach runs faster, as the voltage does. Set $\omega t = \alpha + \theta$, where α is the output angle of the current regulator, and θ is the reference angle to the measurement system.



(a)



(b)

Fig.7. Results of (a) voltages and (b) output reactive power using the same network and loads as in the original system.

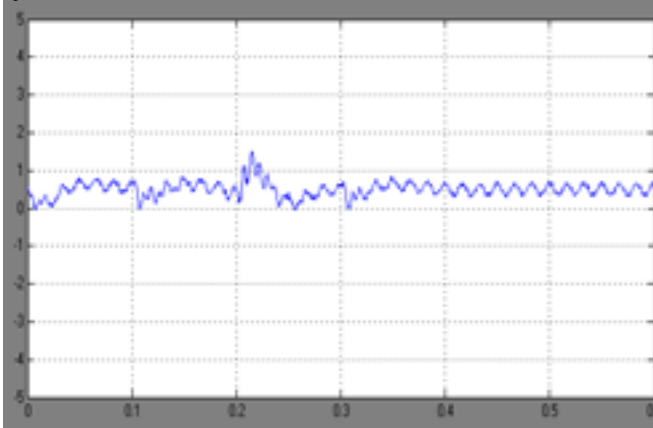


Fig. 8. Results of using the same network and loads as in the original system.

Table I: Performance Comparison for the Original System Parameters

	Original Ctrl.	Adaptive Ctrl.
Lowest Voltage after disturbance	0.9938 p.u.	0.9938 p.u.
Time (sec) when V=1.0	0.4095 sec	0.2983 sec
Δt to reach V=1.0	0.2095 sec	0.0983 sec
Var Amount at steady state	97.76 MVar	97.65 MVar
Time to reach steady state Var	0.4095 sec	0.2983 sec

In the STATCOM, it is ωt that decides the control signal. Since θ is a very large value (varying between 0 to 2π), the ripples of α in the scale shown in Fig. 8 will not affect the final simulation results. Note that there is a very slight difference of 0.12 MVar in the var amount at steady state in

Table I, which should be caused by computational roundoff error. The reason is that the sensitivity of $d\text{Var}/dV$ is around 100 MVar/0.011 p.u. of voltage. For simplicity, we may assume that $\Delta\text{Var}/\Delta V$ sensitivity is a linear function. Thus, when the voltage error is 0.00001 p.u., ΔVar is 0.0909MVar, which is in the same range as the 0.12-MVar mismatch. Thus, it is reasonable to conclude that the slight Var difference in Table I is due to roundoff error in the dynamic simulation which always gives tiny ripples beyond 5th digits even in the final steady state.

C. Change of PI Control Gains

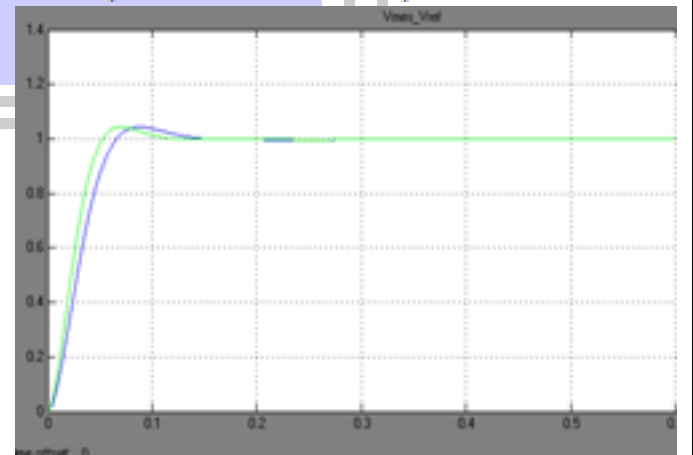
In this scenario, the other system parameters remain unchanged while the PI controller gains for the original control are changed to $K_{p-V}=1$, $K_{i-V}=1$, $K_{p-I}=1$ and $K_{i-I}=1$. The dynamic control gains, which are independent of the initial values before the disturbance but depend on the post fault conditions, are given as

$$\begin{aligned}
 K_{p-V}(t) &= \frac{80.1632 \times \Delta V(t)}{(\Delta V(t) + 732.3115 \times \int_t^{t+T_s} A dt)} \\
 K_{i-V}(t) &= 732.3115 \times K_{p-V}(t) \\
 K_{p-I}(t) &= \frac{47.4959 \times \Delta I_q(t)}{(\Delta I_q(t) + 1.8232 \times \int_t^{t+T_s} B dt)} \\
 K_{i-I}(t) &= 1.8232 \times K_{p-I}(t)
 \end{aligned} \quad (24)$$

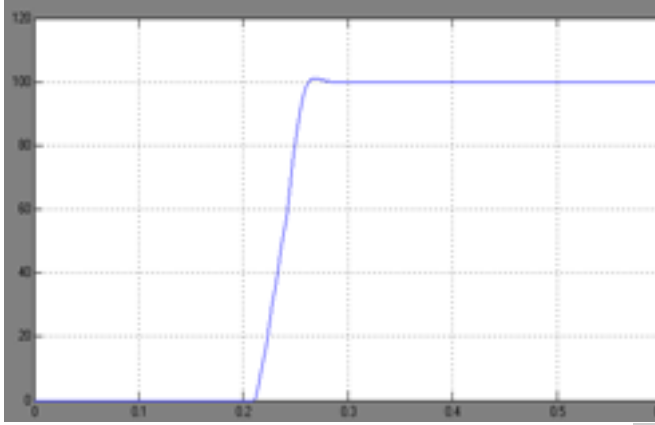
Based on, the adaptive PI control model can be designed, and the results are shown in Figs. 9 and 10, respectively. From Fig. 9(a), it can be observed that when the PI control gains are changed to different values, the original control model cannot make the bus voltage get back to 1 p.u., and the STATCOM has poor response. The reactive power cannot be increased to a level to meet the need. However, with adaptive PI control, the STATCOM can respond to disturbance perfectly as desired, and the voltage can get back to 1 p.u. quickly within 0.1 s. Fig. 9(b) also shows that the reactive power injection cannot be continuously increased in the original control to support voltage, while the adaptive PI control performs as desired.

D. Change of Load

In this case, the original PI controller gains are kept, which means $K_{p-V}=12$, $K_{i-V}=3000$, $K_{p-I}=5$ and $K_{i-I}=40$.

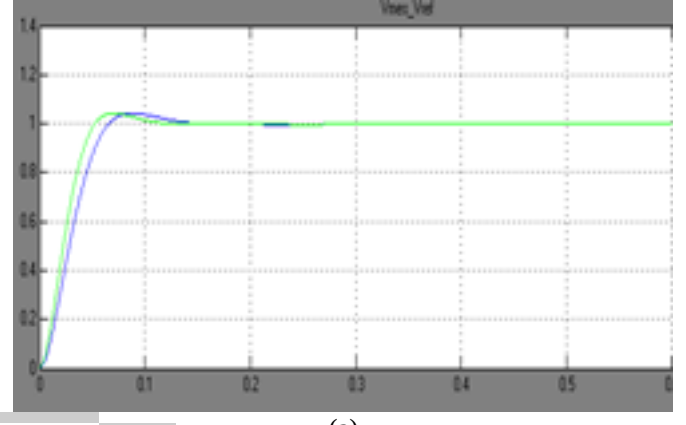


(a)



(b)

Fig. 9. Results of (a) voltages and (b) output reactive power with changed PI control gains.



(a)

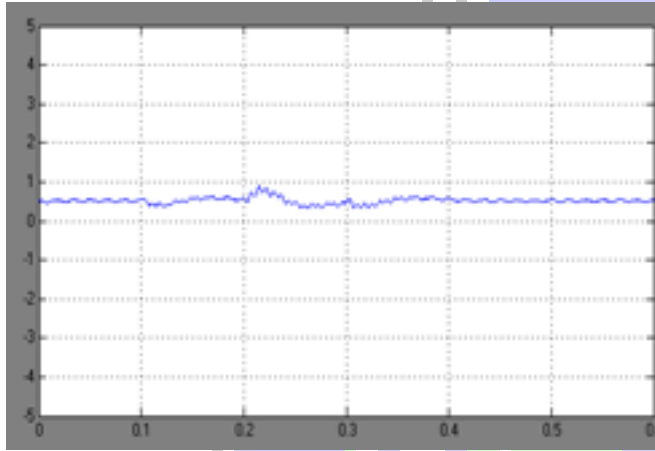


Fig.10. Results of with changed PI control gains.

However, the load at Bus B1 changes from 300 to 400 MW. In this case, we have the given dynamic control gains by

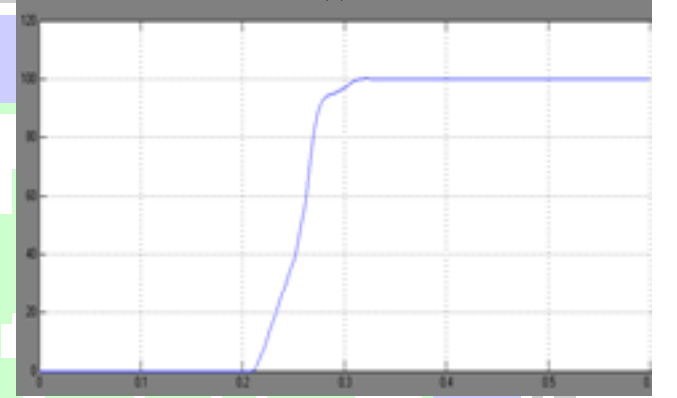
$$\begin{aligned} K_{p-V}(t) &= \frac{93.3890 \times \Delta V(t)}{\left(\Delta V(t) + 187.5579 \times \int_t^{t+T_s} \Delta dt \right)} \\ K_{i-V}(t) &= 187.5579 \times K_{p-V}(t) \\ K_{p-I}(t) &= \frac{8.1731 \times \Delta I_q(t)}{\left(\Delta I_q(t) + 13.1652 \times \int_t^{t+T_s} \Delta dt \right)} \\ K_{i-I}(t) &= 13.1652 \times K_{p-I}(t) \end{aligned} \quad (25)$$

Based on (35)–(38), the adaptive PI control model can be designed for automatic reaction to a change in loads. The results are shown in Figs. 11 and 12. Table II shows a few key observations of the performance. From the data shown in Table II and Fig. 11, it is obvious that the adaptive PI control can achieve a quicker response than the original one.

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

$$K_{p-V}(t) = \frac{18.3245 \times \Delta V(t)}{\left(\Delta V(t) + 286.9512 \times \int_t^{t+T_s} \Delta dt \right)} \quad (26)$$



(b)

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

$$K_{i-V}(t) = 286.9512 \times K_{p-V}(t)$$

$$K_{p-I}(t) = \frac{41.4360 \times \Delta I_q(t)}{\left(\Delta I_q(t) + 412.0153 \times \int_t^{t+T_s} \Delta dt \right)}$$

$$K_{i-I}(t) = 412.0153 \times K_{p-I}(t) \quad (27)$$

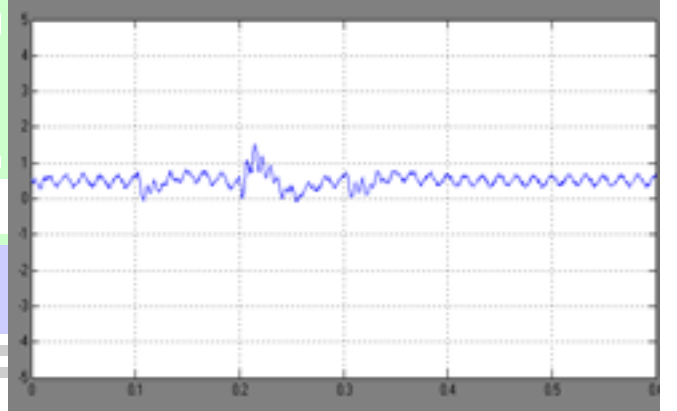
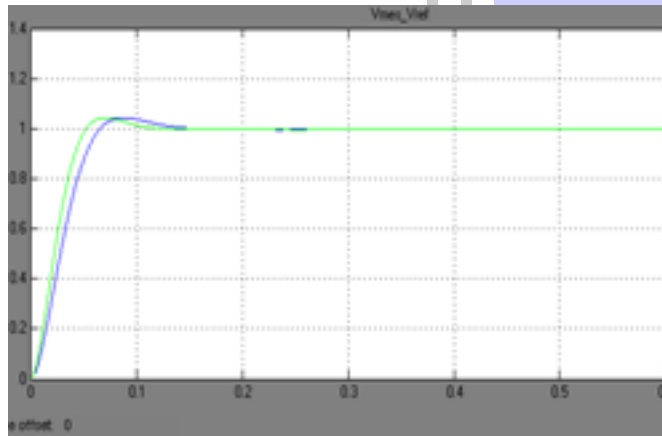


Fig. 12. Results of with a change of load.

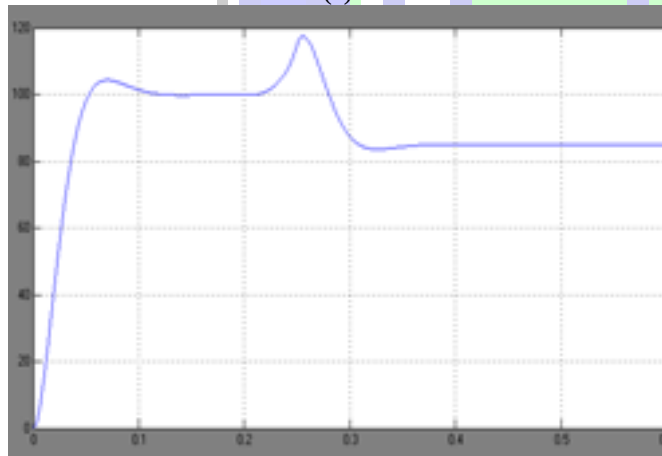
TableII: Performance Comparison with Change of Load

	Original Ctrl.	Adaptive Ctrl.
Lowest Voltage after disturbance	0.9949 p.u.	0.9949 p.u.
Time (sec) when V=1.0	0.4338 sec	0.3125 sec
Δt to reach V=1.0	0.2338 sec	0.1125 sec
Var Amount at steady state	93.08 MVar	92.72 MVar
Time to reach steady state VAr	0.4338 sec	0.3125 sec

Based on (39)–(42), the adaptive PI control model can be designed to automatically react to changes in the transmission network. The results are shown in Figs. 13 and 14. 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. 13.



(a)



(b)

Fig. 13. Results of (a) voltages and (b) output reactive power with a change of transmission network.

Table III: Performance Comparison with Changed Transmission

	Original Ctrl.	Adaptive Ctrl.
Lowest Voltage after disturbance	0.9954 p.u.	0.9954 p.u.
Time (sec) when $V=1.0$	0.4248 sec	0.2744 sec
Δt to reach $V=1.0$	0.2248 sec	0.0744 sec
Var Amount at steady state	-84.92 MVar	-85.02 MVar
Time to reach steady state Var	0.4248 sec	0.2744 sec

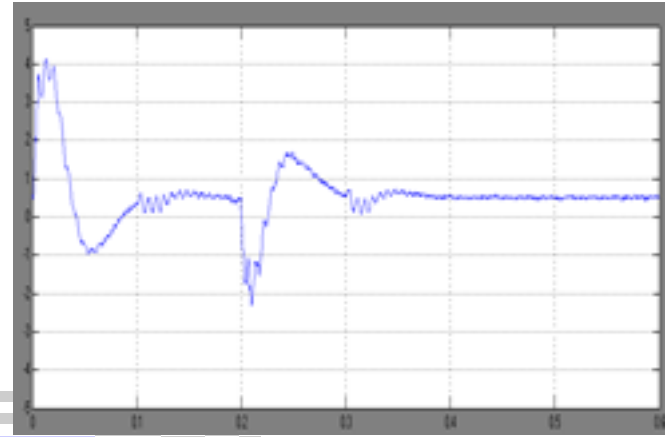
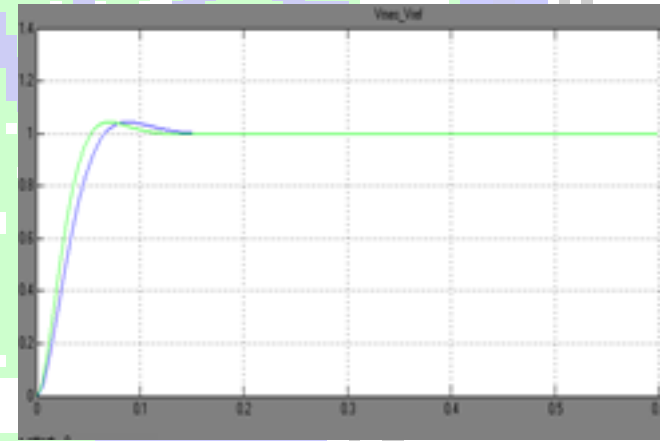


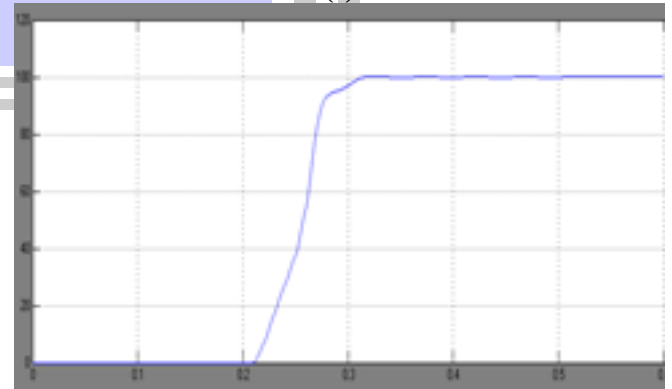
Fig. 14. Results of with a change of transmission network.

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. 15 and 16. From Fig. 15, 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. 15(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.



(a)



(b)

Fig. 15. Results of (a) voltages and (b) output reactive power with two consecutive disturbances.

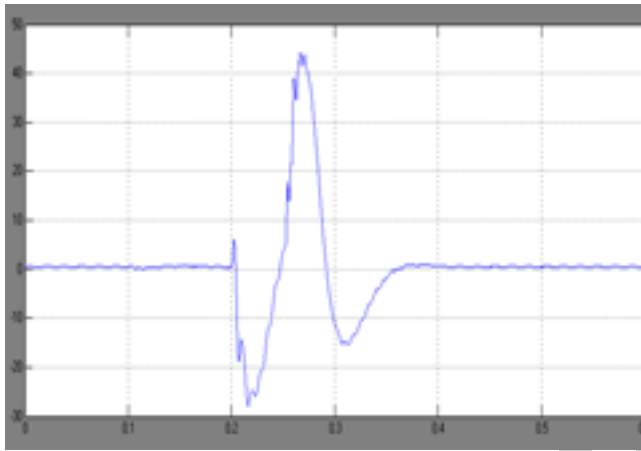


Fig. 16. Results of with two consecutive disturbances.

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. The results are shown in Figs. 17 and 18. 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. 17(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 ($Q_{max} = 40$ MVar) is much less than the Q in the original control ($Q_{max} = 118$ MVar). adaptive PI control are almost identical under various conditions, such as a change of (initial) control gains, a change of load, a change of network topology, consecutive disturbances, and a severe disturbance. In contrast, the response curve of the original control model varies greatly under a change of system operating condition and worse, may not correct the voltage to the expected value. The advantage of the proposed adaptive PI control approach is expected because the control gains are dynamically and autonomously adjusted during the voltage correction process; therefore, the desired performance can be achieved.

V. CONCLUSION AND FUTURE WORK

In the literature, various STATCOM control methods have been discussed including many applications of PI controllers. However, these previous works obtain the PI gains via a trial-and-error approach or extensive studies with a tradeoff of performance and applicability. Hence, control parameters for the optimal performance at a given operating point may not always be effective at a different operating point. To address the challenge, this paper proposes a new 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. In contrast, the conventional STATCOM control with fixed PI gains has acceptable performance in the original system, but may not perform as efficient as the proposed control method when there is a change of system conditions. 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.

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