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Adaptively Controlling STATCOM's PI Controller for Electrical Power System Voltage Regulation

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Abstract— STATCOM is a very fast and efficient device that can provide reactive power support to maintain power system voltage stability. In past, various STATCOM control methods have been proposed. They include many applications of proportional-integral (PI) controllers. However, the methods in the past obtain the PI control gains via an approach called trial-and-error. Due to such approach, we need make compromise in performance. This results in the control parameters being not be effective at different operating point for an optimal performance. The approach of adaptive PI control is presented here which adapts the control gains during a disturbance in such a way that performance always matches a desired response, regardless of the change of operating condition. Since the adjustment is autonomous, STATCOM gets a plug-and-play capability for its 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 nutshell, conventional STATCOM control performs fine in the original system, but may not perform as efficient as the proposed control method when there is a change of system operating conditions.

Index Terms **-** Adaptive control, plug and play, (PI) control, reactive power compensation, STATCOM, voltage stability.

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I. INTRODUCTION

Electrical energy plays an indispensable role for the development of the society. With the ever-growing industrial broadening of nation, there is always has been a great emphasis on an increased consumption of electrical energy. Owing to this, transmission systems are being pushed closer to their stability and thermal limits and the focus on quality of power being delivered is greater than ever. However, transmission systems have been plagued from the likes of various disturbances such as different load levels, change of transmission network, consecutive disturbances, and severe disturbances which add instability to the transmission network. Hence maintaining power system voltage stability is of prime concern for better power delivery.

To improve the stability and reliability of electrical power systems voltage stability is of prime concern.[1], [2] Reactive power compensation helps in enhancing the performance of AC systems [4]. So, to control reactive power flow to and from the power system a popular device named STATCOM from FACTS family of devices has gained lot of interest in last decade. It is based on gate turn off (GTO) thyristors for ratings higher than 100Mvar and for ratings up to 10Mvar it utilizes IGBT or IGCT [5]. STATCOM regulates voltage at its terminals by either absorbing the reactive power from system or injecting it into the system with harmonic reduction. Lot of control methods have been proposed in past for STATCOM control but since these methods obtain the control gains via an approach called trial and error leading to compromise in the performance and efficiency [3], [4]. Practically speaking it is not feasible for utility engineers to perform trial and error studies in order to find parameters that are suitable when a new STATCOM is connected in the system. Also, if the controls gains are tuned to fit current scenario, the performance may be disappointing when a considerable amount of system conditions vary, such as when a line is upgraded or retires from the service. [6] 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.

So, to avoid time consuming tuning and achieve highly efficient results we need a such a method that can offer quick and consistent response when there is a change of operating conditions rather change of the outside parameters won't have a negative impact like slower response, peak overshoot and instability to the performance. 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 STATCOM a "plug-and-play" device

MATLAB's Simulink has been utilized to analyze a model that is adaptive in nature using proportional integral controller of STATCOM for electric power system voltage regulation.

II. MODEL OF STATCOM AND CONTROL

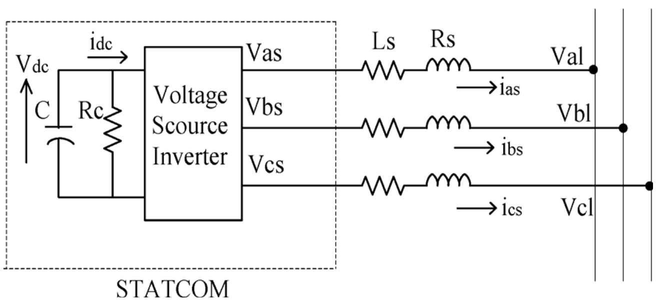

Fig.1. Equivalent circuit of STATCOM

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A. System configuration

The equivalent circuit of the STATCOM is shown in Fig. 1. In this power system, the resistance Rs in series with the voltage source inverter represents the sum of the transformer winding resistance losses and the inverter conduction losses. The inductance Ls represents the leakage inductance of the transformer. The resistance Rc 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, Vas, Vbs and Vcs are the three-phase STATCOM output voltages; and Val, Vbl and Vcl are the three phase bus voltages; and ias, ibs and ics are the three-phase STATCOM output currents [7], [8].

B. STATCOM dynamic model

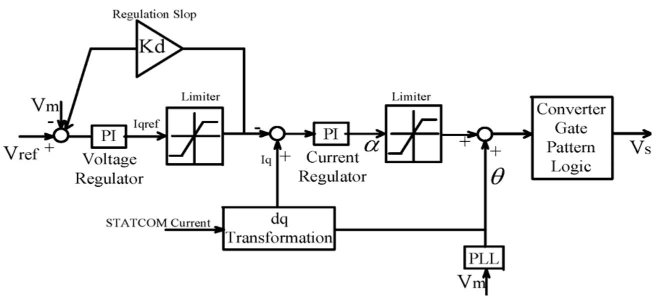

Fig. 2. Traditional STATCOM PI control block diagram.

The three-phase mathematical expressions of STATCOM can be written in the following form:

$$L_s \frac{di_{as}}{dt} = -R_s i_{as} + V_{as} - V_{al} \tag{1}$$

$$L_s \frac{di_{bs}}{dt} = -R_s i_{bs} + V_{bs} - V_{bl} \tag{2}$$

$$L_s \frac{di_{cs}}{dt} = -R_s i_{cs} + V_{cs} - V_{cl} \tag{3}$$

$$\frac{d}{dt}\left(\frac{1}{2} C V_{dc}^2(t)\right) = -[V_{as} i_{as} + V_{bs} i_{bs} + V_{cs} i_{cs}] - \frac{V_{dc}^2(t)}{R_c}. \tag{4}$$

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

$$\frac{d}{dt}\begin{bmatrix} i_{ds} \\ i_{qs} \\ V_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & \omega & \frac{K}{L_s}\cos\alpha \\ -\omega & -\frac{R_s}{L_s} & \frac{K}{L_s}\sin\alpha \\ -\frac{3K}{2C}\cos\alpha & -\frac{3K}{2C}\sin\alpha & -\frac{1}{R_c C} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ V_{dc} \end{bmatrix} - \frac{1}{L_s}\begin{bmatrix} V_{dl} \\ V_{ql} \\ 0 \end{bmatrix} \tag{5}$$

Where i_{ds} and i_{qs} are the d and q currents corresponding to i_{as}, i_{bs}, and i_{cs} and K is a factor that relates the dc voltage to the peak phase-to-neutral voltage on the ac side; V_{dc} is the dc-side voltage; α is the phase angle at which the STATCOM output voltage leads the bus voltage; ω is the synchronously rotating angle speed of the voltage vector; and V_{dl} and V_{ql} represent the d and q axis voltage corresponding to V_{al}, V_{bl}, and V_{cl}. Based on the above equations, the traditional control strategy can be obtained, and the STATCOM control block diagram is shown in Fig. 2.

III. ADAPTIVE PI CONTROL FOR STATCOM

A. Concept of the Proposed Adaptive PI Control Method

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, $V_m(t) \neq V_{ss}$ target steady-state voltage, which is set to 1.0 per unit (p.u.) in discussion and examples, is compared with V_{ss}. Based on desired reference voltage curve, k_{p_v} and k_{i_v} are dynamically adjusted to make measured voltage match the desired reference voltage, and the q-axis reference current 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 and Imax and I_{min} 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, if 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.

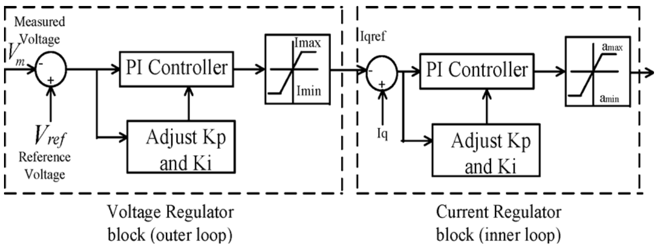

Fig. 3 Adaptive PI control block for STATCOM

B. Key Equations

$$V_m(t) = \sqrt{V_{dl}^2(t) + V_{ql}^2(t)}.$$

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

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

Based on the adaptive voltage-control model,

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

Where T_s is the sample time

$$K_{p\_V}(t) = \frac{k_V \times \Delta V(t)}{\left(\Delta V(t) + m_V \times \int_t^{t+T_s} A dt\right)}$$
$$K_{i\_V}(t) = m_V \times K_{p\_V}(t).$$

$$K_{p\_I}(t) = \frac{k_I \times \Delta I_q(t)}{\left(\Delta I_q(t) + m_I \times \int_t^{t+T_s} B dt\right)}$$
$$K_{i\_I}(t) = m_I \times K_{p\_I}(t)$$

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

C. Studied System

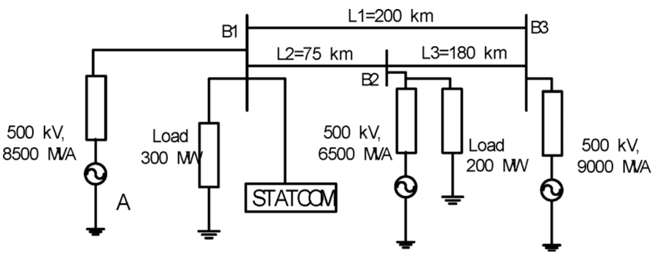


Fig. 4. Studied system

D. MATLAB Simulink Model

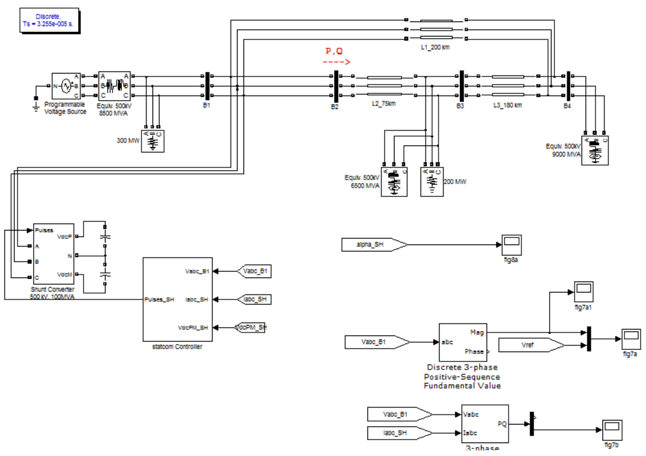


Fig. 5. Simulink model of STATCOM using an adaptive PI control

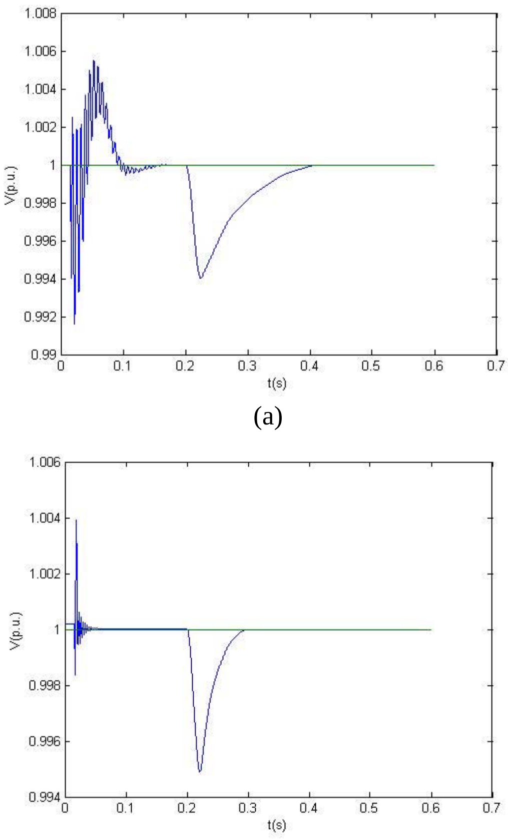
IV. SIMULATION RESULTS FOR DIFFERENT CASES

A. System Data

In the system simulation diagram, a 100-MVAR STATCOM is implemented with a 48-pulse VSC and connected to a 500- kV bus. 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.

B. Response of the Original Model

Steady state voltage assumed is V_{ss} = 1.0 p.u. 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) which is the lowest voltage that the STATCOM system can support due to its capacity limit. In the original model, K_{p_V} =12, K_{i_V} = 3000, K_{p_I} = 5, K_{i_I} = 40. Here, we keep all of the parameters unchanged. The initial voltage source 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_V calculated as m_V =770.8780. Since, in this case, Δ V(t_0) = ΔV_{max} and k_V =84.7425. From this, we have dynamic control gains as K_{p_V} (t) , K_{i_V} (t) , K_{p_I} (t) , K_{i_I} (t) from the key equations.



(a)

(b)

Fig. 6. Results of voltages (a) Original Control (b) Adaptive Control using the same network and loads as in the original system.

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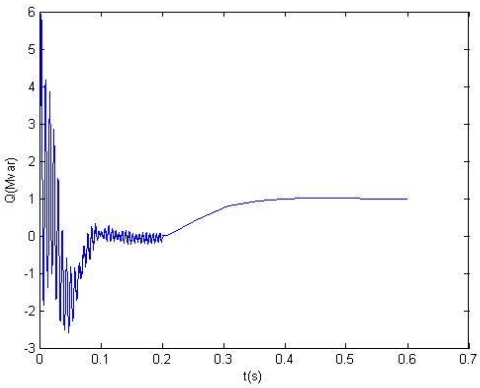

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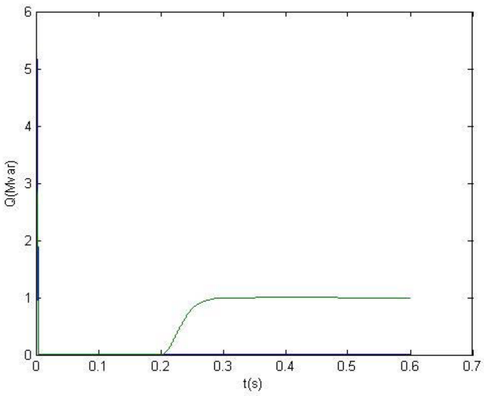

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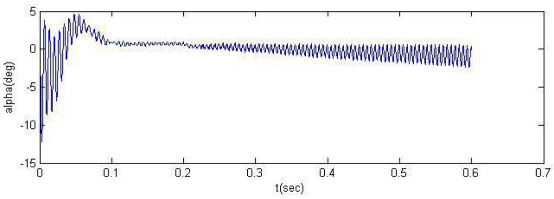
Fig. 7. Results of Output reactive power (a) Original Control (b) Adaptive Control using the same network and loads as in original system



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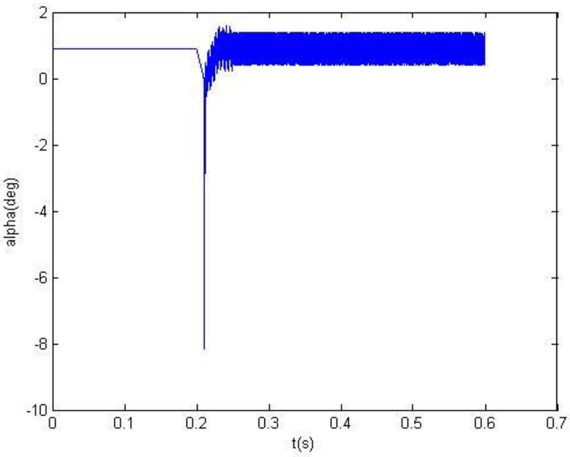


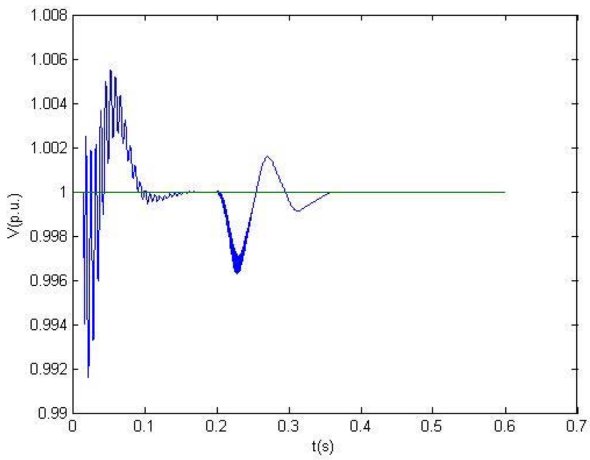
(b)

Fig. 8. Results of α (a) Original Control (b) Adaptive Control using the same network and loads as in the original system

From the results, it is observed that the adaptive PI control can achieve quicker response than the original one. The necessary reactive power amount is nearly same. There is a very slight difference of in the Var amount at steady state, which must be caused by computational round off error.

C. Change of Transmission Network

Steady state voltage assumed is V_{ss} = 1.0 p.u. This simulation case 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 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 the different network which may be correspond to the scheduled transmission maintenance.



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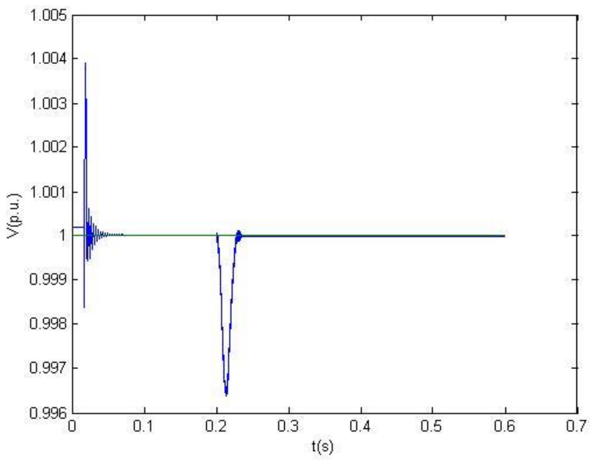

(b)

Fig. 9. Results of voltages (a) Original Control (b) Adaptive Control with change of Transmission Network

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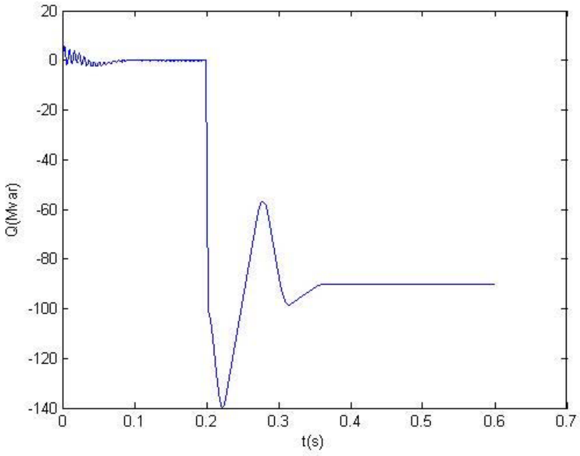

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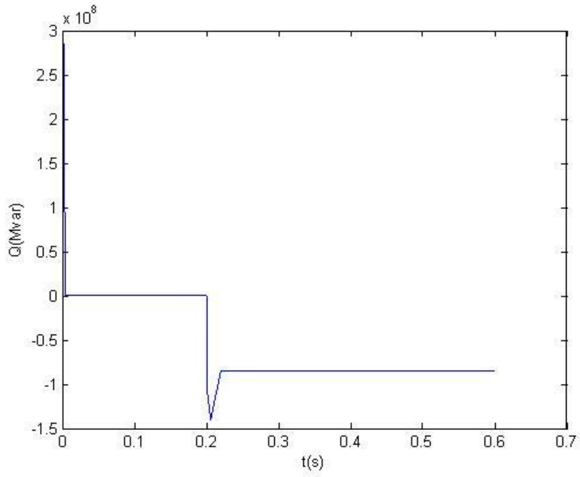
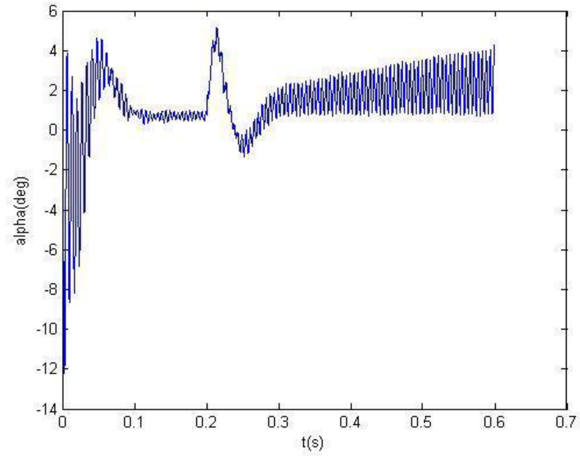


(b)

Fig. 10. Results of Output reactive power (a) Original Control (b) Adaptive Control with change of Transmission Network

STATCOM absorbs VAR from the system in this case. Here, the disturbance is assumed to give a voltage rise at (substation A). The overall impact leads to a voltage rise to higher than that at the controlled bus in the steady state if the STATCOM is not activated.



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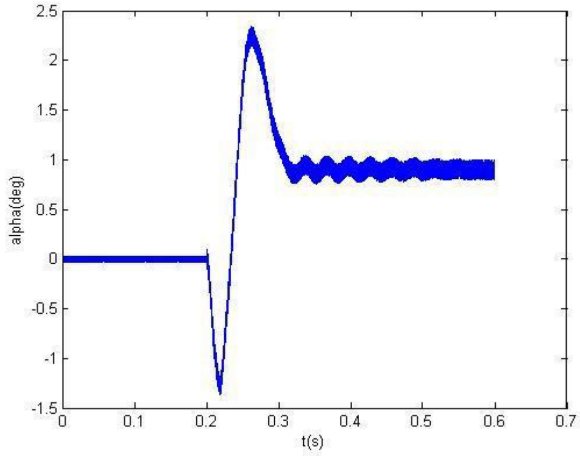
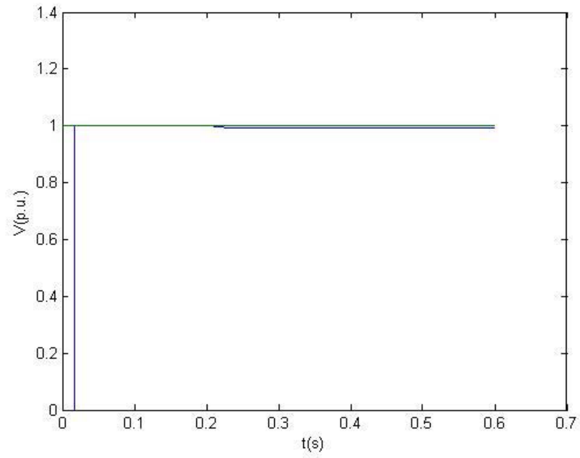


(b)

Fig. 12. Results of α (a) Original Control (b) Adaptive Control with change of Transmission Network

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.

D. Change of PI Control Gains



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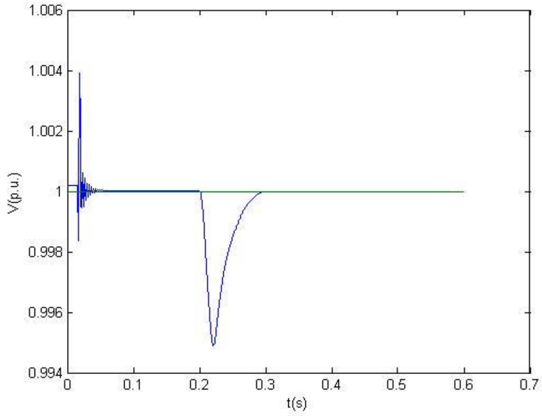

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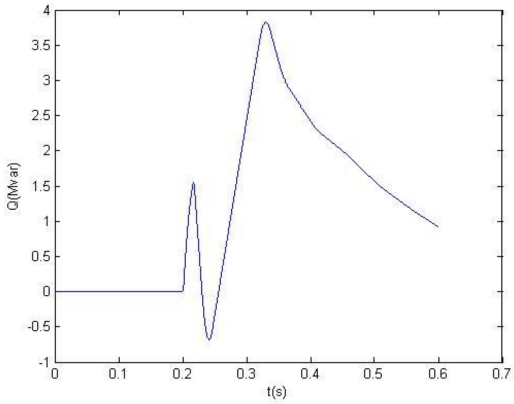
Fig. 7. Results of voltages (a) Original Control (b) Adaptive Control with change of PI control gains

Steady state voltage assumed is V_{ss} = 1.0 p.u. 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) which is the lowest voltage that the STATCOM system can support due to its capacity limit. In this, 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, 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 and calculated from derived equations.



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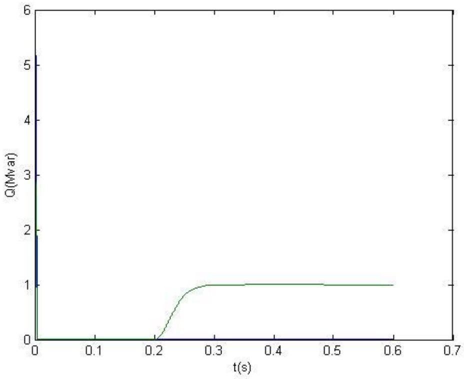
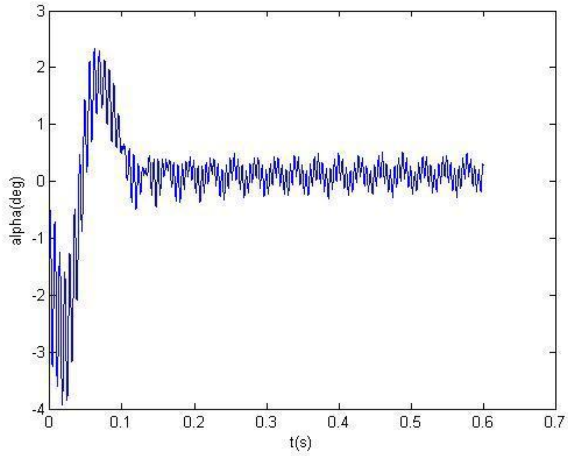


(b)

Fig. 8. Results of Output reactive power (a) Original Control (b) Adaptive Control with change of PI control gains



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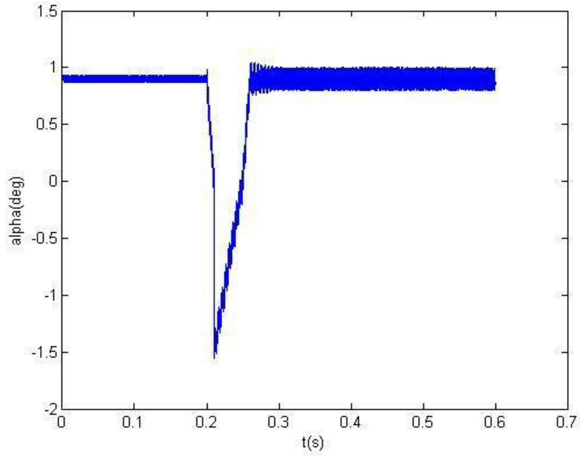

(b)

Fig. 9. Results of α (a) Original Control (b) Adaptive Control with change of PI control gains

From the results, it is observed 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.

From resulting voltage waveforms, 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. From resulting output, reactive power waveforms, it can be shown that the reactive power injection cannot be continuously increased in the original control to support voltage, while the adaptive PI control performs as desired.

V. CONCLUSION AND FUTURE SCOPE

Various STATCOM control methods using PI controllers obtain the PI gains via an approach called a trial and-error or extensive studies with a compromise in performance and applicability. So, the control parameters for the required performance at a given operating point may not always be effective at a different system operating point. Conventional STATCOM control with fixed PI gains performs well in the original system, but may not perform as efficient as the proposed control method when there is a change of operating system conditions.

In this simulation study, the proposed adaptive PI control for STATCOM is compared with the conventional STATCOM control with pre-tuned fixed PI gains and the advantages of the proposed method are verified.

- 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.
- This new control model can self-adjust the control gains dynamically during disturbances so that performance always matches desired response, regardless the change of operating conditions.
- Since the adjustments are autonomous, it gives the plug and play capability for STATCOM operation

Presently the application of STATCOM in the power system for voltage regulation by fast and efficient reactive power support has been discussed over conventional methods. Future work may concern with the investigation of multiple STATCOMs since the interaction among different STATCOMs may affect each other. Also, the work can be extended to explore power system control problems.

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