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Voltage Regulation of Transmission Line Using Adaptive PI Control of STATCOM

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Abstract: ***Power systems are continuously subject to unpredictable and sudden operating point variations Due to this the receiving end voltage decreases well below its normal value and affect power quality. Voltage stability is a critical consideration in improving the security and reliability of power systems. The static compensator (STATCOM), a device for reactive power control based on gate turnoff (GTO) thyristors, has gained much interest because of its it's quicker response. The control parameters or gains play a key factor in STATCOM performance. In the adaptive PI (Proportional-Integral) control of STATCOM for voltage regulation, PI control parameters can be self-adjusted automatically and dynamically under different disturbances in a power system. Thus this control method can ensure a quick and consistent desired response. A simulink model of Adaptive Proportional Integral control of STATCOM has been taken for the analysis using simulation in MATLAB software.***

Keywords: Adaptive control, proportional-integral (PI) control, STATCOM, GTO,voltage stability

1. Introduction

At any point of time, a power system operating condition should be stable, meeting various operational criteria, and it should also be secure in the event of any credible contingency. Present day power systems are being operated closer to their stability limits due to economic and environmental constraints. Maintaining a stable and secure operation of a power system is therefore a very important and challenging issue.

Voltage stability is a critical consideration in improving the security and reliability of power systems [1], [2]. Reactive power (VAR) compensation is nothing but the control of reactive power to enhance the performance of AC system. Reactive power compensators are commonly used for load voltage regulation in the presence of disturbance. In recent years, static VAR compensators like the STATCOM have been developed. These quite satisfactorily do the job of absorbing or generating reactive power with a faster time response and come under Flexible AC Transmission Systems (FACTS). This allows an increase in transfer of apparent power through a transmission line, and much better stability by the adjustment of parameters that govern the power system i.e. current, voltage, phase angle, frequency and impedance. The static compensator (STATCOM) is a popular device for reactive power control to provide better controllability and performance. It is able to exchange reactive power with the A.C. system [3], [4]. STATCOM based on gate turnoff (GTO) thyristors enables voltage regulation along with harmonics elimination [4] ,[5], [10]. Multilevel inverter technology is used in the area of high power and voltage control [8].STATCOM control methods have been developed since last many days. In those methods, logic for setting control parameters was based on 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.

To have dynamic control strategies for efficient performance adaptive PI controllers came into scenario. In adaptive PI control method for , 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 [7], [9]. Since the change is self-governing, this gives the attachment and-play capacity for STATCOM operation.

Simulink is add on tool in MATLAB, used to visually program a dynamic system (those governed by Differential equations) and look at results for analysis [10].

A simulink model of Adaptive Proportional Integral control of STATCOM for voltage regulation has been taken for the analysis using simulation in MATLAB software.

2. STATCOM Model and Control

A. System Configuration

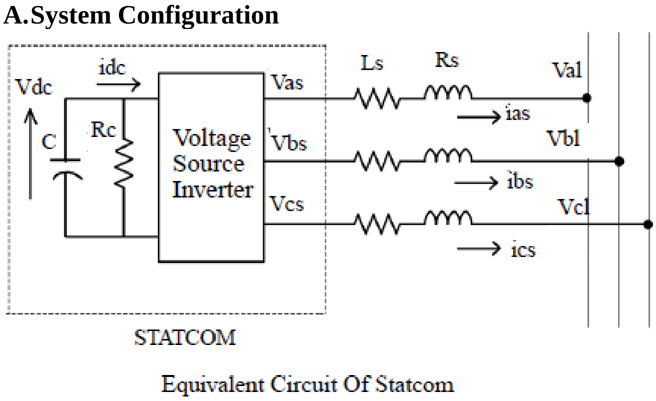


Figure 1: Equivalent Circuit Of STATCOM

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

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

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

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

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

The resistance Rs is 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 C represents the sum of the switching losses of the inverter and the power losses in the capacitor.

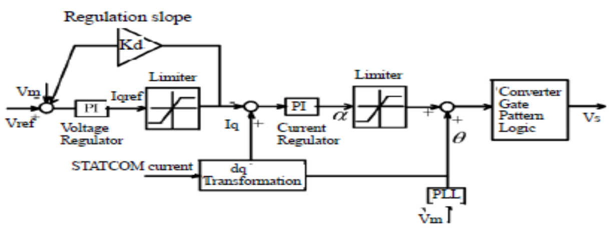
V_{as}, V_{bs}, and V_{cs} are the three-phase STATCOM output voltages; V_{al}, V_{bl}, and V_{cl} are the three phase bus voltages; i_{as}, i_{bs}, and i_{cs}, and are the three-phase STATCOM output currents.

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

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

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}.

B. STATCOM Dynamic Model



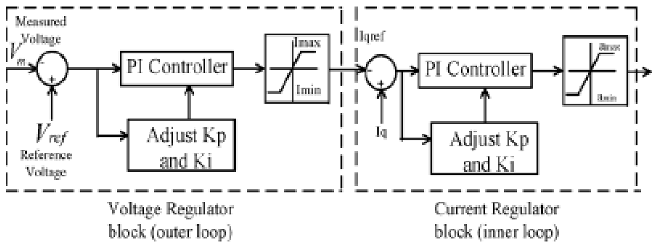
Traditional Statcom PI Control Block Diagram

Figure 2: Traditional STATCOM PI control block diagram

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.

3. Adaptive PI Control for STATCOM

A. Concept of Proposed Adaptive Control



Adaptive PI control block for STATCOM.

Figure 3: Adaptive PI Control for STATCOM

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 , 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 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 I_{max} 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, 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.

B. Key Equations

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

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

When there is a disturbance in the power system. Based on the adaptive voltage-control model, at any arbitrary time instant ,the following equation

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

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

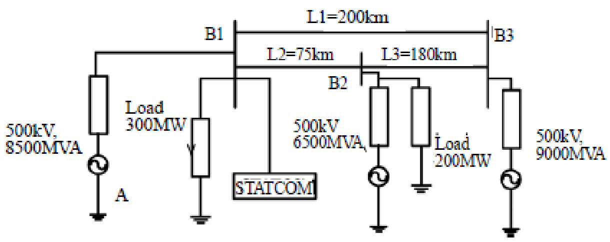
$$K_{i\_V}(t)=m_V\times K_{p\_V}(t).$$

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

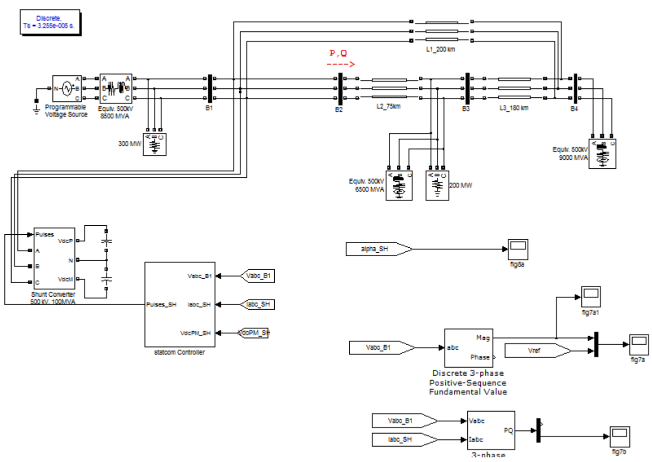
$$K_{i\_I}(t)=m_I\times K_{p\_I}(t)$$

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

C. Considered System



D. SIMULINK Model



4. Simulation Results For Different Cases

A. System Data

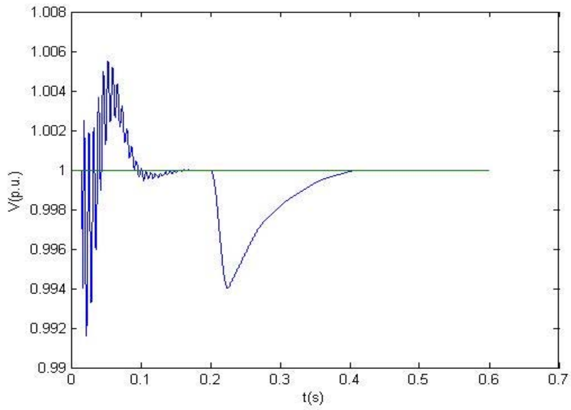
In the system simulation diagram ,a 100-MVAR STATCOM is implemented with a 48-pulse VSC and connected to a 500-kV bus. Here, the attention is focused on the STATCOM control performance in bus voltage regulation mode. In the original model, the compensating reactive power injection and the regulation 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, $\Delta V(t_0) = \Delta V_{max}$ 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 key equations.



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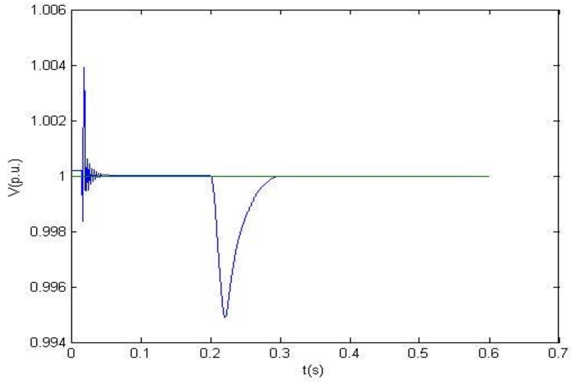
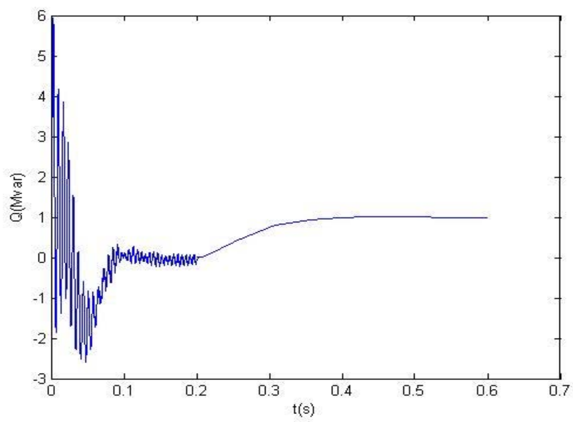


(b)

Figure 4: Results of voltages (a) Original Control (b) Adaptive Control using the same network and loads as in the original system.



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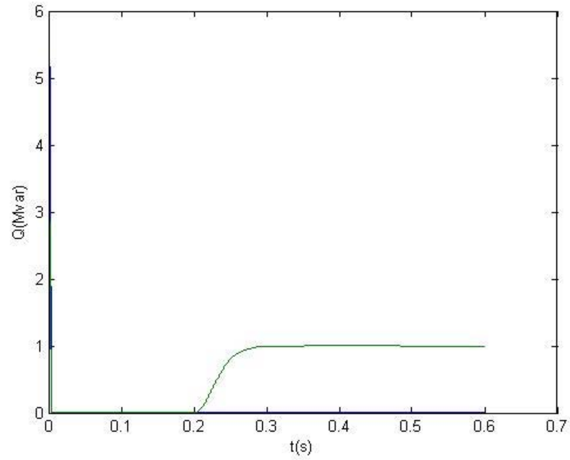

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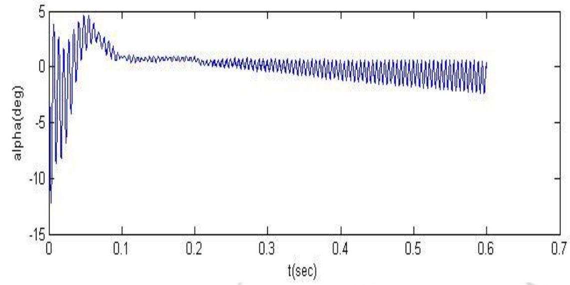
Figure 5: Results of Output reactive power (a) Original Control (b) Adaptive Control using the same network and loads as in the original system



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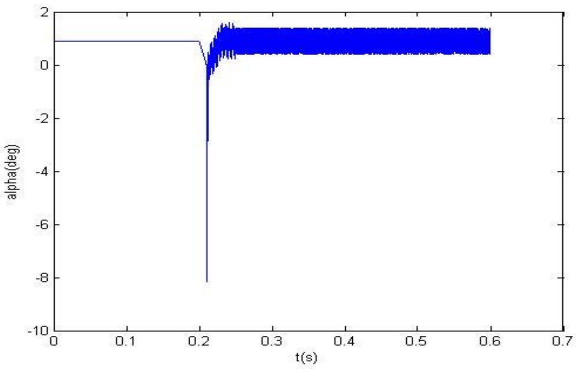


(b)

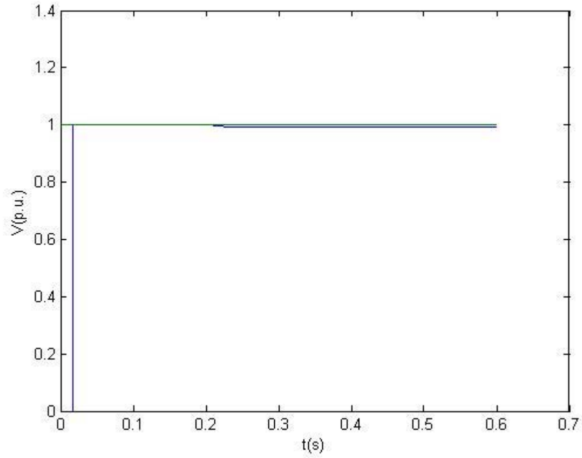
Figure 6: Results of α (a) Original Control (b) Adaptive Control using the same network and loads as in the original system

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 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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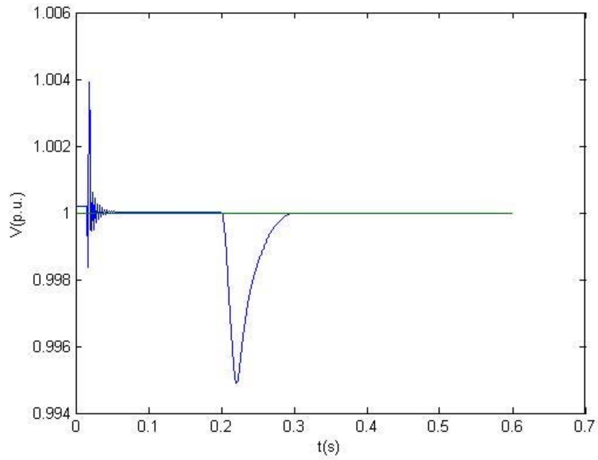
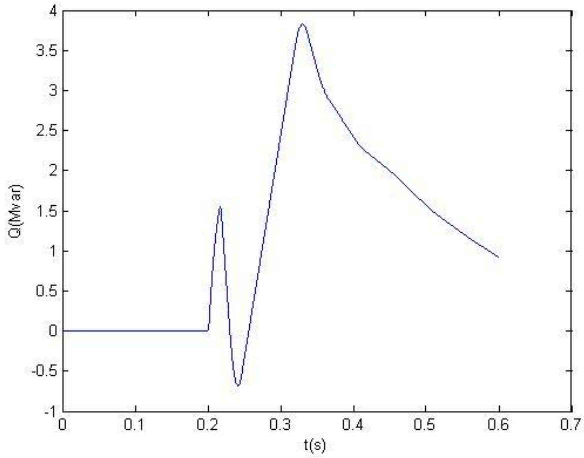


(b)

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



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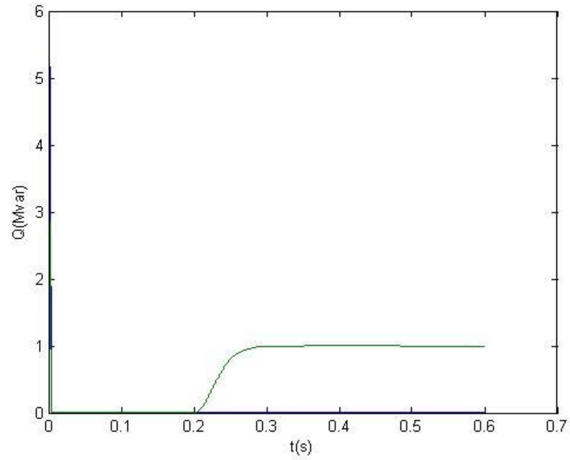
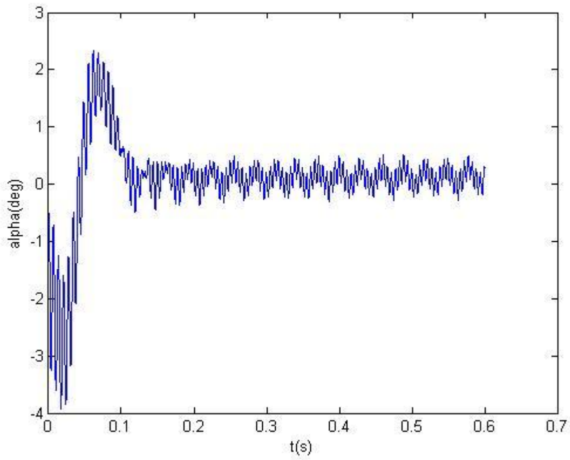


(b)

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



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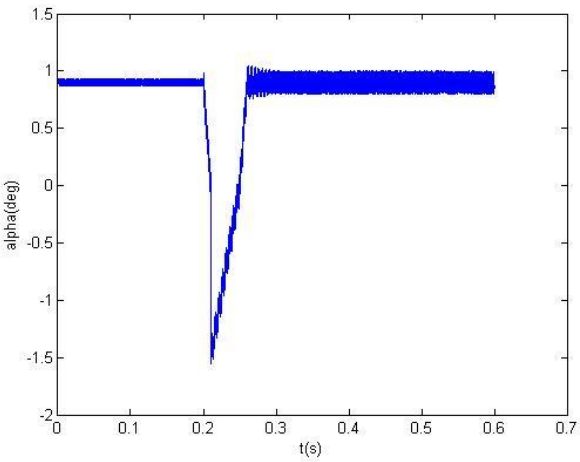


(b)

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

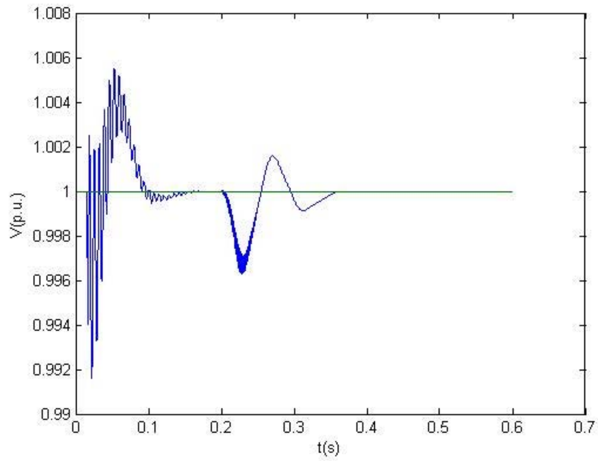
From the results, it is observed that the adaptive PI control can achieve quicker response than the original one. The necessary reactive power amount is the same while the adaptive PI approach runs faster, as the voltage does.

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.

D. 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 a different network which may correspond to scheduled transmission maintenance.



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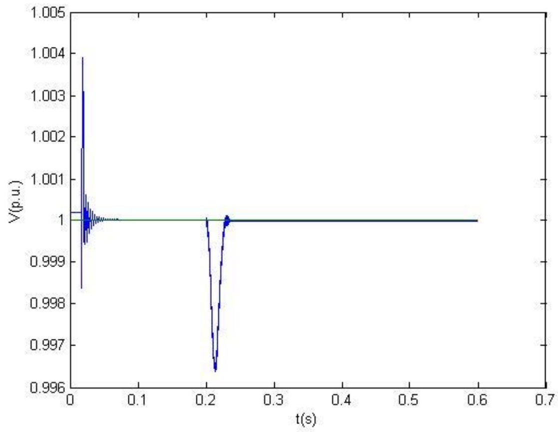
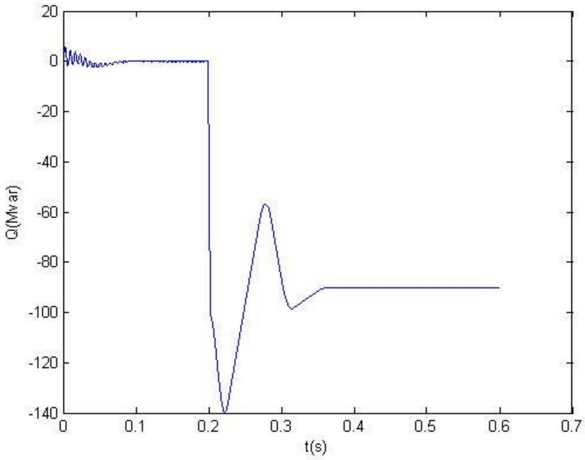


(b)

Figure 10: Results of voltages (a) Original Control (b) Adaptive Control with change of Transmission Network



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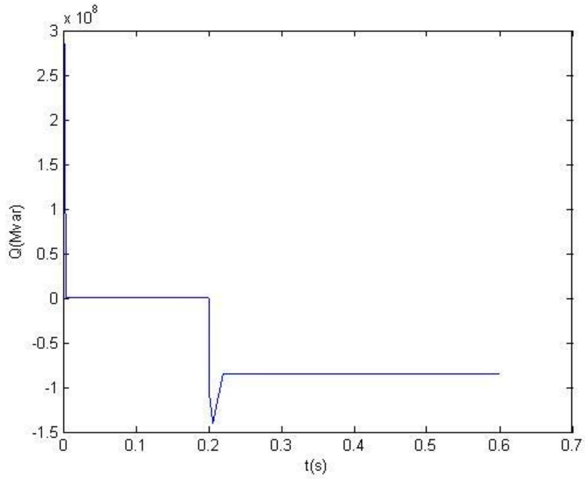

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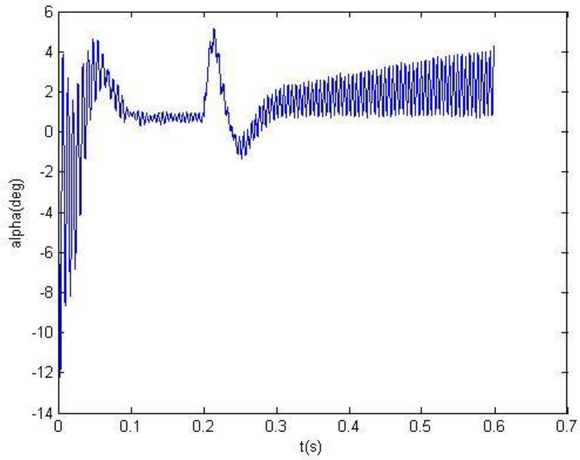
Figure 11: Results of Output reactive power (a) Original Control (b) Adaptive Control with change of Transmission Network



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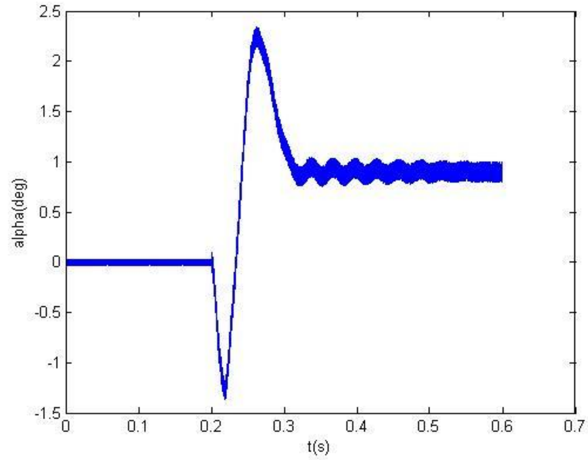


(b)

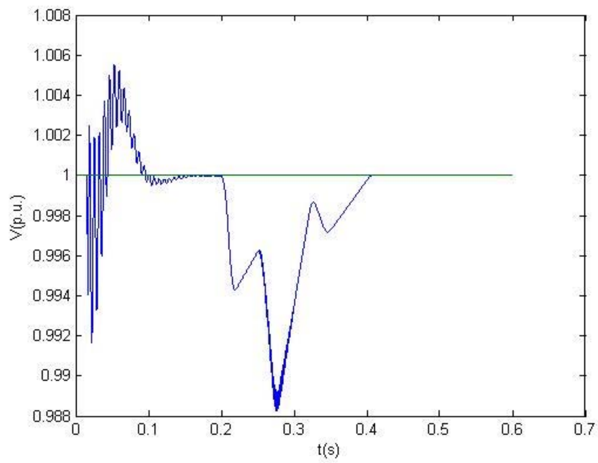
Figure 12: Results of α (a) Original Control (b) Adaptive Control with change of Transmission Network

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. 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.

E. Two Consecutive Disturbances

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 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.



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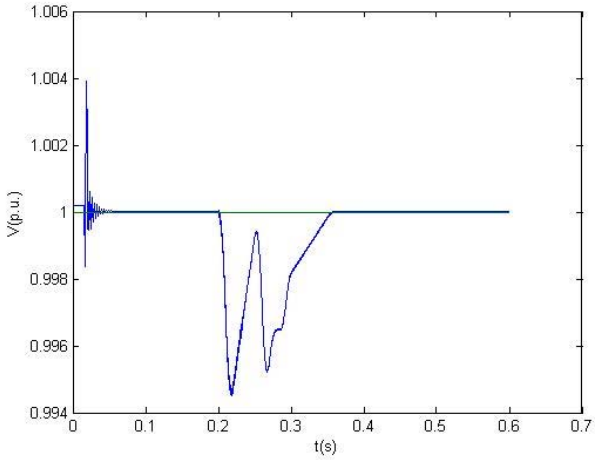

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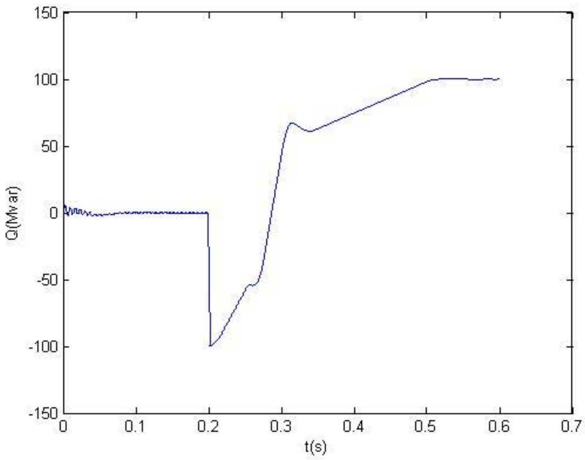
Figure 13: Results of voltages (a) Original Control (b) Adaptive Control with Two consecutive disturbances



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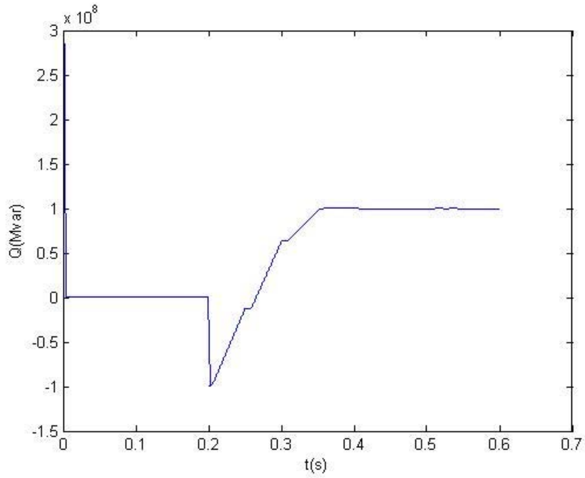
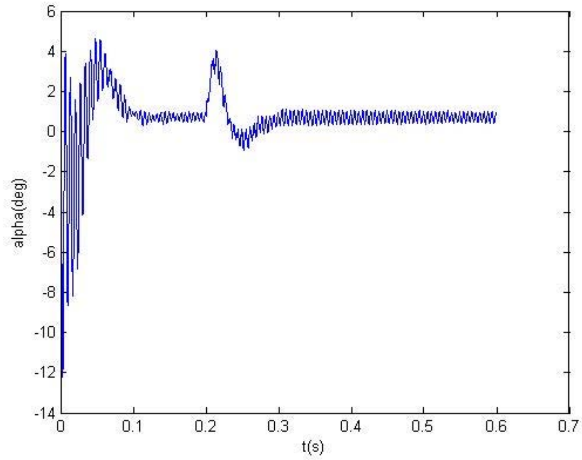
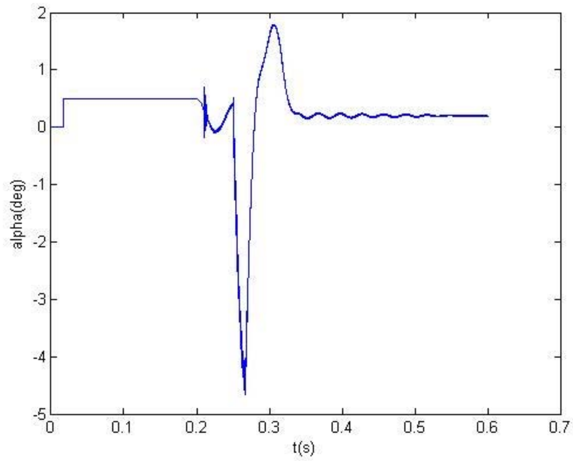


(b)

Figure 14: Results of Output reactive power (a) Original Control (b) Adaptive Control with Two Consecutive Disturbances



(a)



(b)

Figure 15: Results of α (a) Original Control (b) Adaptive Control with Two consecutive disturbances

system voltage drop much less than the original control during the second disturbance.

The largest voltage drop during the second disturbance event with the original control is larger than that with the proposed adaptive control. Therefore, the system is more robust in responding to consecutive disturbances with adaptive PI control.

5. Conclusion and Future Scope

Various STATCOM control methods including many applications of PI controllers 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 points. 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.

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.
It is apparent that the adaptive PI control can achieve much quicker response than the original one, which makes the

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