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Research paper

Voltage Regulation Using STATCOM with PI and Adaptive PI Controls

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Abstract

In power systems, voltage instability problems occur due to its continuous demand in heavily loaded networks. So it is essential to stabilize the voltage levels in power systems. The stabilization of power systems can be improved by Flexible Alternating Current Transmission System (FACTS) devices. One of the FACTS devices named Static Synchronous Compensator (STATCOM) injects the compensating current in phase quadrature with line voltage and replicate as inductive reactance to produce capacitive power for the AC grid or as capacitive reactance to draw inductive power from the AC grid for controlling power flow in the line. This paper proposes Adaptive PI control over conventional PI that normally self-adjusts the controller gains under disturbances and helps in improving the performance and attaining a preferred response, irrespective of the change of working conditions. The work is implemented under MATLAB/SIMULINK environment. This method performs more efficient than the original PI with fixed control gains and also improves the system response speed consistently.

Keywords: *Adaptive control; Proportional Integral (PI) control; Reactive Power; STATCOM; Voltage stability*

1. Introduction

The stable operation of power system has become a significant problem for a secured system operation. Power system instability may occur due to large number of interconnections; more power transmissions through long transmission lines; new technologies; increased power consumption in heavy load areas; use of more number of induction machines and local uncoordinated controls. The stability of power system is that for a given early operational condition, it is the capability to use a state of operating steadiness when open to any physical distraction, with maximum of the system parameters controlled so that nearly the whole system rests unspoiled. Voltage stability is a dangerous stability problem in refining the security and consistency of power systems. Voltage stability is the ability in upholding stable voltages at every buses in the system and also maintaining or restoring balance between demand and source of load from its specified early working circumstances under disturbances. Another problematic, Voltage collapse highly complex voltage insecurity is the sequence by which the assembly of voltage instability leads to an unusual condition of small voltages blackout or blackout in important parts of a power system. Such voltage collapse has some symptoms like heavy reactive power flows; low voltage; heavily loaded systems and inadequate reactive support. Generally, sufficient reserves will be available those settle to a steady voltage level [1]. Though, system instability may occur because of the combined effect of system conditions and events that the deficiency of added reactive power that leads to voltage downfall. Thus the system meets a partial or total collapse.

Figure 1 shows the voltage stability phenomenon. In power systems, voltage steadiness is worried with load regions and load features and basically it is load constancy. Voltage stability is of four types as,

☐ Large disruption
☐ Small disruption
☐ Transient
☐ Longer term

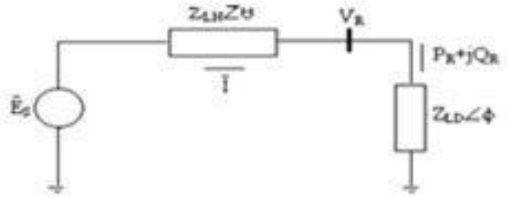


Figure 1. A voltage stability phenomenon

1.1. Causes of Voltage uncertainty

- Surge in load demand
- Failure to meet reactive power request
- Disorders such as system errors, circuit constraints or small perturbations
- Critical load components
- Complex loads in transmission lines
- Too distant voltage sources from the load centres
- Very low generation
- ULTC action during low voltage conditions
- Uncoordinated control and protective systems
- Deficient load reactive compensation.

1.2. Statcom

Power electronic devices play a dynamic part in power transmission and distribution applications. For stable and increasing transmission systems, reactive power compensation techniques are efficient and also economical. And FACTS devices have been familiarised for stability control and the topical device STATCOM substitutes the synchronous condenser by a converter i.e., a voltage source inverter VSI is used with a fixed dc link capacitor. In VAR control the bus voltage and speedy control of power factor utility will be improved by a set of capacitors. The use of this device has more advantages like speed of response over conventional methods using thyristorised converters.

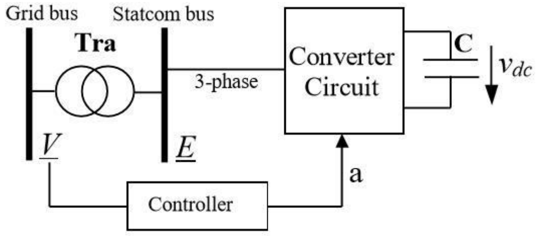
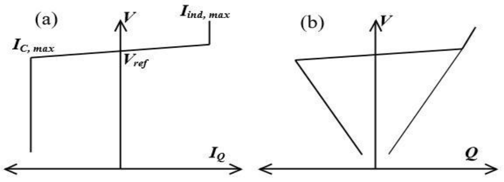


Figure 2. STATCOM in power system

Static Synchronous Compensator of FACTS family is a device that is connected in shunt to the system as shown in Figure 2. It is a 3Ø voltage system that lets both generation and intake of reactive power. It comprises of the blocks namely coupling transformer, measurement system, inverter/converter circuit, controller and a dc-link capacitor. Figure 3 gives its steady-state capability. $I_{Q,}$ the reactive current can be fixed within its extreme inductive and capacitive bounds even during very low voltage circumstances.



Steady-State Capability of a STATCOM
(a) *V-I*-Characteristic
(b) *V-Q*-Characteristic

Figure 3. STATCOM characteristics

The reactive power yield is toughly dependent on the firing angle "a" of thyristor. And the shifting in phase between the STATCOM voltage and the bus voltage decides the firing angle "a". Based on this firing angle, the dc capacitor charging state changes and so the amplitude of STATCOM bus voltage E differs. The injected reactive current in power system is determined by this variance in amplitude of network voltage and bus voltage of STATCOM in addition to leakage reactance X_T of transformer.

$$I = \frac{V-E}{X_T} \tag{1}$$

Without a STATCOM, the voltage drops, when the load connected is highly inductive or if there is a surge in the active power which is drawn by the load. But with an applied STATCOM, there is a flattened voltage profile, because of capacitive power delivery for lower voltages and inductive power delivery for higher voltages due to a lower demand in load. Also at the same time, because of the device's capacitive power support, higher transfer of power can be achieved to the load [2].

2. Statcom Control Model

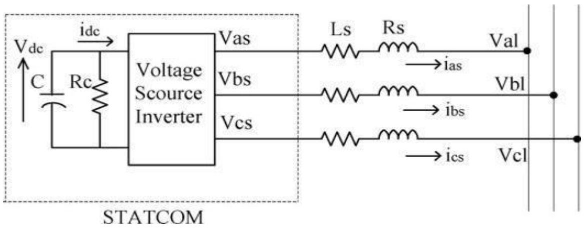


Figure 4. STATCOM - Equivalent circuit

Figure 4 shows the STATCOM's equivalent circuit.
In this structure, consider

R_s – Resistance in series to voltage source inverter.
R_s = inverter conduction losses + transformer winding resistance losses.
L_s – Transformer leakage inductance.
R_c – Resistance in shunt with capacitor.
R_c = capacitor power losses + inverter switching losses.

In Figure 2,

V_{al}, V_{bl}, V_{cl} - 3Ø bus voltages
V_{as}, V_{bs}, V_{cs} - 3Ø output voltages
i_{as}, i_{bs}, i_{cs} - 3Ø output currents [3], [4]

The mathematical expressions of the STATCOM are given as [8], [9]:

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

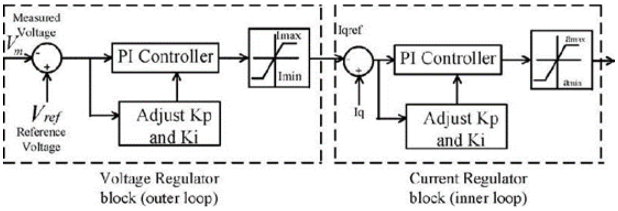
$$L_s \frac{di_{bs}}{dt} = -R_s i_{bs} + V_{bs} - V_{bl} \tag{3}$$

$$L_s \frac{di_{cs}}{dt} = -R_s i_{cs} + V_{cs} - V_{cl} \tag{4}$$

$$\frac{d}{dt}\left(\frac{1}{2} C V_{dc}{}^2(t)\right) = -[V_{as} i_{as} + V_{bs} i_{bs} + V_{cs} i_{cs}] - \frac{V_{dc}{}^2(t)}{R_c} \tag{5}$$

Through abc/dq transformation, the above equations can be written as

$$\frac{d}{dx}\begin{bmatrix} i_{ds} \\ i_{qs} \\ V_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & \omega & \frac{K}{L_s} cos\alpha \\ -\omega & -\frac{R_s}{L_s} & \frac{K}{L_s} sin\alpha \\ -\frac{3K}{2C} cos\alpha & -\frac{3K}{2C} sin\alpha & -\frac{1}{R_c C} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ V_{dc} \end{bmatrix} - \frac{1}{L_s} \begin{bmatrix} V_{dl} \\ V_{ql} \\ 0 \end{bmatrix} \tag{6}$$



where,

i_{ds} and i_{qs} – corresponding d and q currents of i_{as}, i_{bs} and i_{cs};
K - factor relating the dc voltage and the highest value of phase to neutral voltage;
V_{dc} - dc voltage;
α – leading phase angle of the output voltage with respect to bus voltage;
ω - angular rotational speed;
V_{dl} and V_{ql} - d and q axis voltage conforming to V_{al}, V_{bl} and V_{cl}.

The active and reactive powers of the system can be determined by,

$$p1 = \frac{3}{2} V_{dl}\ i_{ds} \tag{7}$$

$$q1 = \frac{3}{2} V_{dl}\ i_{qs} \tag{8}$$

The old-style control approach can be determined based on the equation shown above [5], [6].

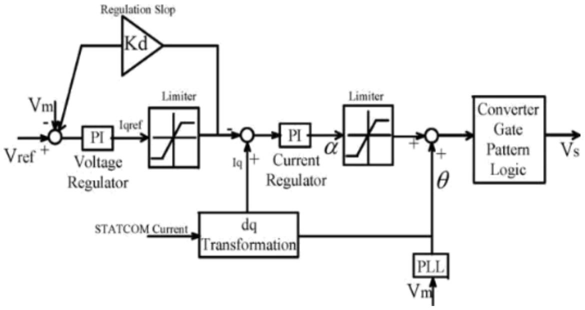


Figure 5. Traditional STATCOM PI

As in Figure 5, the purpose of phase locked loop (PLL) is synchronizing on the positive order component of the 3Ø primary voltage. The PLL output is used to compute the voltage and current components in the direct axis and quadrature axis. And the measurement systems of STATCOM measure the d and q components. The measured bus line voltage V_m and the reference voltage V_{ref} are compared and the required value of reactive reference current is provided by the voltage regulator. Also the reactive current I_q of STATCOM and reference current I_{qref}, are compared and the current regulator provides the angle that the inverter voltage phase shifted with respective to the system voltage as its output. STATCOMs' capability of maximum reactive power can be organised by the limiter[7].

3. Statcom - Adaptive Pi Control

3.1 Adaptive PI control

The PI control with fixed gain parameters of STATCOM may not help as good in reaching the acceptable and desired response under changing power system working conditions (e.g., transmissions or loads). So an adaptive PI control scheme of STATCOM is offered.

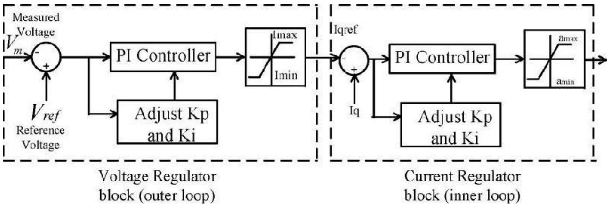


Figure 6. Adaptive PI control

A PI control method is used to get the desired responses. And suitable parameters have to be found for PI controllers while installing a novel STATCOM in a power system. In Figure 6, V_m (t) is the measured voltage, V_{ref}

(t) is the reference voltage, I_{qref} is the quadrature axis reference current and I_q is the quadrature axis current. All these are in per-unit values. K_{p_V} and K_{i_V} are the proportional and integral gains of the voltage regulator correspondingly. Similarly, the proportional and integral gains of the current regulator are represented by K_{p_I} and K_{i_I} respectively. Figure 7 shows the progress of voltage towards the steady state value that is fixed as the V_{ref}.

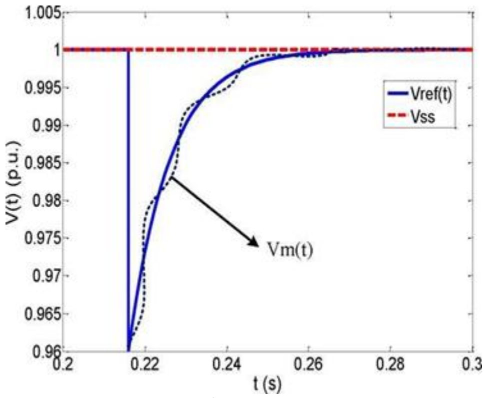


Figure 7. Reference voltage curve

3.2 Control Equations

Both the inner and outer loop controls are similar and the mathematical model is determined for PI controller gain adjustments in the outer loop. Similarly inner loop gains can also be adjusted. V_{dl} (t) and V_{ql} (t) can be computed with the d-q transformation.

$$\begin{bmatrix} V_{dl}(t) \\ V_{ql}(t) \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_{al}(t) \\ V_{bl}(t) \\ V_{cl}(t) \end{bmatrix} \tag{9}$$

$$V_m(t) = \sqrt{V_{dl}{}^2(t) + V_{ql}{}^2(t)} \tag{10}$$

$$V_{ref}(t) = V_{ss} - \left(V_{ss} - V_m(t)\right)e^{-\frac{1}{\tau}} \tag{11}$$

$$K_{p\_V}(t) = \frac{K_V \times \Delta V(t)}{(\Delta V(t) + m_V \times \int_t^{t+T_s} A dt)} \tag{12}$$

$$K_{i\_V}(t) = m_V \times K_{p\_V}(t) \tag{13}$$

$$K_{p\_I}(t) = \frac{K_I \times \Delta I_q(t)}{(\Delta I_q(t) + m_I \times \int_t^{t+T_s} B dt)} \tag{14}$$

$$K_{i\_I}(t) = m_I \times K_{p\_I}(t) \tag{15}$$

Quicker system response can be achieved in adaptive PI control than the original PI control. Also the necessary amount of reactive power is similar whereas the adaptive PI approach runs quicker. The dynamic control gains of the adaptive PI control are given by,

$$K_{p\_V}(t) = \frac{84.7425 \times \Delta V(t)}{(\Delta V(t) + 770.8780 \times \int_t^{t+T_s} A dt)} \tag{16}$$

Where

T_s is the sample time = $2.5 * 10^{-5}$ s (17)

$$A = \Delta V(t) - \Delta V(t - T_s) \tag{18}$$

$$K_{i\_V}(t) = 770.8480 \times K_{p\_V}(t) \tag{19}$$

$$K_{p\_I}(t) = \frac{57.3260 \times \Delta I_q(t)}{(\Delta I_q(t) + 2.3775 \times \int_t^{t+T_s} B dt)} \tag{20}$$

Where

$$B = \Delta I_q(t) - \Delta I_q(t - T_s) \tag{21}$$

$$K_{i\_I}(t) = 2.3775 \times K_{p\_I}(t) \tag{22}$$

3.3 Adaptive PI Control Flowchart

Figure 8 is a flowchart of STATCOMs adaptive PI control corresponding to the diagram shown in Figure 6. The process initiates at Start. The system bus voltage which is measured over time. V_m (t) is sampled to a favourite sampling rate and is then related with V_{ss}. There is no need to adjust any of the parameters, K_{p_V} (t), K_{i_V} (t), K_{i_I} (t) and K_{p_I} (t) if, V_m (t) = V_{ss}. And it is considered as the smooth run of the power system. But the PI control will begin if, V_m (t) ≠ V_{ss}. The measured bus voltage V_m (t) is compared with V_{ref} (t). Then, gain adjustments on K_{p_V} and K_{i_V} are done in the outer loop i.e., voltage regulator block, based on (16) and (19), and thereby an updated I_{qref} is obtained through the current limiter as shown in Figure 4. Then, this I_{qref} and measured q-current I $_q$ are compared. The control gains K_{i_I} (t) and K_{p_I} (t) can be adjusted based on (20) and (22). At last the phase angle á is obtained and given into a limiter for output, that chooses the required amount of reactive power from the STATCOM.

Following, a small value of tolerance threshold such as 0.0001 p.u is chosen. If | ( )| s greater than the tolerance threshold, the current regulator and voltage regulator blocks have to be repeated until | ( )| becomes a reduced amount of than the tolerance threshold. Hence, the values for K_{p_V} (t), K_{i_V} (t), K_{i_I} (t) and K_{p_I} (t) are kept as constant.

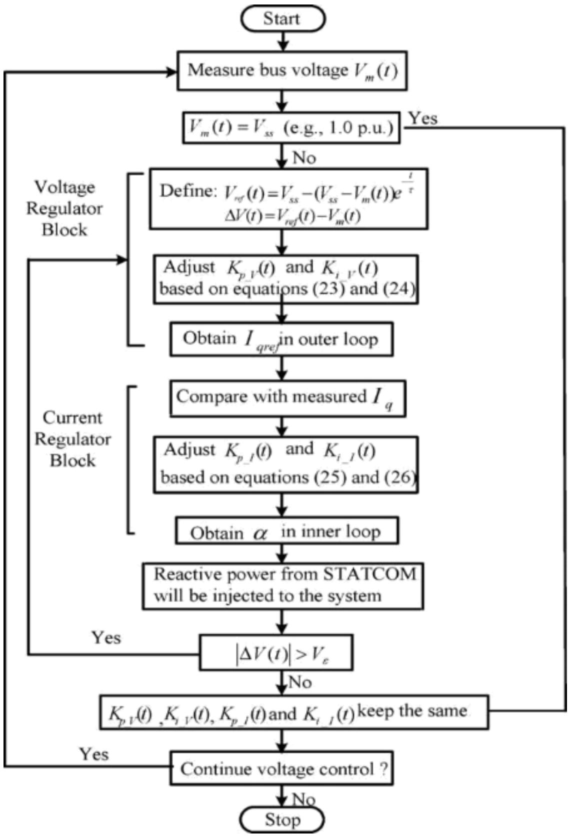


Figure 8. Flowchart of Adaptive PI Control

4. Results and Discussions

The simulations of PI and Adaptive PI for STATCOM are done in MATLAB/SIMULINK and the test system is shown in Figure 9 and Figure 10.

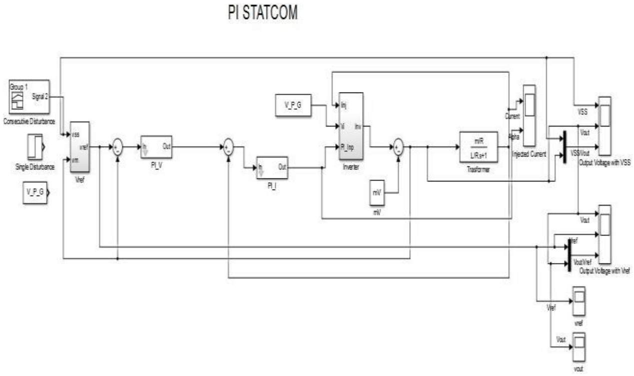


Figure 9. PI STATCOM in MATLAB

Also Figure 11 and Figure 12 show the Adaptive voltage and current regulator blocks respectively. In Matlab/Simulink library a standard STATCOM system sample is chosen. A 100-MVAR STATCOM is applied with a 48-pulse VSC and associated to a 500-kV bus. And machines taken in this work are all dynamical models [8], [5], [6]. Also here, the control performance of STATCOM is clearly focused in the bus voltage regulation mode. In the traditional method, the current and voltage regulator control gains largely affect the regulation speed and the reactive power compensation. This traditional control is now matched with the suggested adaptive PI control method.

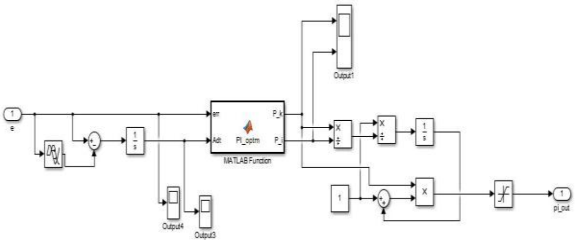


Figure 11. Adaptive PI_V block

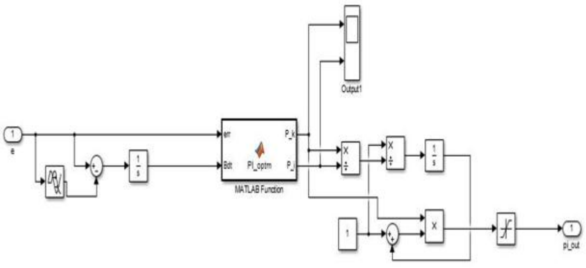


Figure 12. Adaptive PI_I block

Table 1. Comparison table

Time	**PI control**		**Adaptive PI control**	
0	1	0.8945	1	0.9402
0.199	1	0.9917	1	0.9938
0.2	0.5	0.4945	0.5	0.4962
0.202	0.5	0.4938	0.5	0.4955
0.499	0.5	0.4933	0.5	0.4988
0.5		0.1965	0.2	0.1993
0.504		0.1948	0.2	0.1991
1		0.1946	0.2	0.1997

Table 2. Settling time

Methods used	**Settling time (s)**	
	Voltage output	**Reactive power**
PI	0.997	0.84

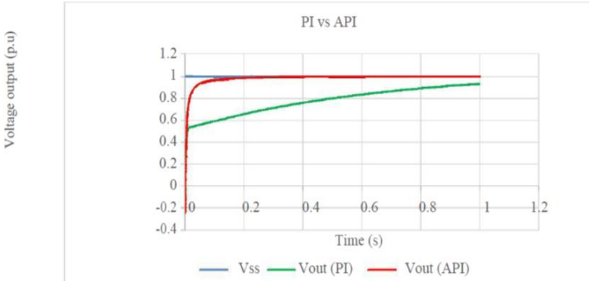


Figure 13. Comparison of Vout

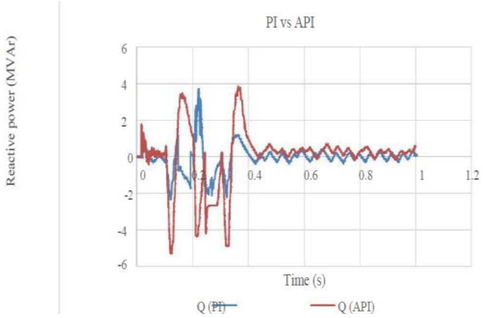


Figure 14. Comparison of Q

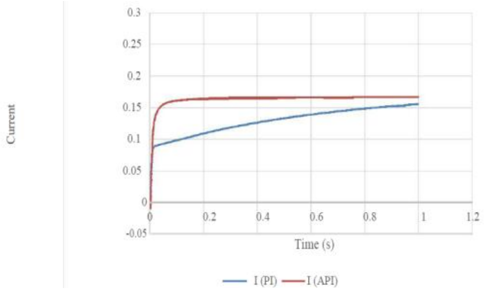


Figure 15. Comparison of I

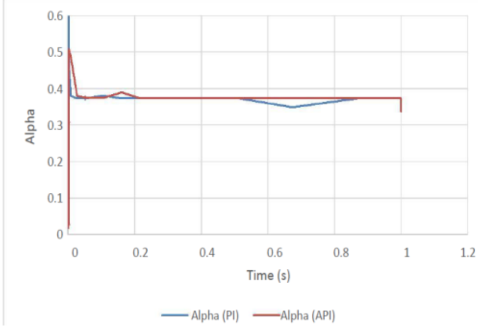


Figure 16. Comparison of alpha

The suggested adaptive PI control approach is more advantageous for adjusting the control gains both independently and dynamically under any voltage correction and regulation processes. Thereby, the wanted control performance can be effectively achieved. Table 1 gives the comparison of output voltages with respect to the reference. And Table 2 gives the comparison over settling time of output voltage and reactive power. Figure 13 shows the output voltage characteristics with respect to reference voltage of Adaptive PI and PI controls respectively.

5. Conclusion

The comparison between Adaptive PI and original PI control is done. And previously the voltage regulation stability problems have been discussed in many literatures with different STATCOM control methods using PI controllers. However, the PI gains of the regulator are obtained as extensive studies of controller performance and applicability or trial and error approach. Hence, at any given operating point, the performance of the controller may not be effective for all the times at a different working point. A novel control method created on Adaptive PI control is projected in this paper for STATCOM for voltage regulation. This adaptive PI control can dynamically self-adjust the control gains during any disturbance so as to improve the performance to match the desired response, irrespective of the change of working circumstance. In this simulation study, the suggested scheme of adaptive PI control is related with the traditional PI control for STATCOM which has pretuned fixed control gains. And it is proved in Figure 13, Figure 14 that the proposed adaptive PI control gives outstanding performance even under different system conditions. Figure 15 and Figure 16 illustrates the comparison of current and angle alpha respectively. The result shows that the proposed adaptive PI control performs more efficient than the original PI with fixed control gains and also improves the system response speed consistently. In future this work can be extended in systems with multiple STATCOMs, and also optimization intelligent techniques can be implemented to improve the performance further

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