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Mathematical modelling of Adaptive PI Controller of STATCOM for Voltage Stability

Shubham O. Shewatkar[1]

[1]*PG Scholar*
Government College Of Engineering, Amravati, Pin444604

***Abstract –** In power system, voltage stability is considered as performance measurement parameter. Hence to achieve voltage stability Static Compensator (STATCOM) is used. Last few years STATCOM has been used to enhance the performance of the power system. It can regulate a systems voltage by providing fast and efficient power support. However, previously there are many different STATCOM control systems that have been studied which includes fundamental Proportional Integral (PI) controller. The experimentation approach to obtain the PI gains or studies with trade off of relevance and execution. Hence, the performance at an operating point for some control parameters may vary for same control parameter at different operating point. To improve performance of control system at different operating conditions, this paper proposes the control model which can self-adjust the control gains such that always give desired response during disturbances. Since the changes is self-governing, this gives the attach-and-play capability for STATCOM operation. The simulations results of the adaptive PI control for different operating conditions such as transmission network, load level, control gain, severe and consecutive disturbances shows excellent consistence. The conventional STATCOM perform well for same operating condition, but when it comes for system condition change proposed control method shows upper hand over previous conventional method.*

Keywords-** Adaptive control, proportional-integral (PI) control, reactive power compensation, STATCOM, voltage stability.

I INTRODUCTION

In power system, voltage stability is considered as performance measurement parameter. Hence to achieve voltage stability Static Compensator (STATCOM) is used. Reactive power exchange between the STATCOM and the transmission line can be controlled by controlling the STATCOM output voltage V_s. The operation and control of the STATCOM have been discussed in [1]–[3]. Previously, different control methods have been discussed for STATCOM control in [2]-[6]. Most of these methods focus on controller design rather than going for setting the PI controller gains. The experimentation approach to obtain the PI gains or studies with tradeoff of relevance and execution is given in [7]-[8]. Hence, the performance at an operating point for some control parameters may vary for same control parameter at different operating point. Performance of STATCOM may be undesirable as operating condition changes.

An adaptive PI control of STATCOM for voltage stability of power system network is presented in this paper. In STATCOM with conventional PI controller, control gains are already fixed. Performance of this STATCOM decreases as operating condition changes. With this adaptive PI control method, the control parameters of PI controller can be self-adjusted automatically under different operating conditions in a power system.

II STATCOM MODEL AND CONTROL

The corresponding equivalent circuit of the STATCOM is shown in Fig.1. In this power system, the sum of the transformer winding resistance losses and the inverter conduction losses are given by resistance R_s. L_s is the leakage inductance of the transformer. The sum of the switching losses of the inverter and the power losses in the capacitor are represented by resistance R_c.

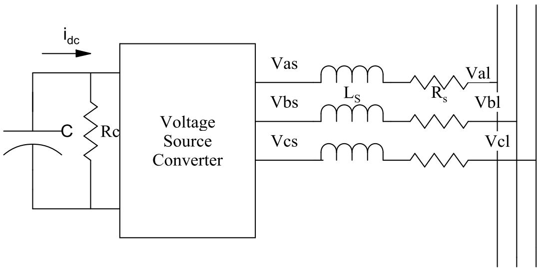

Fig. 1. Equivalent circuit of STATCOM.

The three-phase mathematical expressions of the STATCOM can be written in the following form [9], [10]:

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

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

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

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

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

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

Where i_{ds} and i_{qs} are the d and q currents respected to i_{as},i_{bs},and i_{cs}. 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 for the STATCOM output voltage leads to the bus voltage; ω is the synchronously rotating angle speed of the voltage vector; V_{dl} and V_{ql} represent the d and *q* axis voltage corresponding V_{al}, V_{bl}, and V_{cl}.Since V_{ql}=0, based on the instantaneous active and reactive power definition, (6) and (7) can be obtained as follows [2],[10].

$$p_l = \frac{3}{2} V_{dl} i_{ds} \quad (6)$$

$$q_l = \frac{3}{2} V_{dl} i_{qs} \quad (7)$$

Based on the above equations, the traditional control strategy for STATCOM is obtained shown in Fig. 2 [7], [8],[11].

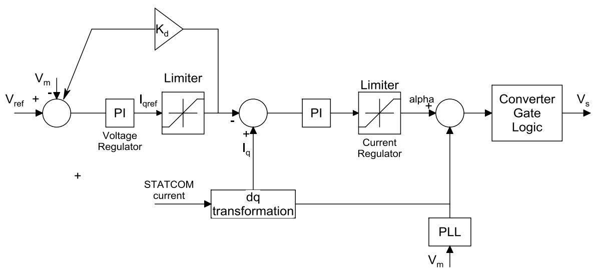

Fig. 2. Block diagram of Traditional STATCOM PI control.

As shown in Fig. 2, the phase-locked loop (PLL) provides the basic synchronizing signal which is the reference angle to the measurement system. In voltage regulator block measured bus line voltage V_m is compared with reference voltage V_{ref}. The voltage regulator provides the required reactive reference current of STATCOM I_{qref}. Here K_d is defined as the allowable voltage error when rated reactive current flow through the STATCOM[1]. .In current regulator block the STATCOM reactive current I_q and reactive reference current I_{qref} are compared, and the output of the current regulator is the angle phase shift of the inverter voltage with regard to the system voltage. The limiter represents the limit on the value of control considering the maximum reactive power capability of the STATCOM[2].

III ADAPTIVE PI CONTROL FOR STATCOM

The proposed adaptive PI control method is given in this section so as to obtain desired response at different operating conditions without performing trial-and-error studies to control parameters for PI controllers. With adaptive PI controller the control gains can be self adjusted depending upon the disturbances so that desired response is obtained under different operating conditions.

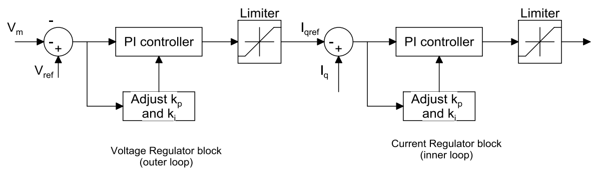

Fig. 3. Adaptive PI control block for STATCOM

An adaptive PI control block for STATCOM is shown in Fig. 3. the measured voltage $V_m(t)$ and the reference voltage $V_{ref}(t)$, and the q -axis reference current $I_{qref}(t)$ and the q -axis current are in per–unit values.
The proportional and integral gains of the voltage regulator block are represented by K_{p_V} and K_{i_V} respectively. Similarly, the gains K_{p_I} and K_{i_I} represent the proportional and integral gains of the current regulator block.Fig. 4 shows the reference voltage curve.

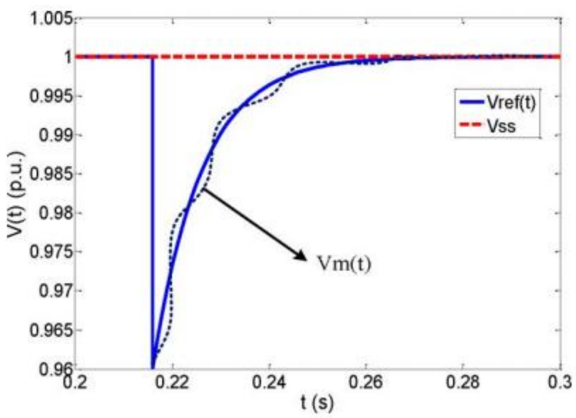

Fig. 4. Reference voltage curve

The proposed adaptive PI control method of STATCOM is described as follows.

1) The bus voltage $V_m(t)$ is measured in real time.
2) After measuring the bus voltage $V_m(t)$ over time, the $V_m(t)$ is compared with target steady state voltage V_{ss}. K_{p_V} and K_{i_V} are automatically adjusted so that measured voltage $V_m(t)$ matches the desired reference voltage curve.The voltage regulator block provides required q-axis reference current I_{qref} .
3) In current regulator block I_{qref} and actual q-axis current I_q are compared. Gains K_{p_I} and K_{i_I} are automatically adjusted based on error similar to voltage regulator block. Desired angle alpha represented by α can be obtained and dc voltage in STATCOM can be adjusted so as inject desired reactive power to maintain bus voltage at required level.

Here I_{min} and I_{max} and the angle α_{min} and α_{max} gives the limits on maximum reactive support provided by STATCOM.

By using d-q transformation $V_{dl}(t)$ and $V_{ql}(t)$ can be obtained.

$$\begin{bmatrix} V_{dl} \\ V_{ql} \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_{al} \\ V_{bl} \\ V_{cl} \end{bmatrix} \quad (8)$$

$$V_m(t) = \sqrt{V_{dl}^2(t) + V_{ql}^2(t)} \quad (9)$$

Reference voltage $V_{ref}(t)$ can be calculated using $V_m(t)$

$$V_{ref}(t) = V_{ss} - \left(V_{ss} - V_m(t)\right)e^{-\frac{t}{\tau}}. \quad (10)$$

Here, V_{ss} is target steady state voltage which is set to 1 p.u. and τ = 0.01 s.

Under normal operating condition $V_m(t)$=1 p.u. and $V_{ref}(t)$=1p.u. So control gains will not change. Here ΔV(t) is error between $V_m(t)$ and $V_{ref}(t)$.

$$\Delta V(t) = V_{ref}(t) - V_m(t)$$

From voltage regulator block at any instant t following equation is obtained.

$$\Delta V(t) K_{p_V}(t) + K_{i_V}(t) \int_t^{t+T_s} \Delta V(t)dt = I_{qref}(t + T_s) \quad (11)$$

Here T_s represents the sampling time set to 2.5×10^{-5} sec.

Resulting expression for the output of the discrete-time integrator block using Forward-Euler method at any instant t is,

$$y(t) = y(t - T_s) + K_{i\_V}(t - T_s) \times T_s \times \Delta V(t - T_s) \quad (12)$$

Assuming $y(t - T_s) = I_{qref}(t)$ we can write equation (11) as,

$$\Delta V(t) K_{p\_V}(t) + K_{i\_V}(t) \int_t^{t+T_s} \Delta V(t)dt - K_{i\_V}(t - T_s) \int_{t-T_s}^{t} \Delta V(t - T_s)dt = I_{qref}(t + T_s) - I_{qref}(t). \quad (13)$$

For very short duration of time, we consider

$K_{i\_V}(t) = K_{i\_V}(t - T_s)$

so equation (13) can be rewritten as

$$\Delta V(t) K_{p\_V}(t) + K_{i\_V}(t) \int_t^{t+T_s} A dt = I_{qref}(t + T_s) - I_{qref}(t) \quad (14)$$

Where,$A = \Delta V(t) - \Delta V(t - T_s)$

Based on equation (12) if we find out ideal response ratios of $(I_{qref}(t+T_s)-I_{qref}(t))/(\Delta V(t))$ and $(K_{i\_V}(t))/(K_{p\_V}(t))$ the required K_{p_V} and K_{i_V} can be calculated.

Assuming ideal response we have,

$$I_{qref}(t+T_s)-I_{qref}(t)=R\times\Delta V(t) \quad (15)$$

Assuming bus voltage will come back to 1 p.u. in 5τ.

Since $I_{qref}(t_0)=0$ from equation (15) and equation(11) we can write,

$$\Delta V(t_0)K_{p\_V}(t_0)+K_{i\_V}(t_0)\int_{t_0}^{t_0+5\tau}\Delta V(t)dt = R\times\Delta V(t_0) \quad (16)$$

Here t_0 is the time at which system disturbance occurs.

Considering $K_{i\_V}(t_0^-)=0$, We have

$$K_{p\_V}(t_0)=R \quad (17)$$

Considering $K_{p\_V}(t_0^-)=0$, We have

$$K_{i\_V}(t_0)=\frac{\Delta V(t_0)\times R}{\int_{t_0}^{t_0+5\tau}\Delta V(t)dt}. \quad (18)$$

Ratio $m_V=(K_{i\_V}(t_0))/(K_{p\_V}(t_0))$ can be considered as required ideal ratio for finding ideal gains K_{p_V} and K_{i_V}. so from equation (15) we can write,

$$I_{qref}(t+5\tau)-I_{qref}(t)=k_V\times\Delta V(t_0) \quad (19)$$

K_v is considered as ideal ratio of $(I_{qref}(t+T_s)-I_{qref}(t))/(\Delta V(t))$.

Here ΔV_{max} depends upon STATCOM rating.

$$\frac{\Delta V(t_0)}{\Delta V_{max}} = k_V\times\frac{\Delta V(t_0)K_{p\_V}(t_0)+K_{i\_V}(t_0)\int_{t_0}^{t_0+5\tau}\Delta V(t)dt}{R} \quad (20)$$

Using equations (16), (19) and (20) k_v can be calculated as shown in equation (21)

$$k_V=\frac{R\times\Delta V(t_0)}{(K_{p\_V}(t_0)\Delta V(t_0)+K_{i\_V}(t_0)\int_{t_0}^{t_0+5\tau}\Delta V(t)dt)\times\Delta V_{max}} \quad (21)$$

From equation (14) we can write,

$$\Delta V(t)K_{p\_V}(t)+m_V K_{p\_V}(t)\int_t^{t+T_s}Adt=k_V\times\Delta V(t) \quad (22)$$

So K_{p_V} and K_{i_V} can be calculated from following equations

$$K_{p\_V}(t)=\frac{k_V\times\Delta V(t)}{\left(\Delta V(t)+m_V\times\int_t^{t+T_s}Adt\right)} \quad (23)$$

$$K_{i\_V}(t)=m_V\times K_{pV}(t) \quad (24)$$

Therefore from equations (23) and (24) control gains can be adjusted dynamically.

Similarly, for current regulator block PI control gain can be calculated dynamically.

$$K_{p\_I}(t)=\frac{k_I\times\Delta I_q(t)}{\left(\Delta I_q(t)+m_I\times\int_t^{t+T_s}Bdt\right)} \quad (25)$$

$$K_{i\_I}(t)=m_I\times K_{p\_I}(t) \quad (26)$$

Here, Fig. 5 shows the Flowchart for adaptive PI control method.

V CONCLUSION

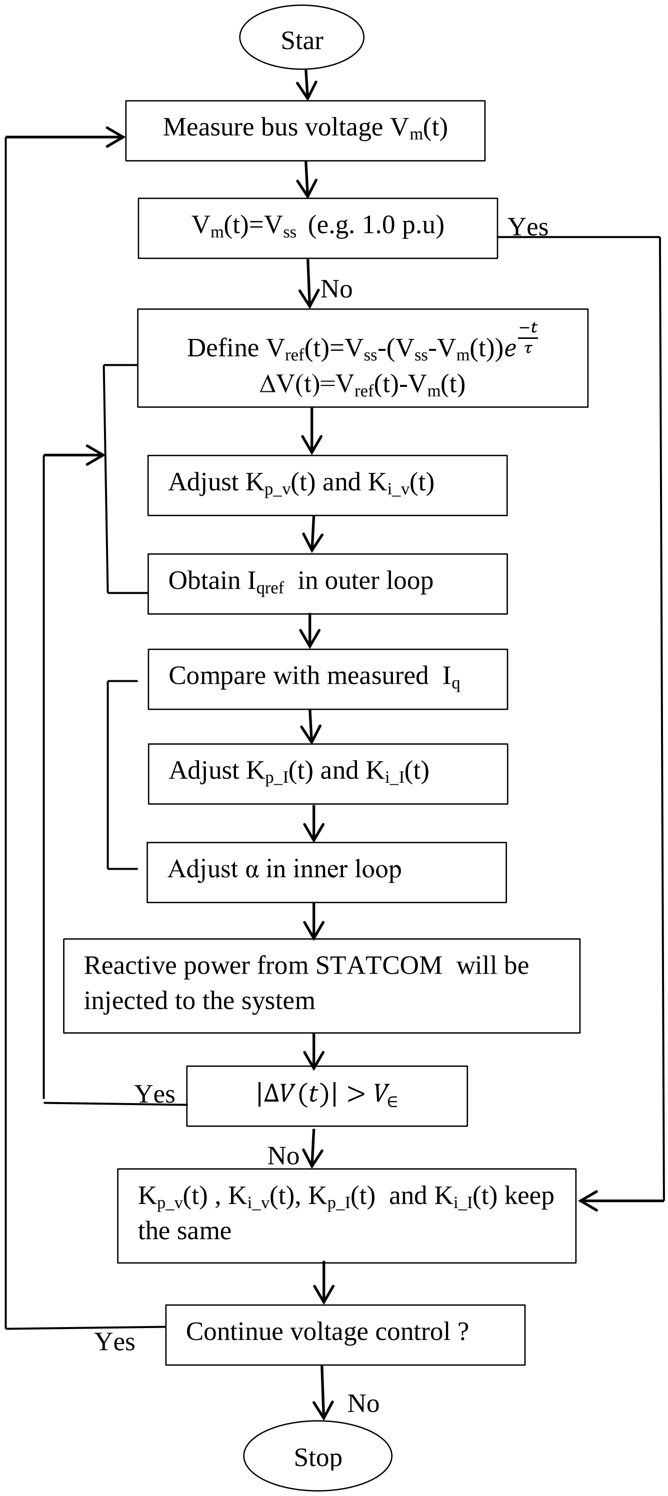

Fig. 5 shows the Flowchart for adaptive PI control method.

In the simulation, STATCOM with proposed adaptive PI controller is examined under different operating conditions. Results thus obtained are compared with the STATCOM with traditional PI controller. The results shows that the proposed adaptive PI controller gives excellent response under different operating conditions as the control parameters are modified automatically based on the disturbances.

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