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Adaptive Pi Control of Statcom for Voltage Regulation

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Abstract : *Static compensator (STATCOM) can provide fast and efficient reactive power support to maintain power system voltage stability. In the literature, various STATCOM control methods have been discussed including many applications of proportional-integral (PI) controllers. However, these previous works obtained the PI gains via a trial-and-error approach or extensive studies with a tradeoff of performance and applicability. Hence, control parameters for optimal performance at a given operating point may not be as effective at a different operating point. This paper proposes a new control model based on adaptive PI control, which can self-adjust the control gains during a disturbance such that the performance always matches a desired response, regardless of the change of operating condition. Since the adjustment is autonomous, this provides the plug-and-play capability for STATCOM 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 contrast, the conventional STATCOM control with tuned, fixed PI gains usually performs fine in the original system with a fuzzy logic controller, but may not perform as efficiently as the proposed control method when there is a change in system conditions.*

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

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I. Introduction

Voltage stability is a critical consideration in improving the security and reliability of power systems. The static compensator (STATCOM), a popular device for reactive power control based on gate turnoff (GTO) thyristors, has gained much interest in the last decade for improving power system stability [1]. In the past, various control methods have been proposed for STATCOM control. References [2]–[9] mainly focus on the control 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 role in STATCOM performance. Presently, few studies have been carried out in the control parameter settings. In [09-10], the PI controller gains are designed in a case-by-case study or a 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. Furthermore, 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 [1]. 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.

A few, but limited, previous works in the literature discussed the STATCOM PI controller gains in order to better enhance voltage stability and to avoid time-consuming tuning. For instance, in [1-2], linear optimal controls based on the linear quadratic regular (LQR) control are proposed. This control depends on the designer's experience to obtain optimal parameters. In [8], a new STATCOM state feedback design is introduced based on a zero set concept. Similar to [2–4], the final gains of the STATCOM state feedback controller still depend on the designer's choice. In [3–5], a fuzzy PI control method is proposed to tune the PI controller gains. However, it is still up to the designer to choose the actual, deterministic gains. In [6], the population-based search technique is applied to tune the controller gains. However, this method usually needs a long running time to calculate the controller gains.

A tradeoff of performance and the variety of operation conditions still has to be made during the designer's decision-making process. Thus, highly efficient results may not always be achievable under a specific operating condition. Unlike these previous works, the objective of this paper is to propose a control method that can ensure a quick and consistent desired response when the system operation condition varies. In other words, the change of the external condition will not have a negative impact, such as slower response, overshoot, or even instability on the performance. Based on this fundamental motivation, an adaptive PI control of STATCOM for voltage regulation is presented in this paper. With this adaptive PI control method, 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

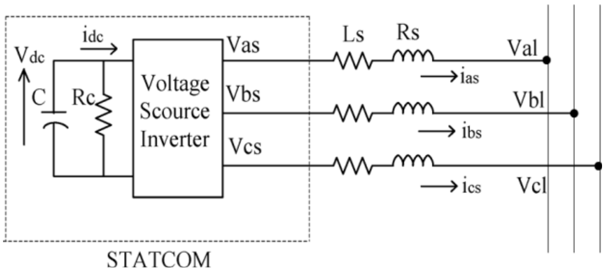

Fig. 1. Equivalent circuit of STATCOM.

and can be adjusted in real time to track the reference voltage. Unlike other control methods, this method will not be affected by the initial gain settings, changes in system conditions, and the limits of human experience and judgment. This will make the STATCOM a "plug-and-play" device. In addition, this research work demonstrates fast, dynamic performance of the STATCOM in various operating conditions.

II. System Configuration& Dynamic Model

The equivalent circuit of the STATCOM model is shown in Fig. 1. In this power system, the resistance in series with the voltage source inverter represents the sum of the transformer winding resistance losses and the inverter conduction losses.

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

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

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

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

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

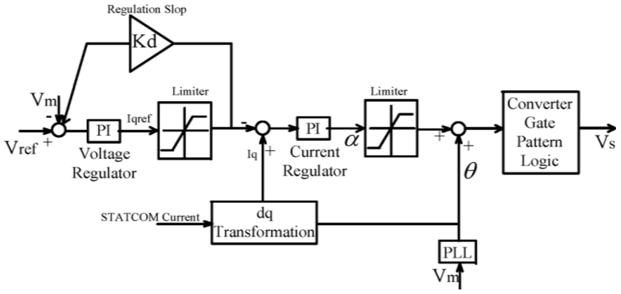

Fig. 2. Traditional STATCOM PI control block diagram.

Using the *abc/dq* transformation, Equations (1)–(4) can be rewritten as follows:

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

where and are the and currents corresponding to , and is a factor that relates the dc voltage to the peak phase-to-neutral voltage on the ac side is the dc-side voltage; is the phase angle at which the STATCOM output voltage leads to the bus voltage; is the synchronously rotating angle speed of the voltage vector; and and represent the and axis voltage corresponding to and , respectively. Equations (6) and (7) can be obtained as follows

$$pt = \frac{3}{2} V_{dl} i_{ds} \tag{6}$$

$$qt = \frac{3}{2} V_{dl} i_{qs} \tag{7}$$

Based on the above equations, the traditional control strategy can be obtained, and the STATCOM control block diagram is shown in Fig. 2. As shown in Fig. 2, the phase-locked loop (PLL) provides the basic synchronizing signal, which is the reference angle to the measurement system. The measured bus line voltage is compared with the reference voltage, and the voltage regulator provides the required reactive reference current. The droop factor is defined as the allowable voltage error at the rated reactive current flow through the STATCOM. The STATCOM reactive current is compared with , 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 the control while considering the maximum reactive power capability of the STATCOM.

III. Adaptive Pi Control For Statcom & Flowchart

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 the 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 and the reference voltage , and the -axis reference current and the -axis current are in per-unit values. The proportional and integral parts of the voltage regulator gains are denoted by and , respectively. Similarly, the gains and represent the proportional and integral parts, respectively, of the current regulator. In this control system, the allowable voltage error is set to 0. The , and can be set to an arbitrary initial value such as simply 1.0. One exemplary desired curve is an exponential curve in terms of 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 the desired time duration. The process of the adaptive voltage-control method for STATCOM is described as follows.

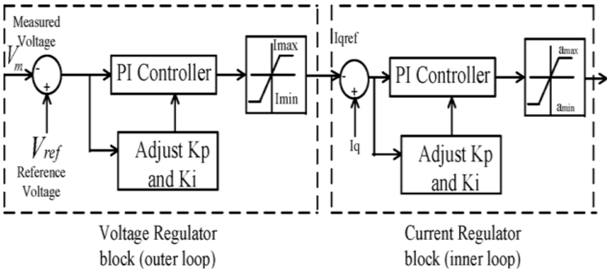

Fig. 3. Adaptive PI control block for STATCOM.

1) The bus voltage 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, is compared with . Based on the desired reference voltage curve, and are dynamically adjusted in order to make the measured voltage match the desired reference voltage, and the -axis reference current can be obtained. 3) In the inner loop, is compared with the -axis current. Using a similar control method like the one for the outer loop, the parameters and 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 the reactive power injected into the system to keep the bus voltage at the desired value. It should be noted that the current and and the angle and are the limits imposed with the consideration of the maximum reactive power generation capability of the STATCOM controlled in this manner.

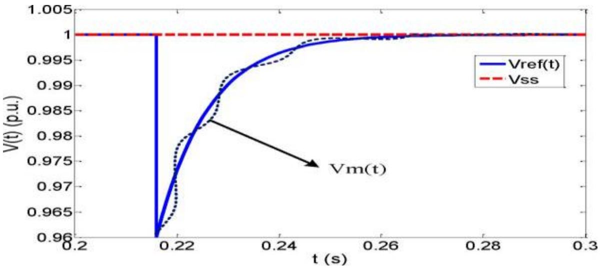

Fig. 4. Reference voltage curve.

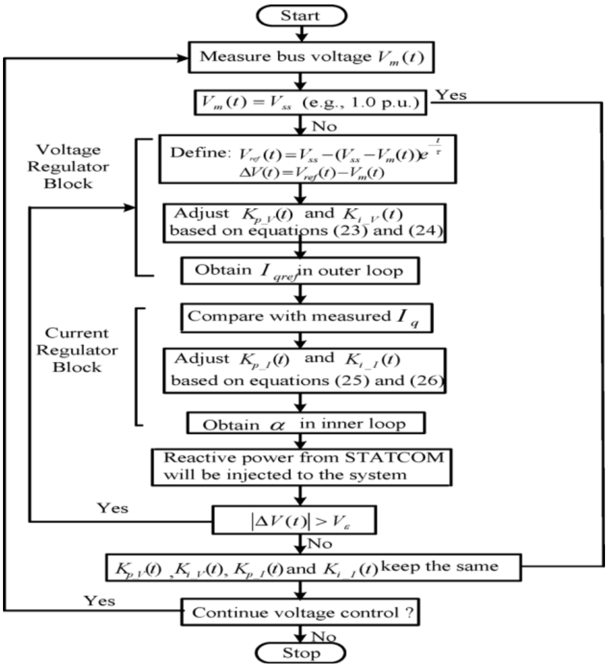

Fig. 5. Adaptive PI control algorithm flowchart.

If one of the maximum or minimum limits is reached, the maximum capability of the STATCOM to inject reactive power is considered to have been reached. Certainly, as long as the STATCOM sizing has been appropriately studied during the planning stages for inserting the STATCOM into the power system, the STATCOM should not reach its limit unexpectedly.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 over time is sampled according to a desired sampling rate. Then, is compared with . If , then there is no reason to change any of the identified parameters and the power system is running smoothly.

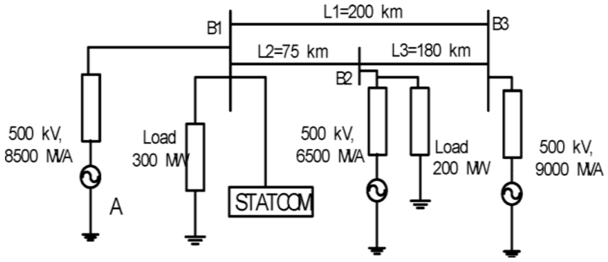

Fig. 6. Studied system.

blocks and the current regulator blocks are rentered until the change is less than the given threshold . Thus, the values for, and 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 .

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 the MATLAB/Simulink library, and all machines used in the simulation are dynamical models . Here, attention is focused on the STATCOM control performance in the bus voltage regulation mode. In the original model, the compensating reactive power injection and the regulation speed are mainly affected by the 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 is 1.0 p.u. 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.In the fuzzy logic toolbox software, fuzzy logic should be interpreted as fuzzy logic (FL), that is, fluffy rationale in its wide sense. The essential concepts basic FL are clarified plainly and adroitly in Foundations of Fuzzy Logic. Fuzzy logic controller as shown in Fig 8.

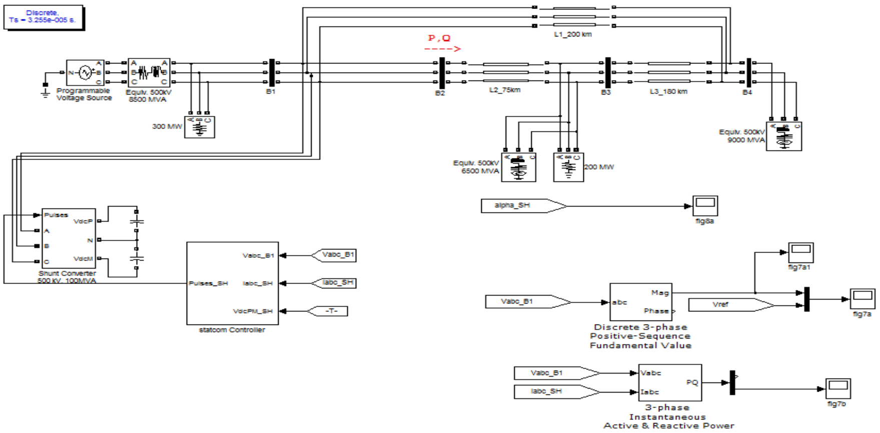

Fig.7. Simulation Diagram

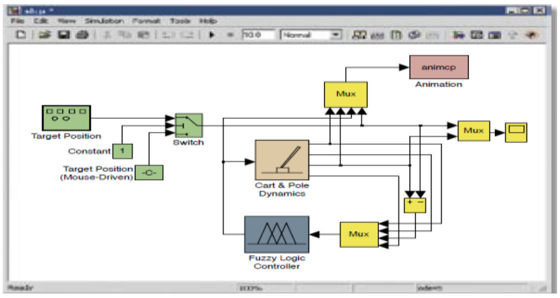

Fig.8 Fuzzy Logic controller

B.Response of the Original Model

In the original model, 12, 3000, 5, 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 500kv.

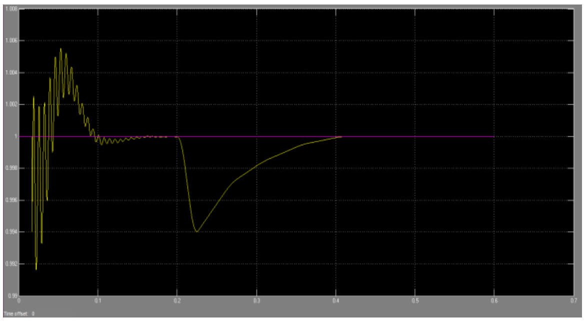

Fig:(a)

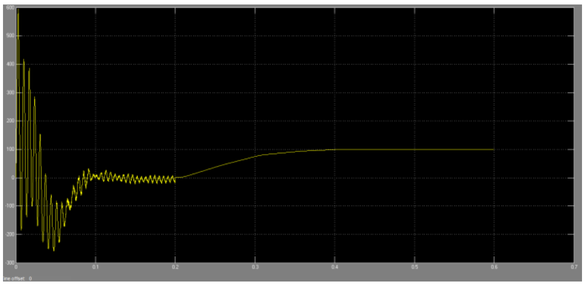

Fig:(b)

Fig. 9. Results of (a) voltages and (b) output reactive power using the same network and loads as in the original system

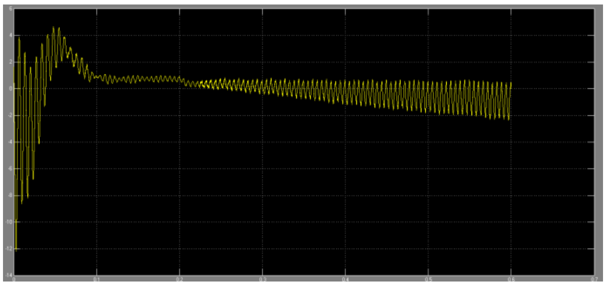

Fig:(a)

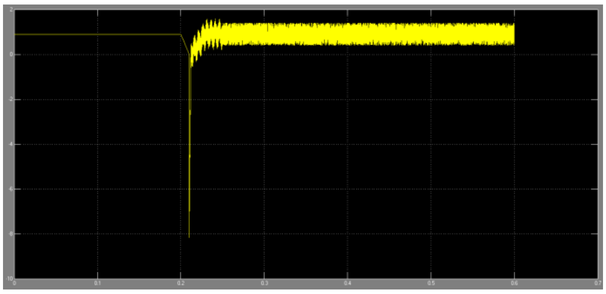

Fig:(b)

Fig. 10. Fig.11 Results of (a) voltages and (b) output reactive power using the same network and loads with out adaptive control as in the original system

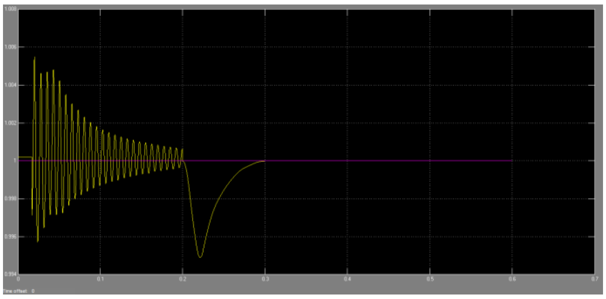

Fig:(a)

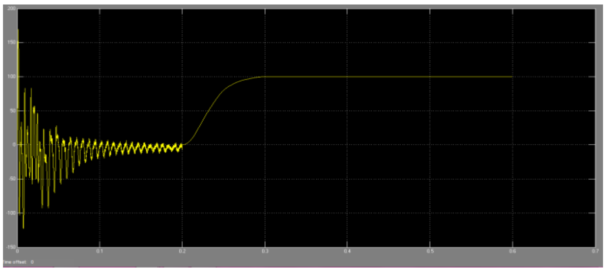

Fig: (b)

Fig.11 Results of (a) voltages and (b) output reactive power using the same network and loads of adaptive control as in the original system

C. 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. 12 and 13. From Fig. 14, 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. 12(a) that the

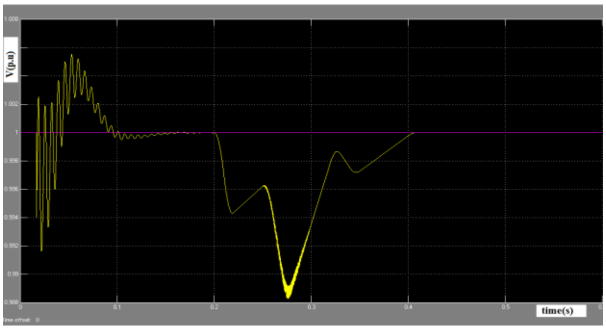

Fig:(a)

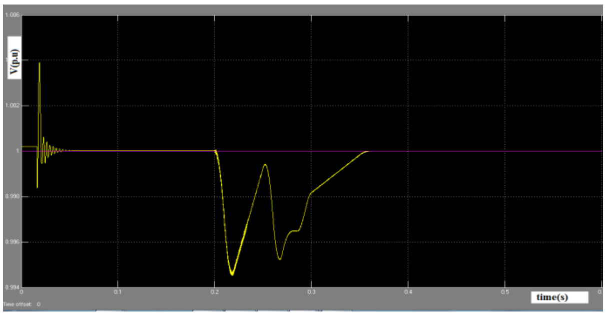

Fig:(b)

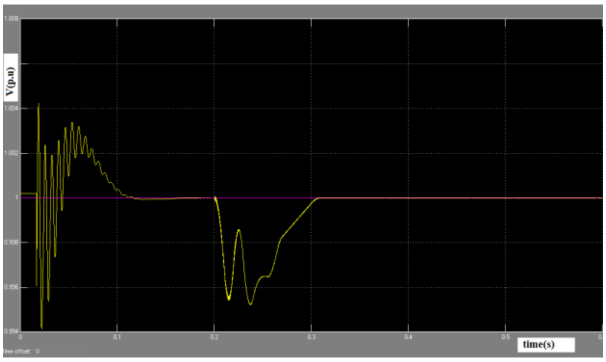

Fig:(c)

Fig. 12. Results of (a) voltages and (b)&(c) output reactive power with first Disturbances

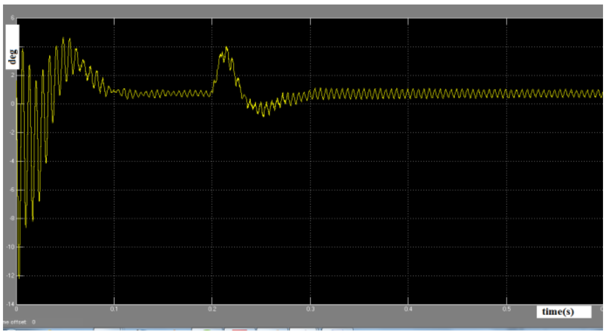

Fig:(a)

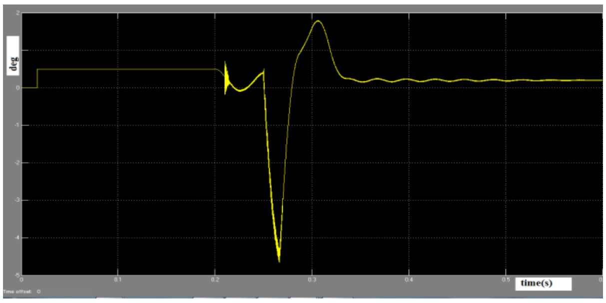

Fig:(b)

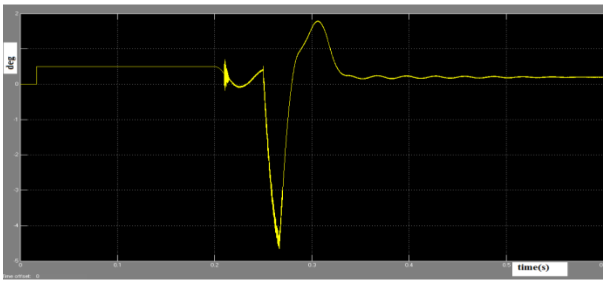

Fig:(c)

Fig. 13. Results of (a) voltages and (b)&(c) output reactive power with second Disturbances

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.

D. 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. 14 and 15. 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. 14(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 (40 MVar) is much less than the Q curve in the original control (118 MVar).

E.Summary of the Simulation Study

From the above case studies shown in fig's it is evident that the adaptive PI control can achieve faster and more consistent response than the original one. The response time and the curve of the proposed 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.

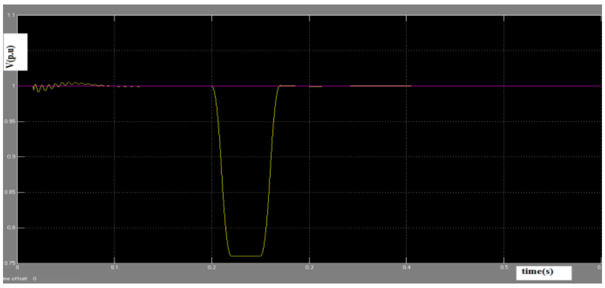

Fig:(a)

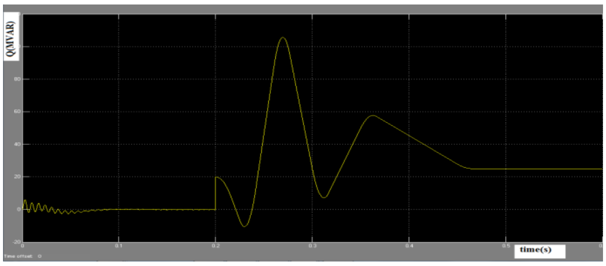

Fig:(b)

Fig. 14. Results of (a) voltages and (b) output reactive power in a severe Disturbance

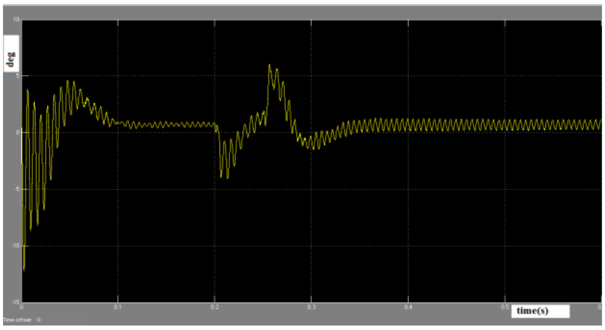

Fig:(a)

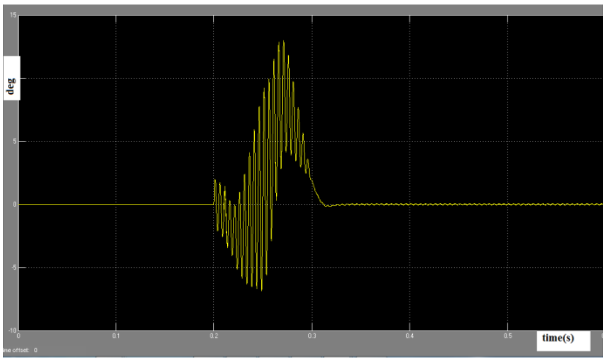

Fig:(b)

Fig. 15. Results of Results of (a) &(b) in 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.

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