

Active and reactive energy storage STATCOM distribution system power management

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ABSTRACT

One of the critical factors influencing the overall development of modern power systems is the control of active and reactive power flows in distribution power systems. The static synchronous compensator (STATCOM) with storage energy is a powerful device that can control active and reactive power flow in a distribution system. A simulation model of power management using STATCOM with energy storage is presented in this paper. A fuzzy logic controller is proposed to manage the powers. The simulation results demonstrate STATCOM's ability to manage the active and reactive power flow in a controlled distribution line, and thus the powers regulated between feeders, by utilizing storage energy.

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1. INTRODUCTION

Devices for the flexible AC transmission system (FACTS) are commonly split into two categories: controllers based on voltage source converters and controllers based on other types of voltage source converters. Non-converter-based FACTS controllers, such as thyristor-controlled series capacitors and static volt-ampere reactive (VAR) compensators, have the advantage of being able to produce or absorb reactive power MVAR without the usage of AC reactors and capacitors. Converter types based on FACTS devices and controllers include SSSC and STATCOM and two converter types unified power flow controller (UPFC) and IPFC that have the ability to independently control the parameters voltage, current, and reactive and active power flow on transmission or distribution lines [1].

The power flow through an alternating current distribution line is affected by the line's impedance, the amplitude of the voltages at the sending and receiving ends, and the phase angle between these voltages. The distributed power between the feeders is dependent on the impedance and reactance of the network's transmission or distribution [2]. The static synchronous compensator (STATCOM) is the second-generation member of FACTS devices that utilizes the synchronous voltage source (SVS) concept to provide a comprehensive control capability for distribution systems. Under the scope of standard power distribution system principles, the STATCOM with energy storage (ES) may control all parameters impacting power flow in distribution lines simultaneously or selectively. Alternatively, it can give the exceptional functional capacity of independently managing both active and reactive power flows in the distribution system [3].

The STATCOM is connected in parallel with a distribution line and primarily consists of a 3-phase 6-pulses bridge inverter that is controlled by the STATCOM controller to inject 3-phase synchronous currents [4]. A STATCOM without ES can regulate reactive-power as a source. It provides the desired amount of reactive-power that can be generated or absorbed solely through power electronic processing of the reference signal of voltage or current waveforms in a voltage-source converter (VSC). Figure 1 shows the schematic diagram of STATCOM where, Figure 1(a) depicts a STATCOM single-line diagram in which a VSC is coupled to a controlled bus via a magnetic coupling reactor and Figure 1(b) depicts a STATCOM as an adjustable voltage converter ($E_{STATCOM}$ or E_s) back of a reactance, implying that no capacitor banks or shunt reactors are required for reactive-power production and absorbing, resulting in a simple package, compact size, low noise, and minimal magnetic impact. The current injected at the utility bus is where the voltage $E_{utility}$ (E_t) and the current at DC side I_{dc} and the voltage is V_{dc} also the injected current $I_{STATCOM}$ (I_q):

$$I_{STATCOM} = \frac{E_{STATCOM} - E_{util}}{X_S} \quad (1)$$

where $I_{STATCOM}$ delivered or absorbed power to/from the grid.

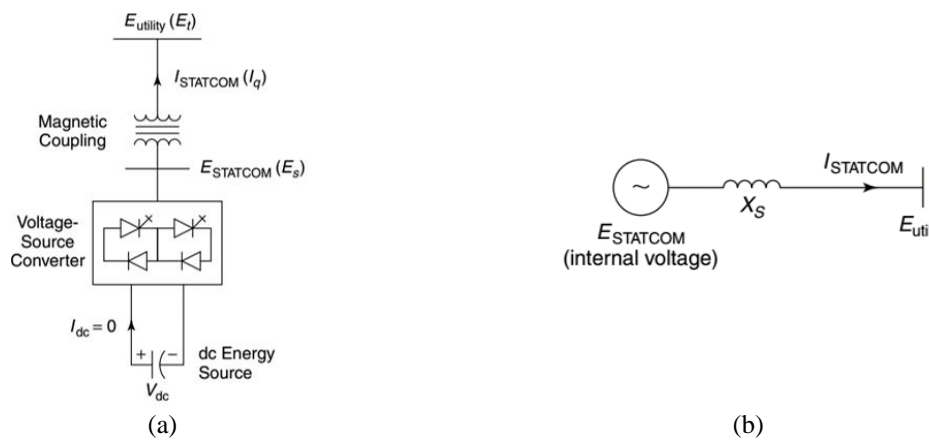


Figure 1. Schematic diagram of STATCOM (a) power circuit and (b) an equivalent circuit

Figure 2 depicts a typical voltage-current STATCOM characteristic. As shown in Figure 2, the STATCOM is able to provide compensation in both capacitive and inductive directions, and it is also capable of independently controlling the injected current to the network's common point through its rated range maximum inductive side or capacitive side, regardless of the network side's current or voltage. STATCOM is able to provide reactive power for capacitive/inductive compensation at any voltage level, including for less than 0.2 pu. Another advantage of STATCOM's technology is its capable to generate full capacitive/inductive current regardless of the grid's voltage. This means that STATCOM is able to provide a constant current to the grid. This feature is especially beneficial when the STATCOM is required to support the power system's voltage during and after disturbances, when system voltage collapse would be a limiting issue [5].

The STATCOM has increased transient rating currents supplies from the inverter in both inductive ($E_{STATCOM} < E_{utility}$) and capacitive operating regions ($E_{STATCOM} > E_{utility}$), as shown in Figure 2. The highest permissible transient overcurrent with in capacitive area is determined by the maximum current turn-off converter switch's capabilities. The switches of the converter are naturally commutated in the transient inductive area; thus, the STATCOM transient-current rating is constrained by the maximum junction temperature of the switch's converting [6]. In actuality, semiconductor converter switches include internal losses; as a result, the amount of energy stored in the capacitor as dc power is eventually used to offset the internal losses of the switches converter, and the dc energy stored as voltage declines. When the static synchronous compensator is used to generate reactive power, the converter can keep the capacitor voltage constant [7]. This is achieved by permitting the output converter voltages to lag behind the AC-grid voltages at common connection by a modest angle (typically within the range of 0.2–0.3). Within that technique, the switches converter takes a little amount of active power from the grid system to compensate for the switches' internal losses and maintain the desired voltage of the capacitor [8]. This identical mechanism controls the voltage used to decrease or increase the capacitor voltage and, consequently, the magnitude of the converter-output voltage as well as the phase shift used to regulate the reactive power (VAR) that is absorbed or

generated [9]. As a result, the megawatts (MW) and MVAR (active and reactive-power) can exchange between STATCOM and the grid via a single connection that can be adjusted independently as shown in Figure 3 for various power combinations active and reactive power generating or absorbing depending on magnitude of $E_{STATCOM}$ and phase shift between $E_{STATCOM}$ and $E_{utility}$ [10].

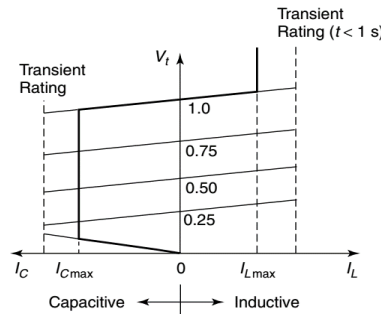


Figure 2. The voltage vs current characteristic of STATCOM

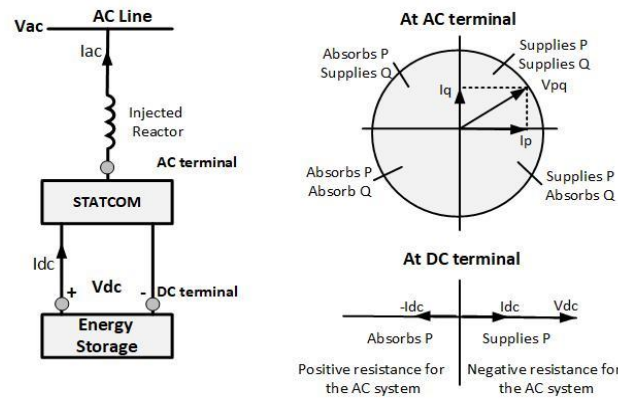


Figure 3. The power exchange

2. ACTIVE POWER MANAGEMENT

STATCOM with connection of battery as an energy storage, connected in shunt to the grid arrangement as shown in Figure 1 at the point of common coupling (PCC). It is able to compensate Active and/or Reactive power independent of the grid parameters voltages and currents control ability. Energy storage (ES) battery, DC-to-DC converter in bidirectional process, a three phase-inverter with controlled switches and injected reactor as output connected to the grid at PCC without the need for an intermittently efficient huge transformer are the primary sections [11]. A reactive power compensator-based STATCOM with an inverter requires an interrupted transformer with step-up to its output level to work on an AC grid [12]. DC load with a low power factor (PF) result in a penalty for the DC load's operator from the utility. Similarly, the use of energy storage batteries to generate active power in MW at a common coupling point in order to meet the intermittently large power demand from the grid utility can avoid the hefty penalties imposed by the use supplier to the DC operator due to the infrequently large load demand from the grid utility [13]. STATCOM can compensate based on energy storage (ES) likely used to provide uninterruptible power supply (UPS) supply at utility of grid level in the absence of a power utility [14]. Consequently, it is necessary to maintain operating costs by avoiding penalties and increasing electrical efficiency through the power compensation benefits for both active and reactive loads connected [15], [16]. The following equations illustrate the simultaneous independent compensation of reactive (q) and active power (p) using STATCOM, which can be achieved by controlling magnitude and also δ (phase shift between V_s , the STATCOM output voltage, and V_{GRID} , the grid voltage at PCC parameters:

$$p = \frac{3V_{GRID}V_S \sin \delta}{\omega L} \tag{2}$$

$$q = \frac{3V_{GRID}(V_S \cos \delta - V_{GRID})}{\omega L} \quad (3)$$

Where V_{GRID} is the grid voltage, V_S is the output of STATCOM, L smoothing reactor and $\omega=2\pi f$ line frequency. Referring to Figure 1(b). During normal DC operation, the load is supplied by the AC power grid. Real power from the network is also absorbed to charge the storage battery [17] when V_{GRID} leads V_S with phase $\delta < 0$. Similarly, real power is delivered to the network when the voltages V_{GRID} lag behind V_S with a phase shift of ($\delta > 0$) [18]. This is accomplished by discharging energy stored in batteries due to abnormal conditions in network power losses to DC or unusually high DC load demand [19]. Real power flow to the network is zero when there is no phase shift between V_{GRID} and V_S , or when $\delta = 0$ [20]. Utilizing a reactive power VAR compensator to supply VAR at the network's PCC so that the displacement factor of line in PCC is unity [16]. STATCOM acts as a compensator when the current is lagging and as a VAR source when V_S is greater than V_{GRID} . In the same manner, STATCOM acts as a compensator with current in leading to supply reactive power in lagging when $V_S < V_{GRID}$ [19]. When both V_S and V_{GRID} are equal, reactive power compensator supplies will be 0 VAR [21]. Table 1 and Figure 4 show the calculated real and reactive powers p & q at grid voltage (V_{GRID}) in per unit with respect to V_S , greater than or less than V_{GRID} by using (2) and (3) respectively. The series-connected reactor (smoothing reactor) is to be set to 5% of the line's impedance. Figure 4 depicts the relationship between active and reactive power and phase angle for the two cases $V_S < V_{GRID}$ and $V_S > V_{GRID}$.

Table 1. Active and reactive vs phase angle

δ	$V_S > V_{GRID}$		$V_S < V_{GRID}$	
	Active Power P	Reactive Power q	Active Power P	Reactive Power q
5	1.00301	0.948571	1.01011	-1.00697
4	0.801354	0.964286	0.808824	-0.99024
3	0.48909	0.978571	0.413603	-0.9205
2	0.300978	0.985714	0.367647	-0.90656
1	0.150489	0.992857	0.340074	-0.89261
0	0	1.015714	0	-0.86471
-1	-0.15049	0.992857	-0.34007	-0.89261
-2	-0.30098	0.985714	-0.36765	-0.90656
-3	-0.48909	0.978571	-0.4136	-0.9205
-4	-0.80135	0.964286	-0.80882	-0.99024
-5	-1.00301	0.948571	-1.01011	-1.00697

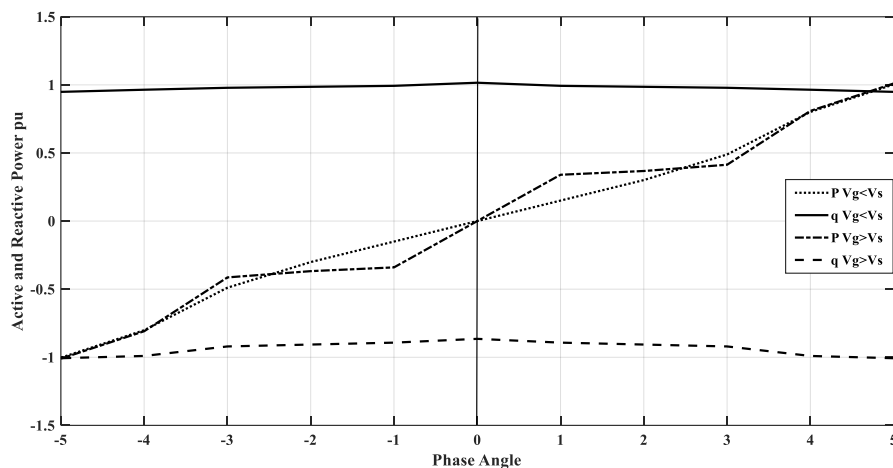


Figure 4. Active and reactive power vs phase angle

3. POWERS MEASURING

Instantaneous power theory was utilized for rapid response to any change in the grid's real and reactive powers. Watanabe *et al.* [16] developed the instantaneous power theory, also known as the p-q theory, in 1983 with the goal of applying and controlling active power filter (APF). The pq theory is based on Time-Domain analysis, which is relevant and valid for both transient and steady-state analysis, and is able to be applied to the general form of current and voltage in the power system's waveforms, allowing real-time control of active power filters (APFs) [22]. Another advantage of pq theory is its simplicity in calculations, which includes an exception to the separation requirement between the alternated value and mean value in the calculated

components of power [23] for algebraic calculations. The "Clarke Transformation" is used by the pq theory to change a reference frame system of abc coordinates to α - β -0 coordinates [24].

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (5)$$

The active and reactive power compensation is then computed as (6),

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (6)$$

from the matrix above the active and reactive power are:

$$p = v_\alpha i_\alpha + v_\beta i_\beta \quad (7)$$

$$q = v_\beta i_\alpha - v_\alpha i_\beta \quad (8)$$

where i_α and i_β are the two-orthogonal components of the line currents i_a , i_b and i_c and v_α and v_β are the two-orthogonal voltage components of the voltage and v_a , v_b and v_c are the phase voltage.

The desired reactive and real power values, p_{ref} and q_{ref} , are compared to the measured values, p and q , to generate error signs Δ_p and Δ_q . These signs are processed in the controller, which does the (9) and (10).

$$\Delta_p = p_{ref} - p \quad (9)$$

$$\Delta_q = q_{ref} - q \quad (10)$$

The injected currents after modify the active and reactive power in pq theory:

$$\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\Delta_p \\ -\Delta_q \end{bmatrix} \quad (11)$$

where i'_α and i'_β the injected orthogonal currents, the inverse Clarke transformation to get the injected three phase current:

$$\begin{bmatrix} i'_a \\ i'_b \\ i'_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} \quad (12)$$

where i'_a , i'_b , and i'_c are the injected currents in three phase form.

The control system of power management is shown in Figure 5. It consists of inputs of two signal three phase voltages and currents are convert to two pair of orthogonal signals i_α and i_β , v_α and v_β . Clarke transforms are used to determine the measurement real power p and reactive power q based on the line voltage and current. Such signals are used to provide feedback to the control system with a closed loop. The desired real and reactive power p_{ref} and q_{ref} are then evaluated to the measured p and q to generate error signals Δ_p and Δ_q , which are sent to the controller. These fault signals are processed in the controller, which does the following: Then the currents that compensated are determined by (12). The compensated currents are i'_α and i'_β convert to three phase for injection to compensate the active and reactive power respectively.

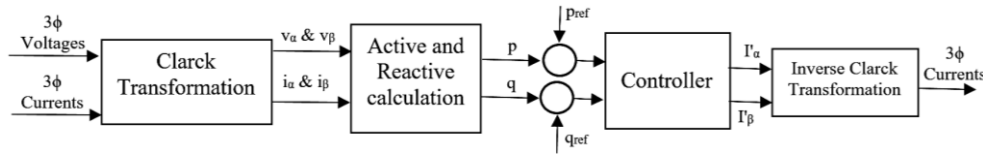


Figure 5. Block diagram of power management

4. CONTROL SCHEME

The selected controller was fuzzy control (FC). It is suitable for approximate reasoning systems or uncertain systems, particularly those that are difficult to model mathematically [25]. In this paper, FC is employed as a PI controller:

$$i_s(t) = K_p \text{Error}_p + K_I \int \text{Error}_p dt \tag{13}$$

where:

i_s : is the parameter (the current of STATCOM)

Error_p : is the controller fault signal

K_p and K_I are gains of proportional and integral, respectively.

The derivative for (13) is (14).

$$\dot{i}_s = K_p \dot{\text{Error}}_p + K_I \text{Error}_p \tag{14}$$

The procedure defined by (13) and (14) is then converted into a set of fuzzy rules [26] to drive a FC that functions like a PI controller. The inputs supplied to the controller are vectors of the output from (13) and (14) respectively, (Δp) as well as the error signal change (Δerror_p), and the output of the controller controls the inverter pulses. Table 2 displays the $\text{Error}_p/\Delta \text{error}_p$ (error and change) values for fuzzy-like PI. In this Fuzzy logic controller, the two input variables to the FC were partitioned into five-membership triangle functions (NB, NS, Z, PS, PB) whose terms denote the following: (negative big, negative small, zero, positive small, positive big). Consequently, there are twenty-five control rules for two input signals. The form type having a 50 percent overlap. Figure 6 depicts the proposed FC structure. The error between the testing and training stages is around 1.75×10^{-7} , and all intended output values are achieved.

Table 2. Rules-based values for fuzzy logic controller

$\text{Error}_p/\Delta \text{error}_p$	NB	NS	Z	PS	PB
	-1	-1/2	0	1/2	1
NB	1	NB	NB	NS	Z
NS	-1/2	NB	NS	Z	PS
Z	0	NB	NS	Z	PS
PS	1/2	NS	Z	PS	PB
PB	1	PB	PS	PB	PB

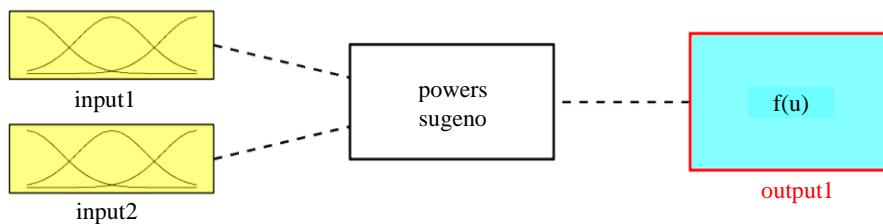


Figure 6. Block diagram of fuzzy logic control

5. MODELING AND SIMULATION RESULTS

As shown in Figure 7, the suggested system model comprises of a feeder with two load branches and three busbars. The STATCOM system is installed between busbar 1 (B1) and busbar 3 (B3) to compensate the power in busbar 1 (B1). The test begins by varying the loads in two branches and measuring the three-phase voltages and currents at B1; following a comparison with the reference value, the controller sends a signal to start injecting current starts at 1sec, as depicted in Figure 8. The real and reactive powers at B1 change from 0.84 pu to 1 pu for active power and from -0.82 pu to about -1 pu for reactive power, as depicted in Figures 9

and 10. The voltages in Busbars B1, B2, and B3 are depicted in Figure 11. A voltage drop occurs in Busbar B1 due to an increase in load from the two branches; the voltage at Busbar B1 was less than 0.8 pu before to injection at $t=1$ sec, when it rose to approximately 1 pu. From the results, it can be shown that the voltage drops at the buses grew proportionally with the load; the greatest voltage drop was 0.8 pu within 1 second. Figure 12 depicts the injection current following the reference value in response to any system change, the power losses in all cases not exceed 0.0162 pu. Figure 13 depicts the system's step-change response to active power. The figure shows that the new controller design (Fuzzy controller) has a smoother response and reaches the steady state faster than without the controller.

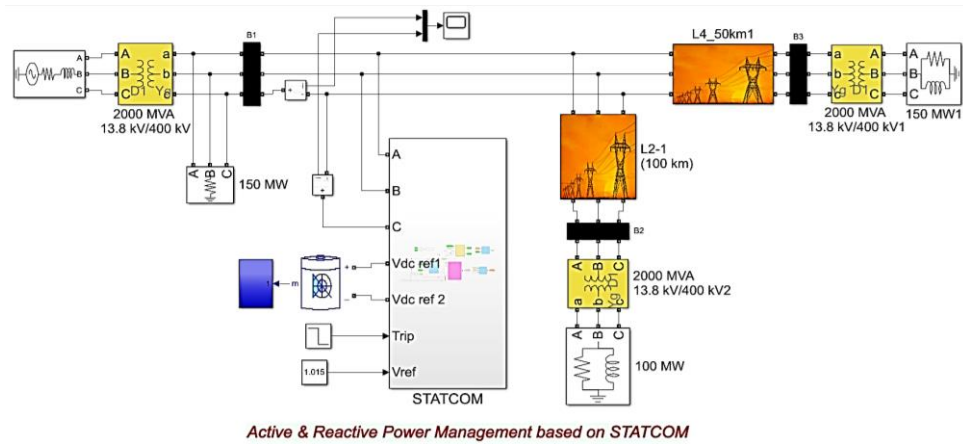


Figure 7. The proposed model

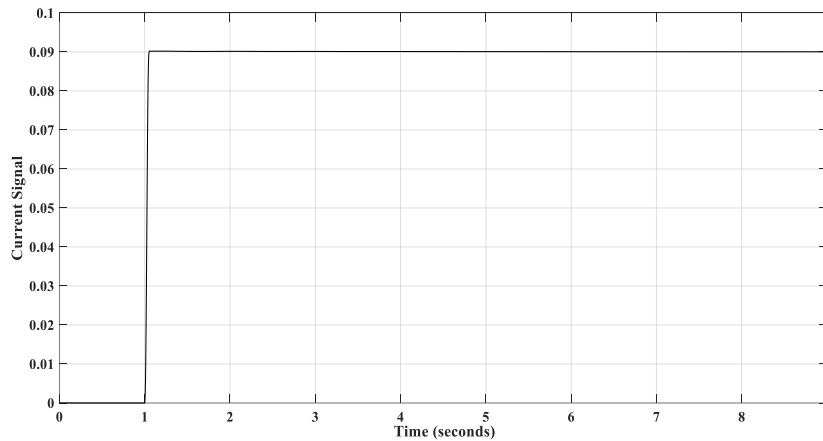


Figure 8. The current signal

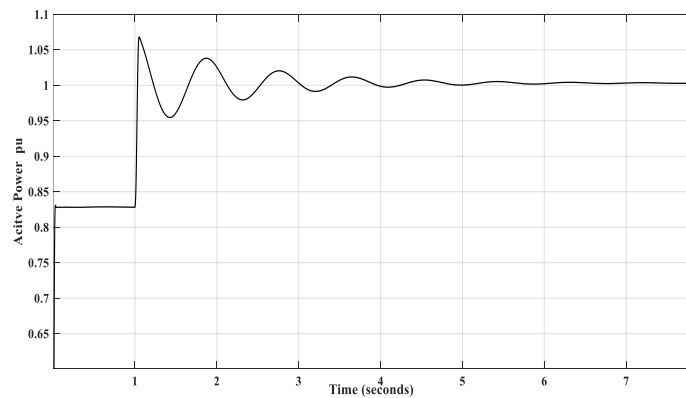


Figure 9. Active power

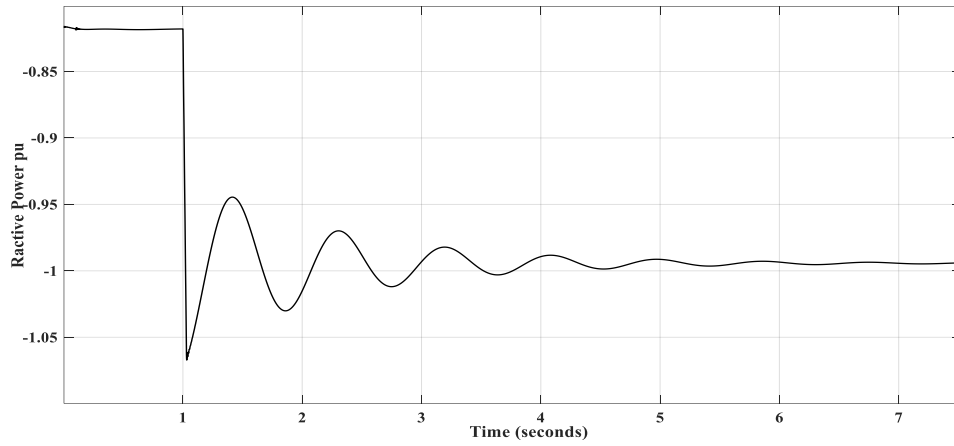


Figure 10. Reactive power

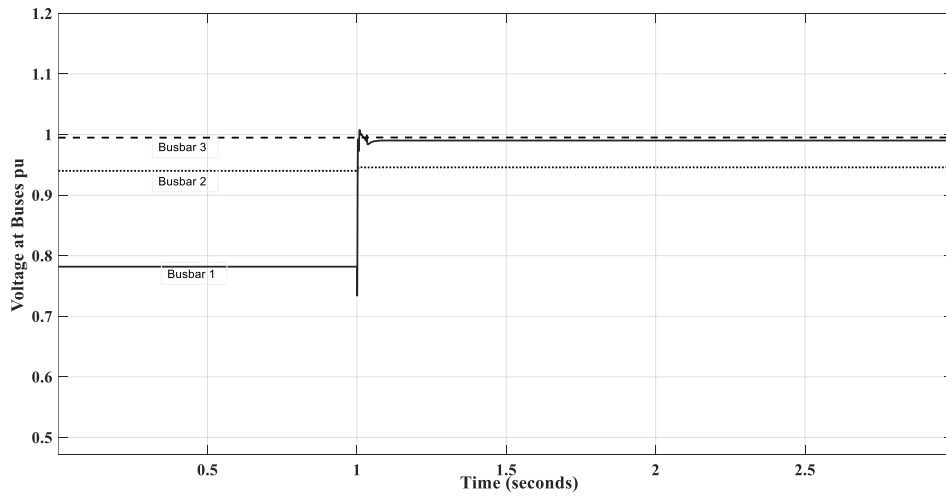


Figure 11. Busbars voltages

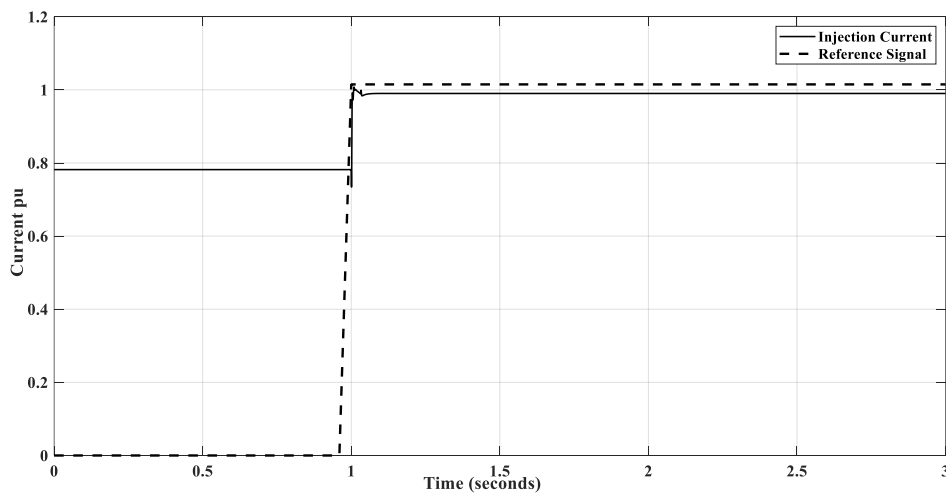


Figure 12. Injection current

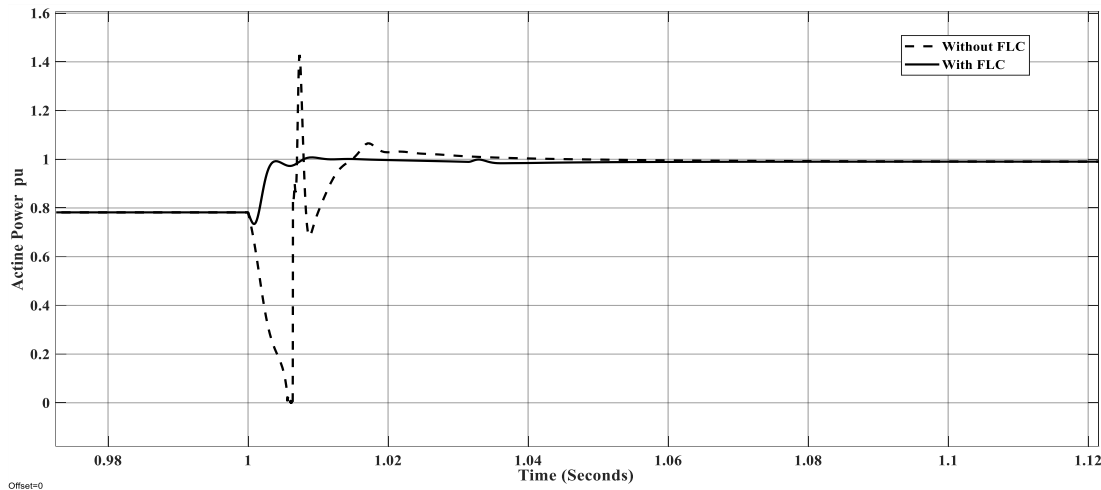


Figure 13. Active power step change

6. CONCLUSION

In this paper, STATCOM with energy storage is deployed to manage active and reactive power in a distribution system. STATCOM with energy storage demonstrated the ability to control active power in addition to reactive power. The tuning algorithm is executed off-line using the ANN-fuzzy system concept. The tuning procedure is initiated by the rules specified by training the change in error for actual and reactive power. Real-time implementation of the controller is possible due to its low processing time. The proposed controller has been effectively implemented to regulate the reactive power and then the line voltage at busbars, particularly those closest to the STATCOM. The simulation findings indicate that the proposed strategies employing a fuzzy logic controller based on STATCOM can give appropriate performance for managing the active and reactive power as well as the bus voltage.

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