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# Coordinated control of DSTATCOM with switchable capacitor bank in a secondary radial distribution system for power factor improvement

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## Abstract

This paper exhibits the coordinated control of 30 kVAr Distribution STATic synchronous COMpensator (DSTATCOM) with 125 kVAr Switchable Capacitor Banks for compensation of reactive power in a 750 kVA secondary radial distribution system. With the control of reactive power in a radial distribution system, the power factor can be improved near to unity. The selected radial distribution system mainly feeding power to vital loads of an Educational Institution. In this paper, the study of 750 kVA secondary radial distribution system is analyzed in terms of electrical power system of institute, power consumption pattern and tariff related issues. Some conclusions to improve the system performance in terms of power factor and reduction in tariff were drawn. The coordinated control of switchable capacitor bank and DSTATCOM performance depends on the calculation of the reference source currents that generates the gating pulses of the voltage source converter-based DSTATCOM. For this purpose, the control strategy adopted is Real and Reactive power (PQ) control, Synchronous Reference Frame theory, Back Propagation Control algorithm and Adaptive Linear (ADALINE) control is implemented in this system using MATLAB/SIMULINK software. Generation of the PWM pulses triggers the IGBT of the VSI-based DSTATCOM. This is achieved using DSP TMS 320 F 2812, a 32-bit processor that is programmed with CCS V3.3 and C2000 embedded code generation tool using MATLAB/Simulink, and the same is being executed with code composer studio V 6.0.1. The performance of the selected secondary radial distribution system is analyzed experimentally in a hardware prototype to evaluate the effect of DSTATCOM and switchable capacitor bank.

**Keywords:** Coordinated control, Custom power devices, Distribution static synchronous compensator, Power quality, Reactive power control, Power factor correction, Point of common coupling, Switchable capacitor bank

## Introduction

Reactive power supervision in a power distribution system of a power utility or industry plays a key role in (i) dipping distribution loss, (ii) maintaining constant distribution voltage, and (iii) getting better power factor [1]. The perfection of power factor enables the reduction of current demand from the utility resulting in efficient utilization of distribution transformer and reduced electricity bills [2]. The performance and parameter estimation of conventional switched capacitors used for reactive power compensation would only give step control and results in over-compensation or under-compensation for varying loads and changeable reactive power demand [3, 4]. In steel and cement industries, the sudden load variations are more in nature, so that the variation of reactive power in these industries is more in nature, so that the poor power factor of the system can be obtained. To overcome these problems, in this paper, it is proposed to develop a prototype 30 kVAr DSTATCOM for reactive power compensation which would provide instantaneous correction of power factor and always maintains the set power factor near to unity and some of the uncertainty models are studied and considered in this design [5]. The prototype consists of a power panel with IGBT-based voltage source inverter, DC filter capacitor and a DSP-based controller along with necessary power supply units, protection cards and firing pulse generating units [6]. By suitable control strategy [7], the DSTATCOM would generate leading or lagging reactive volt-amp (VAR) at the Point of Common Coupling (PCC) and avoid problems connected with lag and lead power factor [8]. The power factor can be maintained at the desired level irrespective of system voltage [9].

DSTATCOM is an acronym for Distribution STATic synchronous COMpensator [7], and forms a member of the family, widely known as Flexible AC Transmission System (FACTS) or Custom Power devices [8]. Development of DSTATCOM and knowledge of practical aspects of advanced power electronics enable the research center in Electrical Engineering Department (EED) to be a unique one with in-house capability to design and develop a FACTS device. The idea of combining capabilities of IGBT-based voltage source converter, DSP-based controller and allied power electronics as proposed in the Project opens the way in an original generation of FACTS controllers. The present development would open up a path for further studies in the region of other FACTS/Custom Power devices [9]. The know-how gained in the present development will result in tools and techniques for design of other FACTS devices such as high-power STATCOM, Static Synchronous Series Compensator (SSSC), Interline Power Flow Controller (IPFC) and Unified Power Flow Controller (UPFC), Dynamic Voltage Restorer (DVR), active power harmonic filter, and active power line conditioner [10]. A coordinated static synchronous compensator, is a combination of a relay-switched shunt capacitor and a voltage-source inverter based static synchronous compensator. This method adopted for steady-state and dynamic reactive power compensation. The utilization of the shunt capacitor is to restore static synchronous compensator capacity such that the fast voltage control for successive transient disturbances is achievable in the transmission network [11]. The design of this coordinated control method is aimed at making the STATCOM to provide less reactive power in steady state and maximize the reactive power output in the post-fault transient state. According to the authors in steady state, STATCOM is adjusted to absorb as much reactive power as possible, so it is able to provide more reactive power in post-fault transient state [12]. The required reactive power in the transmission system is estimated using a new coordinated control between STATCOM and mechanically switched capacitors (MSCs). The solution relies on the required reactive power estimation method using online grid strength level (OGSL). The objective is to reduce

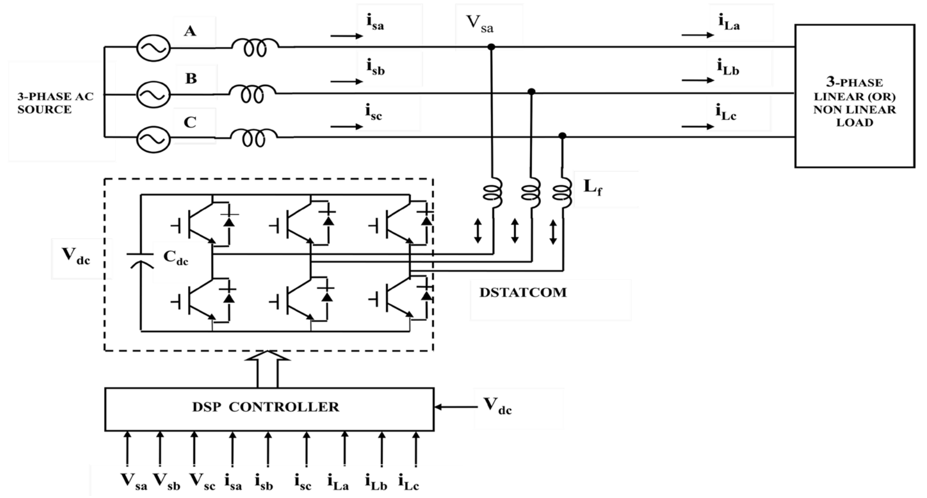


**Fig.1** Control block diagram of DSTATCOM

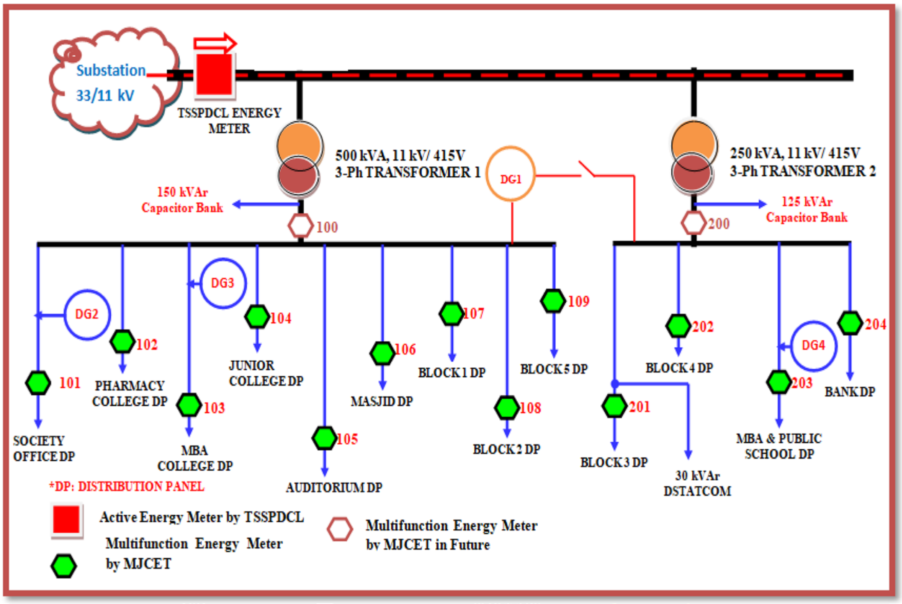


**Fig. 2** Power distribution of Sultan-Ul-Uloom Educational Society

the switching times of the MSCs while maximizing the reserve reactive power margin of the STATCOM in transient state [13]. Control block diagram of DSTATCOM is shown in Fig. 1. The complete Electrical Substation Layout of Sultan Ul-Uloom Education Society is shown in Fig. 2. The incoming supply is 11 kV /440 V divided into two parallel feeders; one is 500 kVA transformer feeder and the other feeder connected to 250 kVA transformers. The output of these two transformers feeds power to different loads in the society; in this system to control reactive power, it is connected to two automatic capacitor panels: one of 150 kVAr to feeder 1 and other of size 125 kVAr to feeder 2. To compensate, no-load reactive power transformers of fixed capacitors of 25 kVAr are directly connected to 500 kVA transformer and 15 kVAr to 250 kVA transformer at the secondary terminals of transformers.

### Objective

This paper deals with the reactive power compensation in a radial distribution system [14, 15]. The detailed objectives are given below.

a. To analyze the existing power factor in a 750 kVA, SUESRDS
b. To fabricate a prototype of 30 kVAr DSTATCOM with PWM control using DSP TMS320F2812 PGFQ board (LQFP-176)
c. To evolve the coordinated control between DSTATCOM and switchable capacitor bank
d. To maintain unity power factor in SUESRDS

This paper proposes a coordinated control of DSTATCOM with switchable capacitor bank to improve the power factor of a secondary radial distribution system. The real and reactive power control method is adopted in hardware, adaptive linear; back propagation control is adopted in MATLAB/Simulink [16–18].

## Methods

A Distribution STATCOM (DSTATCOM) is a shunt compensation device used for reactive power compensation [19, 20]. It can be used either in the power factor correction mode or in the voltage regulation mode. The major problem associated with the design of the controller for the DSTATCOM is the selection of appropriate circuit components. The second major problem is to understand the proper working of the controller and control algorithms. It is necessary to understand the design of hardware components and the controller, so that the DSTATCOM is effectively used for power quality improvement applications [7].

### Design parameters of DSTATCOM

The design parameters are considered as design of the choke (inter-phase inductor), voltage rating, and selection of DC link capacitor, equalizing resistances and pre-charging circuit parameters.

#### *Design of coupling reactor*

Consider a three-phase system with a line voltage $V_{LL}$ of 415 V. The design procedure is explained with respect to a 30 kVAr DSTATCOM connected in shunt with the power system through a coupling inductor, for 30 kVAr DSTATCOM

$$\text{Rated RMS line current } = \frac{kVAr \times 10^3}{\sqrt{3} \times V_{LL}} \cong 42\text{A} \tag{1}$$

Peak value of the line current $I_p \cong 60A$.

Assuming the ripple current $\Delta I$ through the choke to be 20% of the rated peak current,

$$\Delta I = 12\text{A},\ \text{Impedance } Z = 5.7142\Omega \tag{2}$$

For proper operation of system, it will be consider either 15% Impedance or 20% Impedance. The coupling inductor value for 15% Impedance is 2. 7296 mh, and coupling inductor value for 20% Impedance is 3.6395 mh. Hence, a 3.6395 mH, 42 A choke can be used for this application with a tap of 2.7296 mH, and it is as shown in Fig. 3. However, this choke has to filter out currents containing the switching frequency components. Hence, the core losses in the choke will be more than that when it is used to pass the fundamental component of the current. While constructing the choke, this factor should also be taken into consideration. In addition, the core should not be saturated at peak values of current due to the harmonics. In addition, it is necessary to provide enough ventilation between the conductor and the core of the choke.

### *Modeling of pre-charging circuit*

The pre-charging circuit resistor value, current value and resistor wattage calculations are given below.

$$\text{DC link capacitor voltage } V_{dC} = \frac{3\sqrt{3}Vm}{\pi} = 1.35*V_{LL} = \frac{3\sqrt{3}*\frac{440}{\sqrt{3}}*\sqrt{2}}{\pi} = 594.2\text{V} \cong 595\text{V} \tag{3}$$

The D.C. link capacitor is charge to a full value of 90%, i.e., $C_{DC}\sim = 536$ V.

Each resistor wattage = 10 W; each resistor current = 2.27A; each resistor value = 200 Ω [14, 15]. The design purpose of the higher rating of 220 Ω is selected. The Simulink model of pre-charge circuit of 30 kVAr DSTATCOM is shown in Fig. 4a. Figure 4b depicts the simulated waveform of resistor current and charging of DC link voltage with the VSC Inverter Bridge operating in diode bridge rectifier mode.

### *Pictorial representation of Pre-charging circuit*

The hardware model of pre-charge circuit is shown in Fig. 5. It consists of 220 Ω, 10 W three resistors in each phase and a pre-charge contactor of 9A capacity. When the operation starts first, the main contactor (63A) is in bypass mode, and pre-charge contactor of 9A is in supply. When inverter stack dc link capacitor is fully charged, it

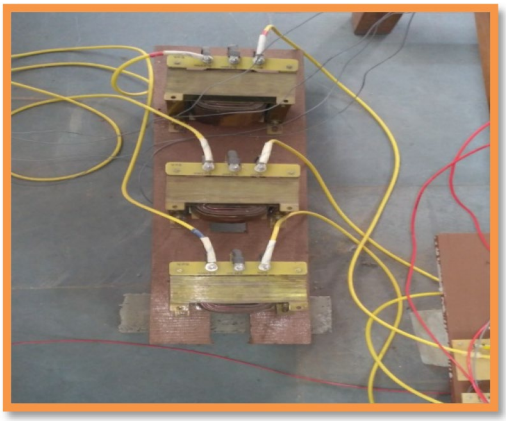
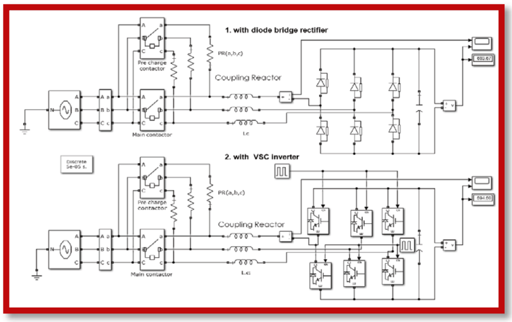
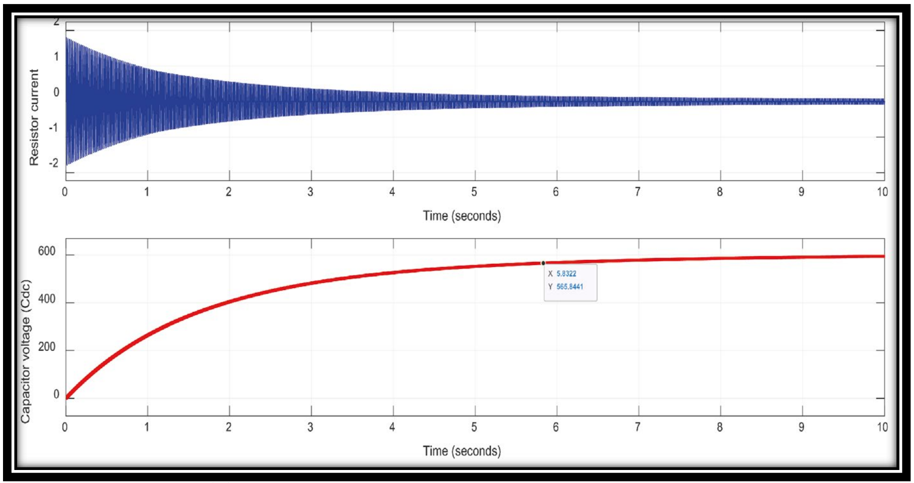


**Fig. 3** Inter phasing Inductor



**(a)** Pre-charging circuit Simulink diagrams



**(b)** DC link capacitor charging current and voltage waveforms

**Fig. 4** **a** Pre-charging circuit Simulink diagrams. **b** DC link capacitor charging current and voltage waveforms

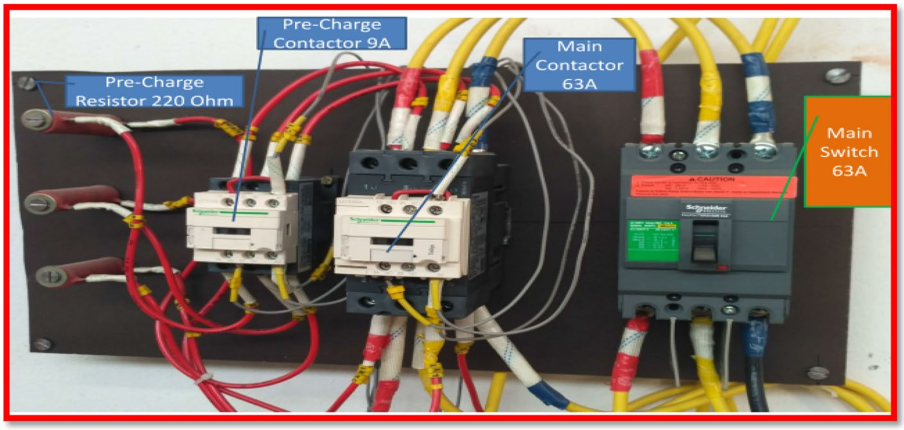


**Fig. 5** Hardware model of pre-charge circuit

bypasses the contactor form pre-charge (9A) to main contactor (63A), and the main switch will be ON continuously. Only the action will be taking in between pre-charge and main contactor. If any problem occurs in the control, the DSP timer will give trip signal to main contactor, so the entire system will be in OFF state. The other design parameters are explained clearly in [21, 22].

## Control methods of DSTATCOM

The control of DSTATCOM in this paper can be divided majorly into IRPT, SRF and ADALINE control; out of these three controllers, first two can be compared with DSP controller and all three can be done simulation using MATLAB/Simulink software and presented the results.

### *Control of DSTATCOM using IRPT/PQ and SRF method*

The Instantaneous Reactive Power Theory (IRPT) control methodology is also known as PQ control method. Detailed analysis of this method and its control strategy is explained clearly with the PQ control block diagram as shown in Fig. 6. This PQ controls the line voltage, and currents can be converted to alpha, beta quantities of voltage and currents; from this the reactive current requirement can be estimated [16–19]. Simultaneously, the DC side voltage control also can be done using dc side PI controller, and ac side voltage can be controlled using the ac side PI controller; from this two ac and dc side PI controller, the reference supply side alpha and beta axis currents can be estimated. These currents can again converted using reverse conversion of alpha, beta to a, b and c; then, we will estimate the reference source currents. By taking actual line currents subtracting from reference, we will be able to generate actual reference control signal currents this complete process as shown in Fig. 6. After generating the actual reference currents, using sine PWM control generates the firing pulse for the turn on and turn off of the inverter stack. With this PQ control, it will be able to control the reactive power in both linear and nonlinear loads; the corresponding conversion mathematical equations can be taken from reference [7–10].

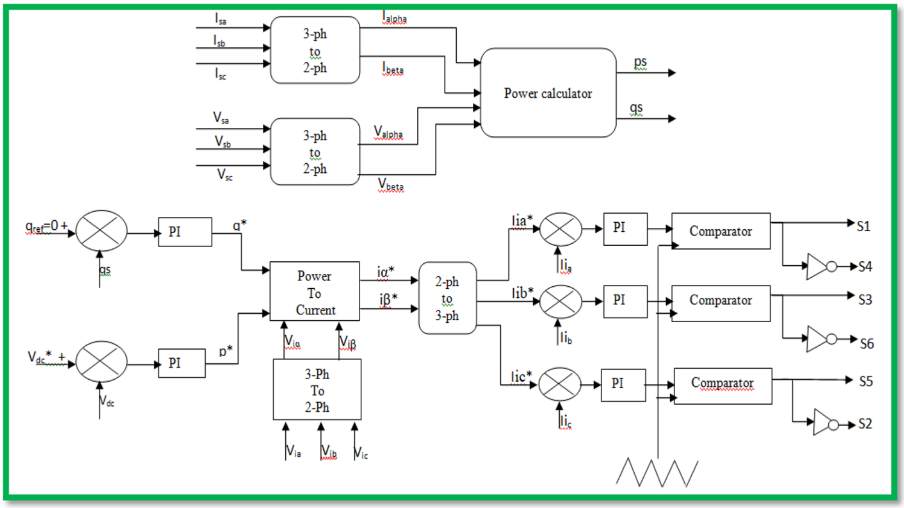


**Fig. 6** PQ Control block diagram

### *Control of DSTATCOM using ADALINE adaptive control algorithm*

Basic Adaline decomposer control is based on least mean square algorithm, and training through Adaline Sensed load current that is made up of real current ($i_p^+$), reactive current ($i_q^+$) for positive sequence, and negative sequence current ($i-$) can be decomposed in parts as:

$$i_L = i_p^+ + i_q^+ + i^- \tag{4}$$

This control algorithm is based on the extraction of current component in phase with the unit voltage template. It tracks the unit voltage templates to maintain minimum error:

$$\left\{ i_{L(k)} - W_{p(k)} * u_{p(k)} \right\} \tag{5}$$

The estimation of weight is given as per the following iterations:

$$W_{p(k+1)} = W_{p(k)} + \eta * \left\{ i_{L(k)} - W_{p(k)} * u_{p(k)} \right\} * u_{p(k)} \tag{6}$$

A comparison of the sensed dc bus voltage to the reference dc bus voltage of VSC results in a voltage error, which, in the nth sampling instant, is expressed as:

$$V_{dcl}(n) = V_{dc}^*(n) - V_{dc}(n) \tag{7}$$

This error signal $V_{dcl}\ (n)$ is processed in a PI controller, and the output $\{I_p\ (n)\}$ at the nth sampling instant is expressed as:

$$I_p(n) = I_p(n-1) + K_{pdc} * \{V_{dcl}(n) - V_{dcl}(n-1)\} + K_{idc} * V_{dcl}(n) \tag{8}$$

where $K_{pdc}$ and $K_{idc}$ are the proportional and integral gains of the PI controller. The control block diagram of ADALINE is shown in Fig. 7.

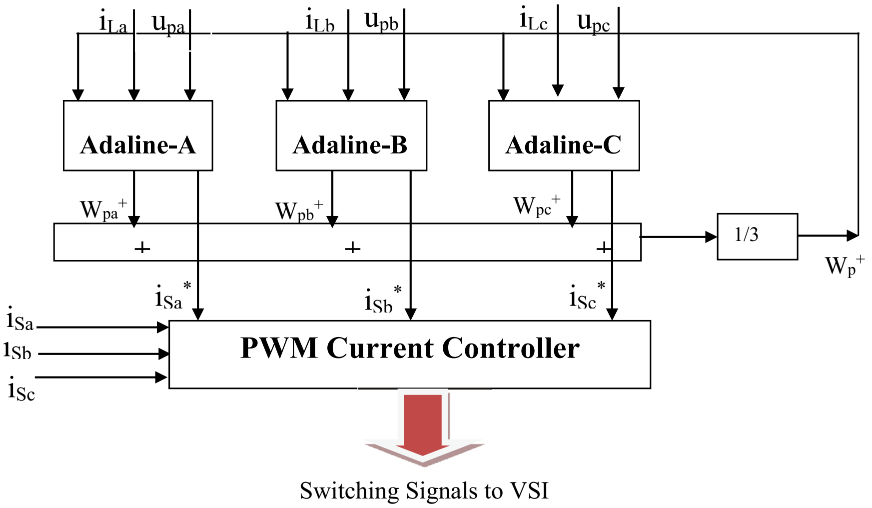


**Fig. 7** ADALINE control block diagram

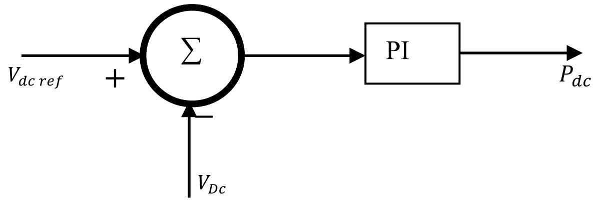


**Fig. 8** Conventional DC link voltage controller

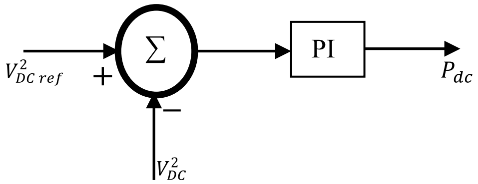


**Fig. 9** Fast acting DC link voltage controller

### Control of DC link voltage using PI controller

Due to transients on the load side, the DC bus voltage is significantly affected. To regulate the dc-link voltage, closed-loop controllers are used. PID controller to regulate dc link voltage is expressed in Eq. 9.

$$u_c = K_p * \left(V_{dcref} - V_{dc}\right) + K_i \int \left(V_{dcref} - V_{dc}\right)\mathrm{d}t + K_d * \mathrm{d}\left(V_{dcref} - V_{dc}\right)/\mathrm{d}t \tag{9}$$

An increase in integral gain $K_i$ reduces steady state error but increases overshoot and settling time. Increasing derivative gain $K_d$ will lead to improved stability. A Ziegler and Nichols closed-loop method is used to tune its parameters.

#### *Conventional DC-link voltage controller*

The conventional PI controller used for maintaining the dc-link voltage is shown in Fig. 8.

To maintain the dc-link voltage at the reference value, the dc-link capacitor needs a certain amount of real power, which is proportional to the difference between the actual and reference voltages. The power required by the capacitor can be expressed as follows:

$$P_{dc} = K_p * \left(V_{dcref} - V_{dc}\right) + K_i \int \left(V_{dcref} - V_{dc}\right)\mathrm{d}t \tag{10}$$

#### *Fast-acting DC link voltage controller*

To overcome the disadvantages of the aforementioned controller, an energy-based dc-link voltage controller is proposed. Fast acting PI voltage controller is shown in Fig. 9.

The energy required by the dc-link capacitor to charge from actual voltage to the reference value is given as:

$$W_{dc} = 0.5 * C_{dc} * \left(V^2_{dcref} - V^2_{dc}\right) \tag{11}$$

The dc power required by the DC-link capacitor is given as:

$$P'_{dc} = \frac{W_{dc}}{T_c} = \frac{C_{dc}}{2 * T_c} * \left(V_{dcref}^2 - V_{dc}^2\right) \tag{12}$$

The total dc power required by the dc-link capacitor is computed as follows:

$$P_{dc} = K_{pe} * \left(V_{dcref}^2 - V_{dc}^2\right) + K_{ie} \int \left(V_{dcref}^2 - V_{dc}^2\right) \mathrm{d}t \tag{13}$$

## Coordinated control process

The coordinated control is nothing but, the combined operation of power factor correction panel and DSTATCOM. The coordinated balance equations are given in Eqs. 14 to 15. The corresponding single line diagram is shown in Fig. 10.

$$q_s = q_l + q_c \tag{14}$$

Under complete compensation by coordinated control,

$$q_s = q_l + q_c = 0 \tag{15}$$

$$q_{sc} = q_c - q_{pfc} = 0 \tag{16}$$

A coordinated control has been developed for achieving the unity power factor by using a switched capacitor units and DSTATCOM together. The modes of operations are shown below:

1. If Q PFC < Qreq, then calculate Q DSTATCOM = Qreq—Q PFC (+ve), and generate firing pulse using specified control, operating DSTATCOM as reactive power injection mode. Qinj (C), i.e., VSC act as a capacitor.
2. If Q PFC > Qreq, then calculate Q DSTATCOM = Qreq—QPFC (-ve), and generate firing pulse using specified control, operating DSTATCOM as reactive power absorbing mode. Qinj (L), i.e., VSC act as an inductor.
3. If QPFC = Qreq, then calculate Q DSTATCOM = Qreq-QPFC = 0, so the DSTATCOM at PCC acts as a floating at bus. The flowchart of coordinated control is given in Fig. 12.

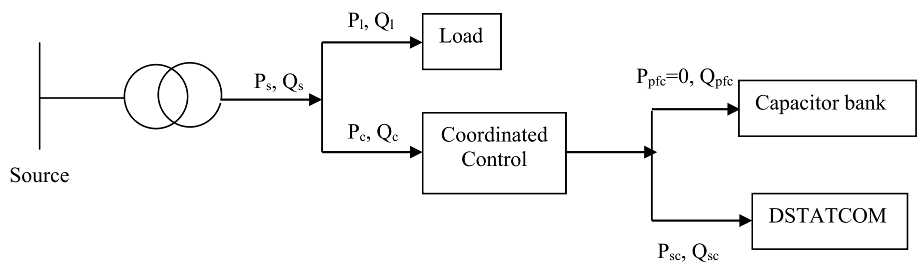


**Fig. 10** Active and reactive power flow in a coordinated control

**Table 1** Capacitor bank details at SUES Substation

| PFC Panel 1 (Old) | | | PFC Panel 2 (New) | | |
|---|---|---|---|---|---|
| **Rating (kVAr)** | **No of capacitors** | **Total kVAr** | **Rating** | **No of capacitors** | **Total kVAr** |
| 5 | 1 | 5 | 10 | 2 | 20 |
| 10 | 2 | 20 | 15 | 2 | 30 |
| 25 | 4 | 100 | 25 | 4 | 100 |
| Total kVAr | | 125 | Total kVAr | | 150 |

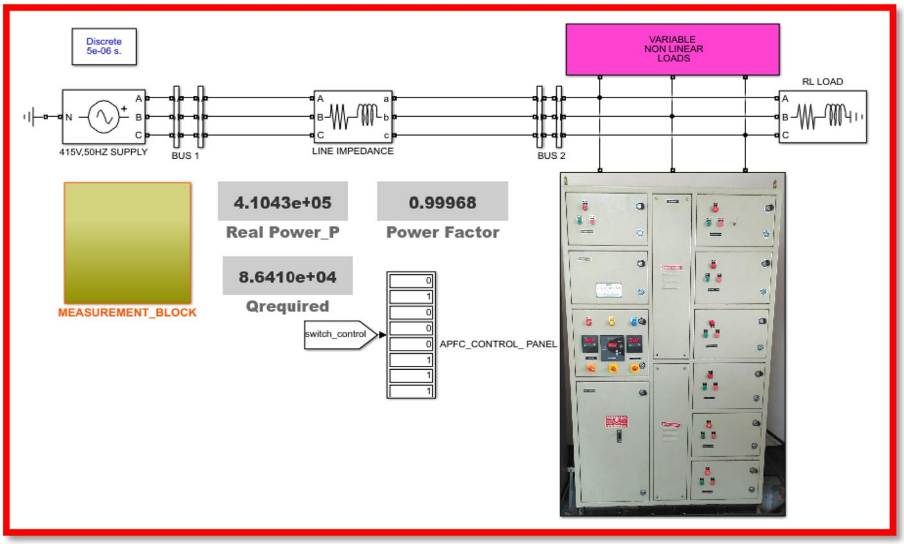


**Fig. 11** Simulink model of 125 kVAr PFC panel

## Capacitor bank details at substation

Switchable capacitor banks in the typical Substation have two panels. The rating of Panel 1 is 125 kVAr having 7 units of capacitors, and rating of Panel 2 is 150 kVAr having 8 units of capacitors. The Substation is operating at a line voltage level of 415 V. The total rating of switchable capacitor banks is 275 kVAr, and the details of switchable capacitor banks in the Substation are shown in Table1. Based on the availability of capacitors in the capacitor bank, the switching selection table is prepared and programmed in MATLAB. Based on program, the turn-on and turn-off of capacitors in switchable capacitor bank will be decided. The detailed procedure and calculations are mentioned in Appendix B.

### *Simulink model of 125 kVAr switchable capacitor bank*

The Simulink model of 125 kVAr capacitor panel for partial load in the Substation is modeled and simulated [23–26]. It is shown in Fig. 11. The flowchart of coordinated control is shown in Fig. 12.

## Test system specifications

1. System capacity = 750 kVA

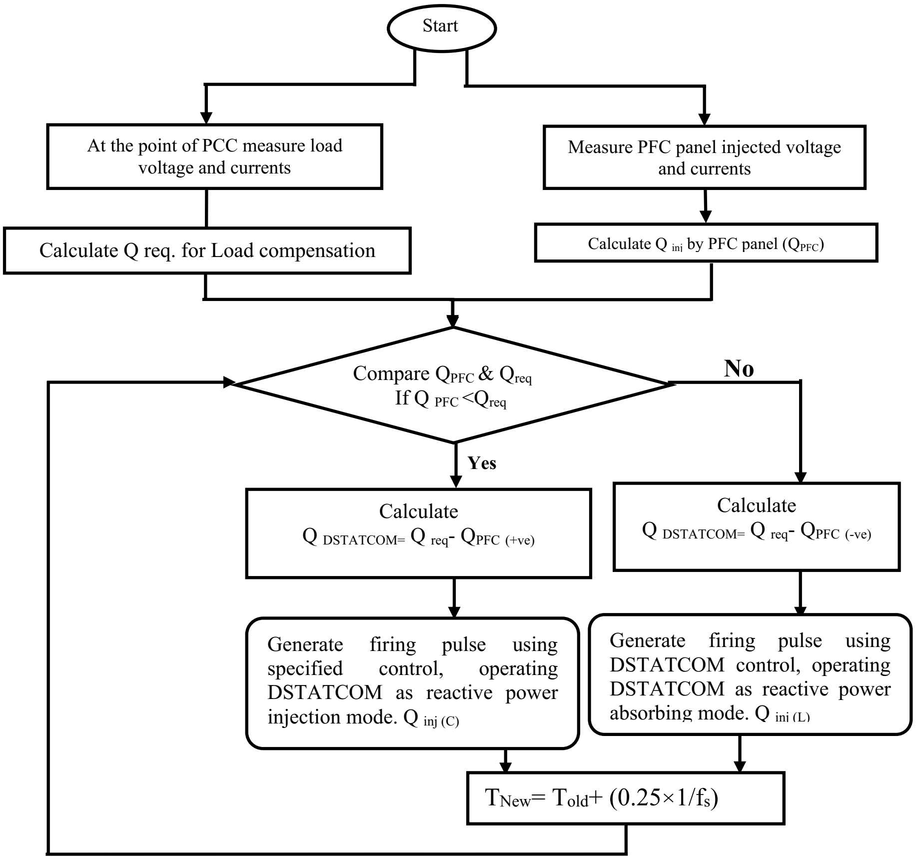


**Fig. 12** Flowchart of coordinated control (SCB + DSTATCOM)

2. The main line is connected to two transformers—500 kVA and 250 kVA.
3. Total reactive demand for the system is approximately 300 kVAr.
4. Existing systems are provided with 150 kVAr and 125 kVAr PFC panels.
5. A 30 kVAr DSTATCOM is proposed for power factor correction (riding over existing 275 kVAr PFC panel).
6. AC supply source: three-phase, 415 V (L–L), 50 Hz.
7. Source Impedance of: $R_s = 0.04$ Ohm and $L_s = 2$ mH (calculated from cable ratings).
8. Loads: Linear/Nonlinear Loads of Educational institute.
9. Load Types: 1. Different types of Motor loads, UPS, Fan and Lighting load of Educational institute.
10. Rating of VSC = 30 kVA.
11. Reactive Power rating of Voltage Source Converter = 30 kVAr.
12. Reactive Power rating of Fixed Capacitor Bank = + 125 kVAr.
13. Total Reactive Power Control Range = 0 to + 155 kVAr.
14. Operating Voltage Range = − 20% to + 15%.
15. Switching frequency of inverter range up to 5 kHz.
16. DC bus Capacitance ($C_{dc}$) = 4700 µf @ 450 V Series connected = 900 V.
17. Interfacing inductor ($L_f$) = 3.6395 mH (at 20% tap) with a tap at 2.7296 mH (at 15% tap).

**Table 2** Load details without controller

| Type of load (RL) → | Quarter load | Half load | 3/4th Load | Full load |
|---|---|---|---|---|
| Source current (A) (RMS) | 299 | 617 | 982.2 | 1357 |
| Active power (kW) | 200 | 400 | 600 | 800 |
| Reactive power (kVAr) | 79 | 192 | 372 | 558 |
| Power factor | 0.93 | 0.9 | 0.85 | 0.82 |

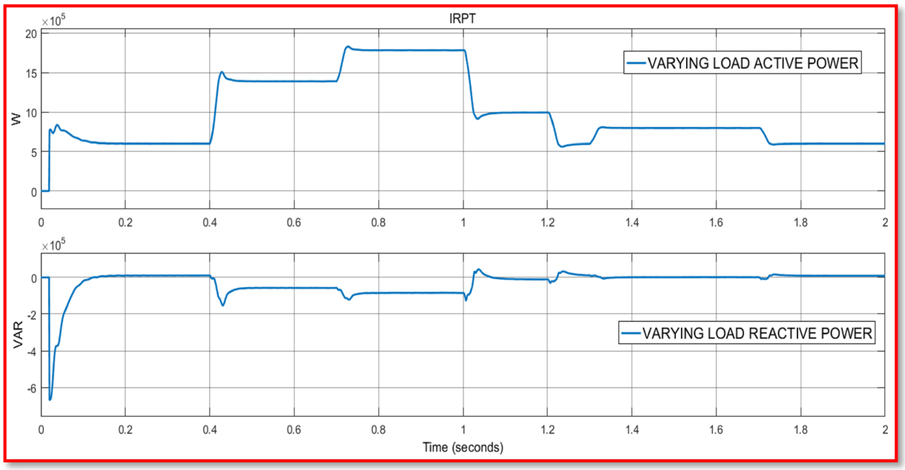


**Fig. 13** Varying load active and reactive power

## Results and discussion

In this section, the system is modeled in MATLAB Software [27] using three modes; they are (i) control of DSTATCOM in PQ Mode; (ii) control of DSTATCOM in SRF Mode and (iii) control of DSTATCOM in Adaptive Linear (ADALINE) control mode. The detailed result analyses for different load conditions with and without DSTATCOM for fixed and varying loads were analyzed in this section.

### Without DSTATCOM

In this section, the system is simulated without controller with a load of quarter, half, ¾Th and full load and the obtained results of different parameters are shown in Table 2.

Varying load of all above four linear loads, switching at different time period with the help of three phase circuit breakers, base load is on throughout the whole simulation time, i.e., 2 s, base load: 600 kW, 372 kVAr 0.85 pf Lag. Load1: 800 kW, 558 kVAr, 0.82 pf lag, duration 0.4 s to 1 s, Load2: 400 kW, 192 kVAr, 0.9 pf lag, duration 0.7 s to 1.2 s Load3: 200 kW, 79 kVAr, 0.93 pf lag, duration 1.3 s to 1.7 s. These variations (varying loads) are shown in Fig. 13.

### With DSTATCOM

The control of DSTATCOM is executed by using DSP TMS 320 F 2812, it is directly connected to personal computer (PC) with JTAG Emulator, and the programming is

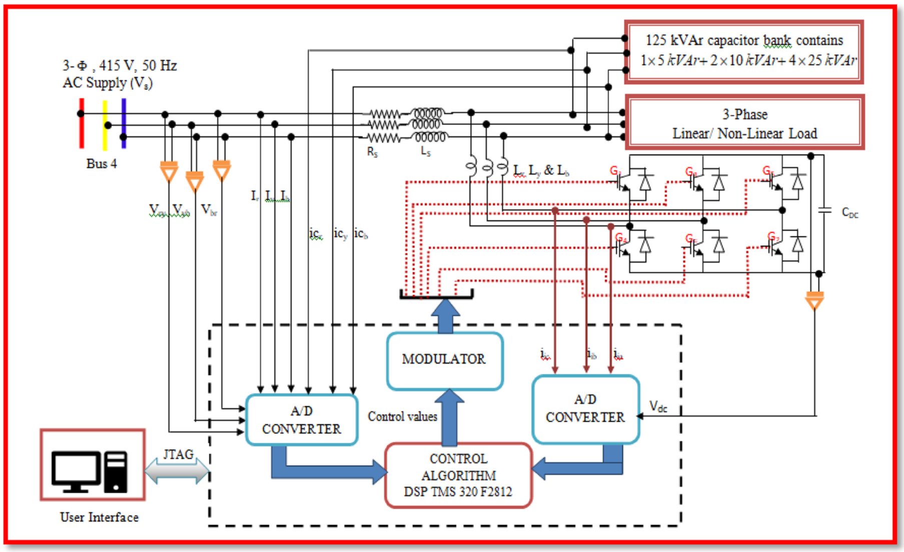


**Fig. 14** Schematic diagram of coordinated control

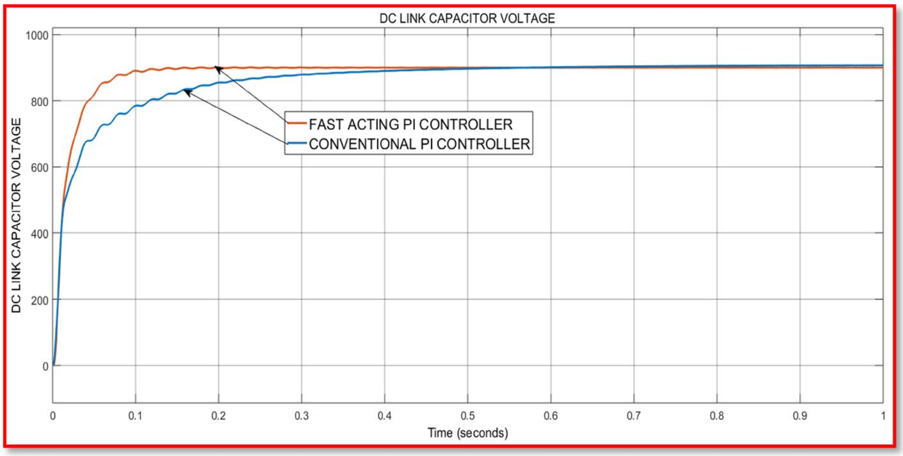


**Fig. 15** Conventional and fast acting PI controller

done through CCS V3.3 [28, 29]. The sensed current and voltage sensor signals of the reactive power are calculated using DSP programming. This is using the theories like SRF; using gating signals, the inverter stack should be fired and required amount of reactive power is pumped or injected into the system and maintain the system power factor near to unity. The schematic diagram of coordinated control is shown in Fig. 14.

Fast acting PI controller has lesser rise time, and improved stability, lesser ripples when compared to conventional PI controller. The response time of fast acting PI controller is better than that of conventional PI controller. We have considered one of the loads for implementing this improved PI controller. Quarter load has been

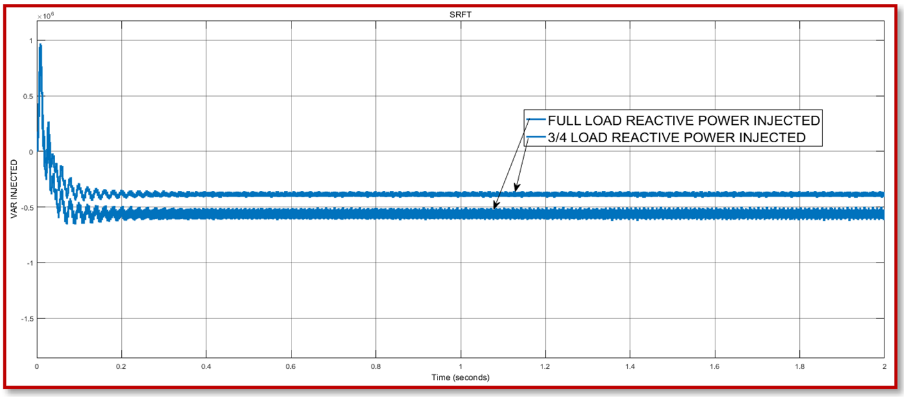


**Fig. 16** Reactive power injections at PCC for 3/4$^{Th}$ and full load conditions

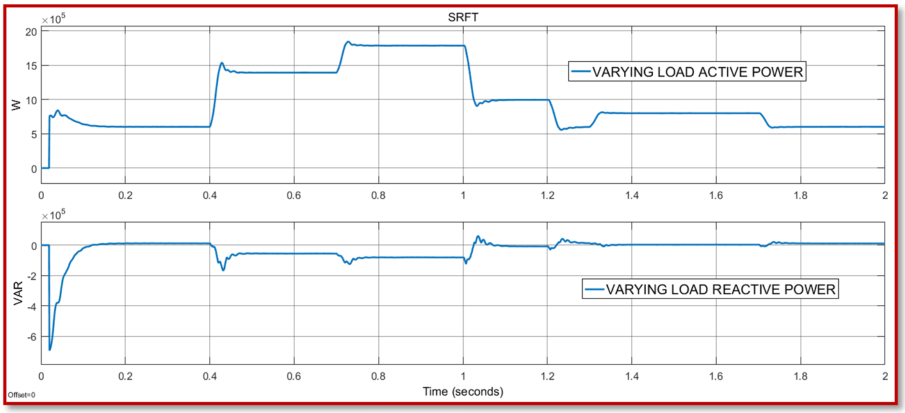


**Fig. 17** Varying load of real and reactive powers

considered for that; Fig. 15 shows us the comparison of 2 different DC link voltages applied on the same load for IRPT, and the response time for conventional PI controller is 507 ms and that of fast acting PI controller is 195 ms. The reactive power injections of 3/4th load and full load are shown in Fig. 16. The corresponding variable load real and reactive powers are shown in Fig. 17. The variation of the angle between voltage and current of phase A with a half and quarter load without controller is shown in Fig. 18. Clearly it is showing that without controller the phase angle between voltage and current of phase A, the power factor of the different loads is shown in Table 3. The correction of power factor and the zero-phase angles are shown in Figs. 19, 20 and 21.

The complete energy consumption details of the substation are collected from the below mentioned sources, and the remaining energy details collected from HTCC monthly energy bills.

The status of 125 kVAr switchable capacitor bank and the 30 kVAr DSTATCOM setups are shown in Fig. 22a, b, respectively. Figure 23a shows the firing pulses of top and bottom switches of first leg in the circuit shown in Fig. 23a. Figure 23b shows the firing pulses of other two top switches of the second and third legs. The switches

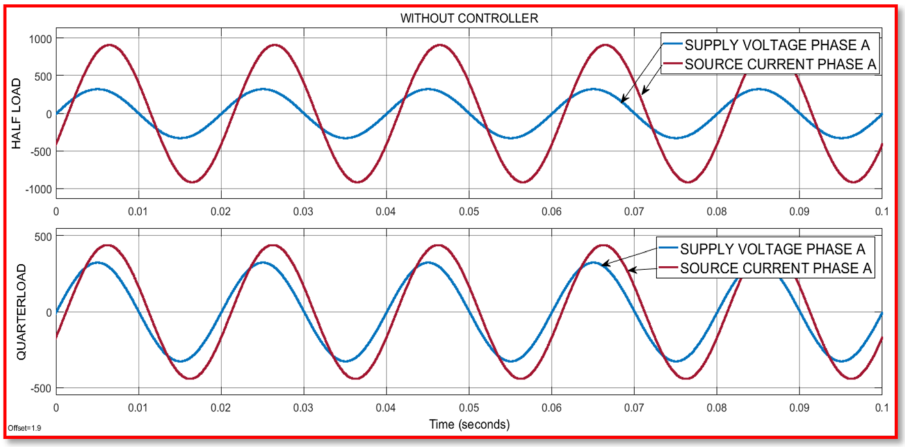


**Fig. 18** Voltage and current wave forms of Phase A showing pf angle

**Table 3** Power factor and correction time of different load conditions with different controllers

| **Loads** | **Quarter load (200 kW)** | | | | **Half load (400 kW)** | | | |
|---|---|---|---|---|---|---|---|---|
| **Control methods** | **no control** | **IRPT** | **ADALINE** | **SRFT** | **No control** | **IRPT** | **ADALINE** | **SRFT** |
| Source Current (A) (RMS) | 299 | 278.37 | 278.35 | 278.39 | 617 | 556.74 | 556.69 | 556.77 |
| Response Time (ms) | – | 28 | 22 | 29 | – | 48 | 46 | 71 |
| Power Factor | 0.93 | 0.9996 | 0.9996 | 0.9994 | 0.90 | 0.9996 | 0.9996 | 0.9995 |
| **Loads** | **3/4th Load (600 kW)** | | | | **Full Load (800 kW)** | | | |
| **Control methods** | **No control** | **IRPT** | **ADALINE** | **SRFT** | **No control** | **IRPT** | **ADALINE** | **SRFT** |
| Source Current (A) (RMS) | 982 | 1193.92 | 1193.84 | 1193.93 | 1357 | 1113.03 | 1113.01 | 1113 |
| Response Time (ms) | – | 47 | 44 | 50 | – | 47 | 44 | 49 |
| Power Factor | 0.85 | 0.9998 | 0.9999 | 0.9998 | 0.82 | 0.9999 | 0.9999 | 0.9999 |

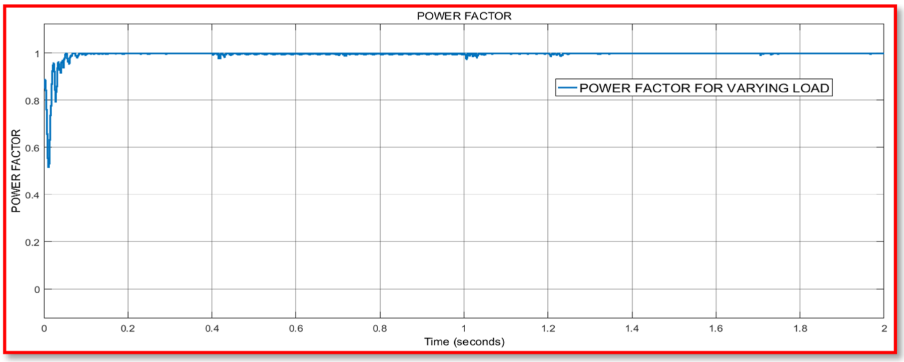


**Fig. 19** Power factor of varying load with controller showing UPF

are operating at a switching frequency of 1 kHz. Figure 23c shows the substation current and voltage waveforms at a load current of 98 A, 236 V at a frequency of 49.967 Hz. The detailed calculations are shown below. CT connected to the 250 kVA

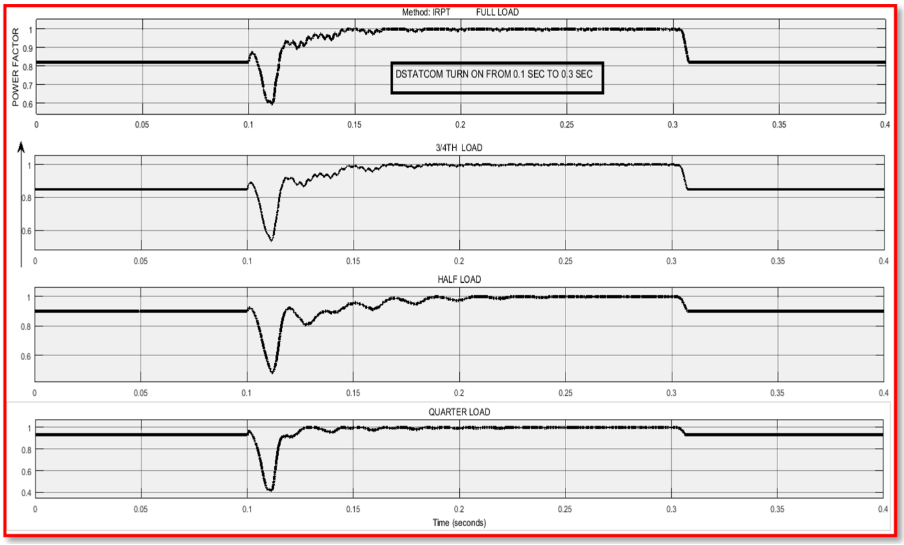


**Fig. 20** Power Factor of a system without controller (duration from 0 to 0.1 s & 0.3 to 0.4 s) and with controller (duration from 0.1 to 0.3 s)

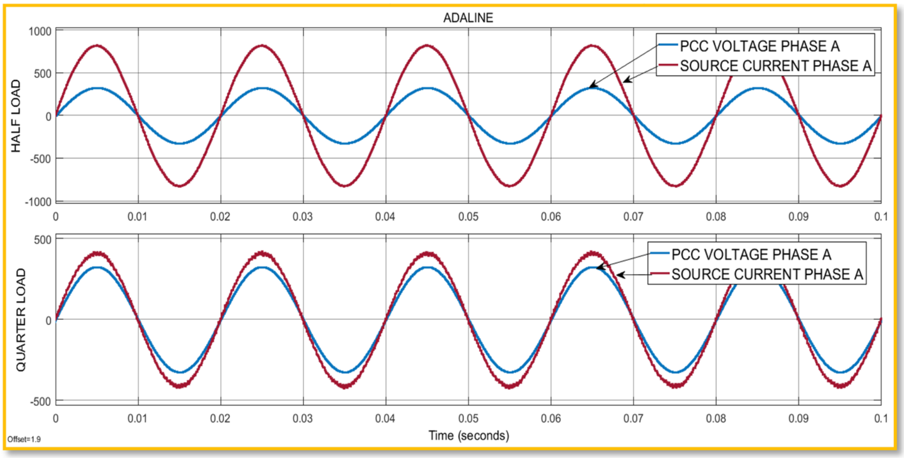


**Fig. 21** Wave form of the voltage and current of phase a with ADALINE controller

transformer is 400/5, the burden resistance used is 10 W, 10 Ω power resistor. The peak voltage measured is 17.2 V. The primary current calculated as:

$$I_P = \left\{ (\text{CT Ratio}) \times \left( \frac{\text{Measured peak voltage}}{\sqrt{2}} \right) \times \left( \frac{1}{\text{Burden resistance}} \right) \right\}$$

$$I_P = \left\{ \left( \frac{400}{5} \right) \times \left( \frac{17.2}{\sqrt{2}} \right) \times \left( \frac{1}{10} \right) \right\} = 97.29 \cong 98\ A$$

**Fig. 22** Photographs of system: **a** 125 kVAr Switchable capacitor bank and **b** 30 kVAr DSTATCOM test bench setup

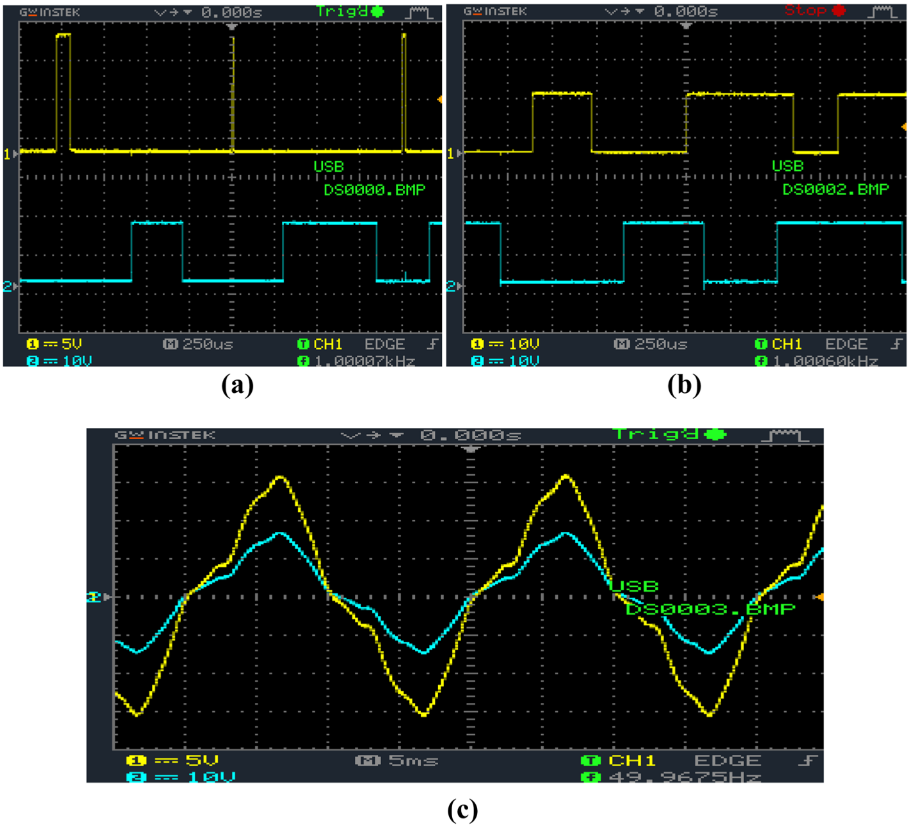


**Fig. 23** Experimental waveforms of: **a** firing pulses of phase 'A'; **b** firing pulses of phases 'B' & C; **c** Substation voltage and current waveforms

## SUES Substation energy data analysis for the calendar year 2020

The data are taken from monthly bills, for the calendar year 2020, the total active energy consumed is 3,44,303 kWh, and the total energy billed by TSSPDCL is 3,46,353 kVAh. From these kWh and kVAh data, it clearly indicates that the reactive energy consumed in the SUES Substation is 37,628 kVArh. The average power factor operated in the

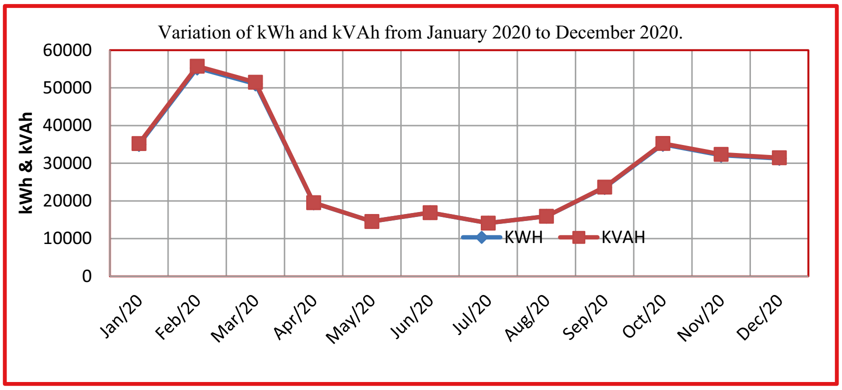


**Fig. 24** kWh and kVAh graphs of SUES Substation of calendar year 2020

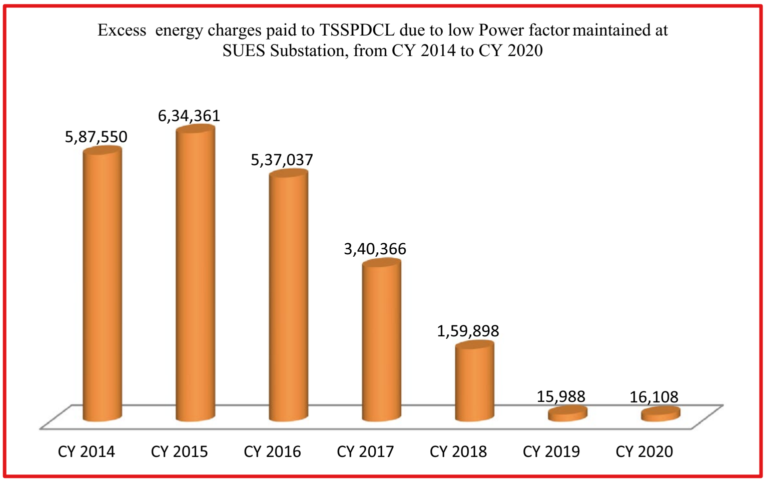


**Fig. 25** Excess energy charges paid to TSSPDCL due to low PF

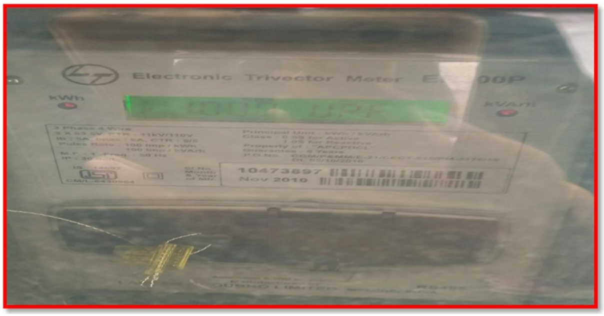


**Fig. 26** Status of substation main incoming energy meter

substation in this period is 0.9955 lagging. From the above data due to low power factor, the excess amount paid to TSSPDCL is Rs. 16,108 during 2020. The kWh and kVAh graphs are shown in Fig. 24. From CY 2014 to CY 2020, excess energy charges paid to TSSPDCL due to low power factor at SUES Substation is shown in Fig. 25.

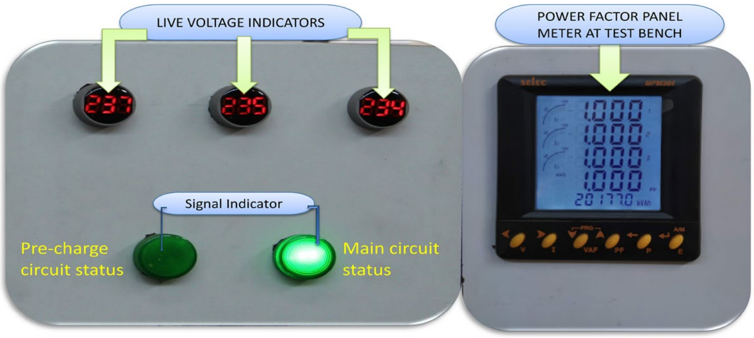


**Fig. 27** Meter status at test bench setup

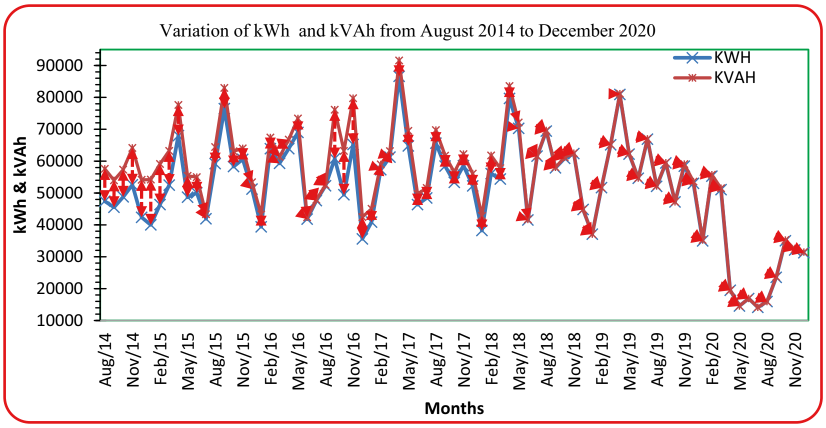


**Fig. 28** kWh and kVAh graphs of SUES Substation from August 2014 to December 2020

The Substation main energy meter and test bench meter status indicate that the Substation is operating at unity power factor. They are shown in Figs. 26 and 27, respectively. With the installation of Switchable capacitor banks and DSTATCOM in the Substation, the system is maintained at unity power factor.

The variation of kWh and kVAh of Substation from August 2014 to December 2020 is shown in Fig. 28. The variation of power factor of substation from January 2016 to December 2020 is given in Fig. 29. From Fig. 28, it is shown that the power factor of substation is very low from January 2016 to May 2018 and the average power factor for this period is 0.9276. After installation of reactive power compensating devices in the substation, the average power factor is improved from 0.9276 to 0.9970. The different stages of photographs of the test setup of 30 kVAr DSTATCOM are shown in Fig. 30.

## Payback period

The payback period of Sultan Ul—Uloom Educational Society Substation is calculated. In the month of November 2016, the125 kVAr old PFC panel is repaired and connected to the system. To meet the reactive power demand in the Substation, a new 150 kVAr PFC panel is purchased and commissioned in the month of May 2018 and at the same time in house designed 30 kVAr DSTATCOM is coordinated with existing 125

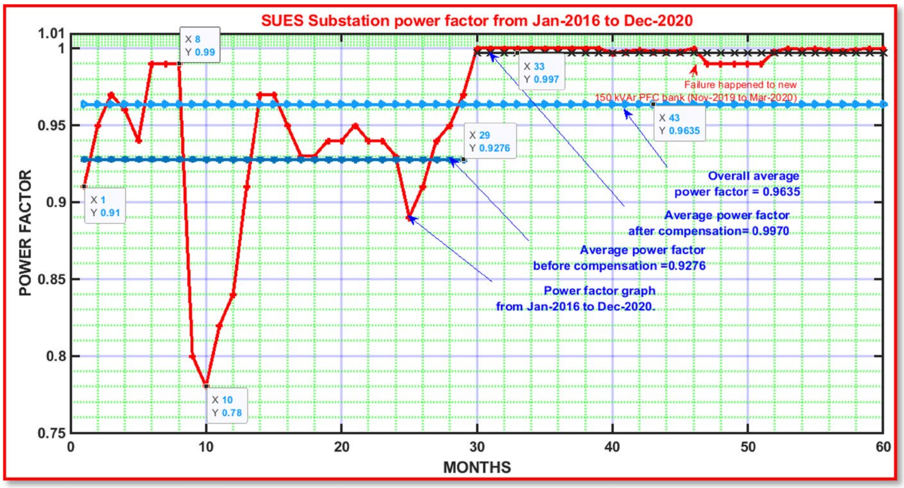


**Fig. 29** Power factor graph of SUES Substation from January 2016 to December 2020

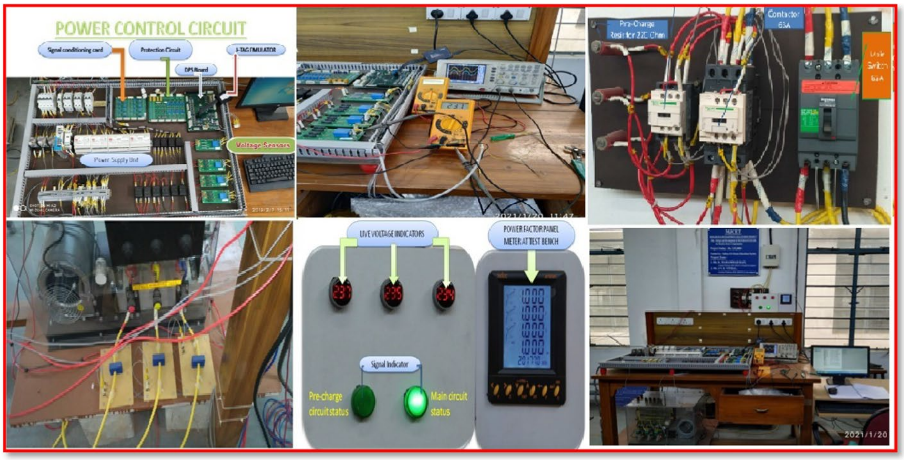


**Fig. 30** Different photographs of the project

kVAr PFC panel. The combined total cost and expenditure of these three units are Rs. 11,48,200/-, and the details are shown in Appendix A. If the system is not installed, the average power factor of the substation is 0.9276. The fictitious kVAh is calculated based on the average power factor (0.9276) in the substation before installation of power factor correction equipment. The SUES would have paid Rs. 1,14,40,762/- extra to TSSPDCL for the active energy consumption of 14,31,615 units. The average Substation power factor is shown in Fig. 29. After the system is installed in June 2018, the power factor has increased near to unity. In this case, the SUES has paid Rs. 1,05,91,462/- to electricity board. The total amount saved because of installation of the system during the period from June 2018 to December 2020 is Rs. 8,49,300/-. The detailed calculations are given in Appendix-A Table 4. The average monthly amount saved with this project is calculated from June 2018 to December 2020 is Rs. 27,397/-. The payback period can easily be calculated as the ratio of total cost to average saving per month. The payback period thus evaluated is nearly 3 Years & 6 Months.

## Conclusions

This paper describes the analysis of control and power circuit of DSTATCOM. The system has been modeled and computer-generated using Simulink. The active and reactive power flow in a DSTATCOM is explained clearly with block diagrams. The Coordinated control of PFC with DSTATCOM is also explained. The PQ control of DSTACOM control diagram with the equations is clearly explained. The power factor of SUES Substation is analyzed before the installation of PFC panels and DSTACOM; from January 2016 to May 2018, the average power factor of Substation is 0.926. After installation of PFC panels and DSTATCOM in the SUES Substation, the average power factor is improved from 0.926 to 0.997 during the period from June 2018 to December 2020. The data pertaining to the SUES Substation are taken in terms of kWh & kVAh, and excess energy charges paid to TSSPDCL due to low power factor in Substation are analyzed clearly.

Analysis of reactive power control of a practical radial distribution system of SUES is explained in terms of power usage and power factor. The system is simulated in Simulink software for reactive power control. The operating conditions of the two switchable capacitor banks are explained along with the costs involved in their operation.

This paper reported a coordinated control of 125 kVAr switchable capacitor bank of total seven capacitors, and it consists of three groups; the first group is a single unit of 5 kVAr capacitor, second group of two capacitors of 10 kVAr each, and the third group consists of 4 capacitors of each 25 kVAr rating $[(1 \times 5\text{kVAr}) + (2 \times 10\ \text{kVAr}) + (4 \times 25\ \text{kVAr}) = 125\ \text{kVAr}]$ with a 30 kVAr DSTATCOM. It is implemented for power factor correction in the SUES, Substation. The simulation is carried out in Simulink environment, for analysis of the performance of DSTATCOM; the parameters considered are source current, PCC voltage, VSC converter voltage and current, DC link voltage, active power, injected reactive power, response time (ms) and power factor for linear and nonlinear loads.

Power factor in 750 kVA SUES Substation is improved near to unity by developing an IGBT-based 30 kVAr DSTATCOM in conjunction with 125 kVAr switchable capacitor bank and 150 kVAr separate PFC panel. The Substation data are gathered from TSSPDCL monthly electricity bills and analyzed before and after installation of power factor correction equipment. The prototype operates round the clock and maintains the power factor near to unity irrespective of fluctuating society loads. The project experience shows that the IGBT-based DSTATCOM can perform reliably the desired function of reactive power management in any 11 kV/415 V Substation and industrial environment.

# Appendix A

See Tables 4 and 5.

**Table 4** Payback calculation of SUES Substation from June 2018 to December 2020

| S. no | Bill month | kWh from TSSPDCL monthly bill | Fictitious kVAh | Actual kVAh charges from monthly bill (Rs.) | Fictitious kVAh amount (Rs.) | Amount saved in energy charges (Rs.) | Saved amount in calendar year wise | Cum. amount saved |
|---|---|---|---|---|---|---|---|---|
| 1 | Jun-18 | 41,528 | 44,769 | 325,416 | 349,198 | 23,782 | Rs. 2,44,981 | 23,782 |
| 2 | Jul-18 | 61,568 | 66,373 | 480,511 | 517,709 | 37,198 | | 60,980 |
| 3 | Aug-18 | 69,440 | 74,860 | 543,036 | 583,908 | 40,872 | | 101,852 |
| 4 | Sep-18 | 57,904 | 62,423 | 520,798 | 559,934 | 39,136 | | 140,988 |
| 5 | Oct-18 | 60,900 | 65,653 | 549,179 | 588,907 | 39,728 | | 180,716 |
| 6 | Nov-18 | 62,372 | 67,240 | 487,281 | 524,472 | 37,191 | | 217,907 |
| 7 | Dec-18 | 44,836 | 48,335 | 349,939 | 377,013 | 27,074 | | 244,981 |
| 8 | Jan-19 | 37,100 | 39,996 | 289,442 | 311,969 | 22,527 | Rs. 4,10,721 | 267,508 |
| 9 | Feb-19 | 51,676 | 55,709 | 403,197 | 434,530 | 31,333 | | 298,841 |
| 10 | Mar-19 | 65,120 | 70,203 | 508,435 | 547,583 | 39,148 | | 337,989 |
| 11 | Apr-19 | 80,916 | 87,232 | 728,077 | 782,471 | 54,394 | | 392,383 |
| 12 | May-19 | 62,220 | 67,076 | 486,221 | 523,193 | 36,972 | | 429,355 |
| 13 | Jun-19 | 54,648 | 58,913 | 426,660 | 459,521 | 32,861 | | 462,216 |
| 14 | Jul-19 | 66,900 | 72,122 | 522,600 | 562,552 | 39,952 | | 502,168 |
| 15 | Aug-19 | 52,100 | 56,166 | 407,066 | 438,095 | 31,029 | | 533,197 |
| 16 | Sep-19 | 59,420 | 64,058 | 464,131 | 499,652 | 35,521 | | 568,718 |
| 17 | Oct-19 | 47,192 | 50,875 | 368,410 | 396,825 | 28,415 | | 597,133 |
| 18 | Nov-19 | 58,420 | 62,980 | 460,762 | 491,244 | 30,482 | | 627,615 |
| 19 | Dec-19 | 53,052 | 57,193 | 418,018 | 446,105 | 28,087 | | 655,702 |
| 20 | Jan-20 | 34,984 | 37,715 | 274,903 | 294,177 | 19,274 | Rs. 1,76,048 | 674,976 |
| 21 | Feb-20 | 55,276 | 59,590 | 434,928 | 464,802 | 29,874 | | 704,850 |
| 22 | Mar-20 | 51,048 | 55,032 | 401,637 | 429,250 | 27,613 | | 732,463 |
| 23 | Apr-20 | 19,488 | 21,009 | 152,380 | 163,870 | 11,490 | | 743,953 |
| 24 | May-20 | 14,564 | 15,701 | 113,599 | 122,468 | 8869 | | 752,822 |
| 25 | Jun-20 | 16,888 | 18,206 | 131,913 | 142,007 | 10,094 | | 762,916 |
| 26 | Jul-20 | 14,136 | 15,239 | 110,261 | 118,864 | 8603 | | 771,519 |
| 27 | Aug-20 | 15,932 | 17,176 | 124,332 | 133,973 | 9641 | | 781,160 |
| 28 | Sep-20 | 23,568 | 25,408 | 184,704 | 198,182 | 13,478 | | 794,638 |
| 29 | Oct-20 | 35,019 | 37,752 | 275,005 | 294,466 | 19,461 | | 814,099 |
| 30 | Nov-20 | 32,127 | 34,635 | 252,502 | 270,153 | 17,651 | | 831,750 |
| 31 | Dec-20 | 31,273 | 33,714 | 245,419 | 262,969 | 17,550 | | 849,300 |

**Table 5** Investment cost details of SUES Substation with power factor correction units

| Item | Cost per unit in Rs | Total cost in Rs |
|---|---|---|
| Cost of 125 kVAr Switchable Capacitor Bank | 2,25,000 | 2,25,000 |
| Cost of 150 kVAr Switchable Capacitor Bank | 2,85,000 | 2,85,000 |
| 30 kVAr DSTATCOM cost | 3,92,000 | 3,92,000 |
| 25 kVAr capacitor cost | 14,500 | 29,000 |
| Repair of PFC panel cost | 25,000 | 25,000 |
| AMC/Break down / System maintenance charges @ Rs. 5000/ month | 5000 | 1,55,000 |
| Additional charges (Electrician + Labor + Miscellaneous) @ Rs. 1200/ month | 1200 | 37,200 |
| Total Expenditure in Rs | | 11,48,200 |

## Appendix B

### Capacitor switching selection

Based on the availability of capacitors in the capacitor bank, the switching selection Table is prepared and programmed in MATLAB. Based on program the turn ON and turn OFF of capacitors in switchable capacitor bank will be decided. Table 6 represents the detailed switching combination of switchable capacitor bank with a varying reactive range from 1 to 125 kVAr. The range of kVAr, considered as ±2.5 kVAr in each step as shown in column 3 of Table 6. The combinations of 55 kVAr are explained in detailed and the same procedure will follow to understand the number of possible combinations in each step in Table 6 from S. No. 1 to 25. From this Table S. No. 11 represents the 55 kVAr reactive demand in the system. In column 2, 55 (6) indicates if the system reactive demand is 55 kVAr the possible number of combinations are six. The combinations are shown in column 4 to column 6. The combinations of column 4 {C4 + (C5 to C7) + (C1) [3]} are [C4 + C5 + C1], [C4 + C6 + C1] & [C4 + C7 + C1]. The combinations of column 5 {C5 + (C6 to C7) + (C1) [2]} are [C5 + C6 + C1] & [C5 + C7 + C1].

**Table 6** Capacitor switching selection of 125 kVAr capacitor bank

| S. no | kVAr (Possible combinations) | Range of kVAr demand (Qc) | Capacitors switching preferences | | |
|---|---|---|---|---|---|
| | | | 1 | 2 | 3 |
| 1 | 5 (1) | 1–5-7.5 | (C1) [1] | | |
| 2 | 10 (2) | 7.6–10–12.5 | (C2) [1] | (C3) [1] | Capacitor switch groups |
| 3 | 15 (2) | 12.6–15–17.5 | (C2) + (C1) [1] | (C3) + (C1) [1] | Group (1) C1 = 5 kVAr |
| 4 | 20 (1) | 17.6–20–22.5 | (C2 + C3) [1] | | Group (2) C2 & C3 = 10 kVAr each |
| 5 | 25 (5) | 22.6–25–27.5 | (C2 + C3) + (C1) [1] | (C4 to C7) [4] | Group (3) C4 to C7 = 25 kVAr each |
| 6 | 30 (4) | 27.6–30–32.5 | (C4 to C7) + (C1) [4] | | |
| 7 | 35 (8) | 32.6–35–37.5 | (C4 to C7) + (C2) [4] | (C4 to C7) + (C3) [4] | |
| 8 | 40 (8) | 37.6–40–42.5 | (C4 to C7) + (C2 + C1) [4] | (C4 to C7) + (C3 + C1) [4] | |
| 9 | 45 (4) | 42.6–45–47.5 | (C4 to C7) + (C2 + C3) [4] | | |
| 10 | 50 (6) | 47.6–50–52.5 | C4 + (C5 to C7) [3] | C5 + (C6 to C7) [2] | (C6 + C7) [1] |
| 11 | 55 (6) | 52.6–55–57.5 | C4 + (C5 to C7) + (C1) [3] | C5 + (C6 to C7) + (C1) [2] | (C6 + C7) + (C1) [1] |
| 12 | 60 (12) | 57.6–60–62.5 | C4 + (C5 to C7) + (C2 to C3) [6] | C5 + (C6 to C7) + (C2 to C3) [4] | (C6 + C7) + (C2 to C3) [2] |
| 13 | 65 (12) | 62.6–65–67.5 | C4 + (C5 to C7) + (C2 to C3) + C1 [6] | C5 + (C6 to C7) + (C2 to C3) + C1 [4] | (C6 + C7) + (C2 to C3) + (C1) [2] |
| 14 | 70 (6) | 67.6–70–72.5 | C4 + (C5 to C7) + (C2 + C3) [3] | C5 + (C6 to C7) + (C2 + C3) [2] | (C6 + C7) + (C2 + C3) [1] |
| 15 | 75 (3) | 72.6–75–77.5 | (C4 + C5 + C6) [1] | (C5 + C6 + C7) [1] | (C6 + C7) + (C1) + (C2 + C3) [1] |
| 16 | 80 (2) | 77.6–80–82.5 | (C4 + C5 + C6) + (C1) [1] | (C5 + C6 + C7) + (C1) [1] | |

**Table 6** (continued)

| **S. no** | **kVAr (Possible combinations)** | **Range of kVAr demand (Qc)** | **Capacitors switching preferences** | | |
|---|---|---|---|---|---|
| | | | **1** | **2** | **3** |
| 17 | 85 (4) | 82.6–85–87.5 | (C4 + C5 + C6) + (C2 to C3) [2] | (C5 + C6 + C7) + (C2 to C3) [2] | |
| 18 | 90 (4) | 87.6–90–92.5 | (C4 + C5 + C6) + (C1) + (C2 to C3) [2] | (C5 + C6 + C7) + (C1) + (C2 to C3) [2] | |
| 19 | 95 (2) | 92.6–95–97.5 | (C4 + C5 + C6) + (C2 + C3) [1] | (C5 + C6 + C7) + (C2 + C3) [1] | |
| 20 | 100 (2) | 97.6–100–102.5 | (C4 + C5 + C6 + C7) [1] | (C5 + C6 + C7) + (C2 + C3 ) + (C1) [1] | |
| 21 | 105 (1) | 102.6–105–107.5 | (C4 + C5 + C6 + C7) + (C1) [1] | | |
| 22 | 110 (2) | 107.6–110–112.5 | (C4 + C5 + C6 + C7) + (C2 to C3) [2] | | |
| 23 | 115 (2) | 112.6–115–117.5 | (C4 + C5 + C6 + C7) + C1 + (C2 to C3) [2] | | |
| 24 | 120 (1) | 117.6–120–122.5 | (C4 + C5 + C6 + C7) + (C2 + C3) [1] | | |
| 25 | 125 (1) | 122.6–125–127.5 | (C4 + C5 + C6 + C7) + (C1) + (C2 + C3) [1] | | |

### List of symbols

APF: Active power filters; CPD: Custom power devices; CY: Calendar year; DSTATCOM: Distribution STATic synchronous COMpensator; FACTS: Flexible alternating current transmission system; IRPT: Instantaneous reactive power theory; LMS: Least mean square; LQFP: Low profile quad flat package; PCC: Point of common coupling; PFC: Power factor correction; PWM: Pulse width modulation; RDS: Radial distribution system; SCB: Switchable capacitor bank; SEBs: State electricity boards; SPWM: Sinusoidal pulse width modulation; STATCOM: STATic synchronous COMpensator; SUES: Sultan-Ul-Uloom Educational Society; SUESRDS: Sultan-Ul-Uloom Educational Society Radial Distribution System; TSSPDCL: Telangana State Southern Power Distribution Company Ltd; ZVR: Zero voltage regulation; $v_{sa}$, $v_{sb}$ and $v_{sc}$: Three-phase source voltages; $v_{dc}$: DC link bus voltage; $i_{sa}$, $i_{sb}$ and $i_{sc}$: Three-phase source currents; $i_{La}$, $i_{Lb}$ and $i_{Lc}$: Three-phase load currents; $i_{ca}$, $i_{cb}$ and $i_{cc}$: Three-phase SCB currents; $C_{DC}$: DC link capacitance; $i_{sa}^*$, $i_{sb}^*$ and $i_{sc}^*$: Three-phase reference currents; $i_{ia}$, $i_{ib}$ and $i_{ic}$: Three-phase inverter injecting currents; $v_\alpha$ and $v_\beta$: $\alpha$-Component, $\beta$-component voltages; $i_\alpha$ and $i_\beta$: $\alpha$-Component, $\beta$-component currents; $p_s$ and $q_s$: Source active power and source reactive power; $q_l$ and $q_c$: Load reactive power and compensator reactive power.

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### Authors' contributions

KMR was mainly involved in table top design, MATLAB/Simulink coding and developing the coordinated control codes and implements them to attain the mentioned results. PVNP and JVRV contributed suggestions while designing phase and editing the article including interpretation of the results to form the tables and figures and supervised the manuscript. All authors read and approved the final manuscript.

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### Availability of data and materials

All data generated or analyzed during this study are included in this published article.

## Declarations

### Competing interests

The authors declare that they have no competing interests.

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