

# Reactive Power Compensation Improvement Technique for Injection Substations in Nigeria

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**Abstract:** The contemporary power system is intricate in structure, it comprises of enormous number of distinct static and dynamic devices. The ever increasing demand for electrical power by consumers on the existing AC transmission power system via injection station due to urbanization poses challenges of voltage thicker, voltage instability, overloaded lines and congestion of lines thus exceeding their thermal limits which result to malfunction and eventually breakdown of transformers due to stress. In this research work, the shunt compensation method is adopted to compensate reactive power, electrical buses and fitter in conjunction with a family of flexible alternating current transmission systems (FACTS) is used to design a system to counter the challenge at the injection station, MATLAB is used to verified the functionality and effeteness of the designed on AC transmission network. Three cases were considered, during fault current, capacitive load and inductive load. The analysis demonstrates a significant improvement on the reactive power of the AC transmission network. This illustrate that the improved technique (STATCOM plus) provides an interpretation to the challenges of malfunction and breakdown of the distribution transformer at the injection station, this is to say that with the integration of the STARTCOM plus on the AC transmission power system reactive power is compensated thus increase in system capacity is achieved, allowing suppliers to have excess of power for marketing and reduction of electricity bills for consumers.

**Index Terms**— Power distribution network, Power loss reduction, Voltage regulation, Reactive power compensation, Capacitive load, Inductive load, STATCOM plus.

## 1 INTRODUCTION

In Nigeria, the transmission system forms the pillar of the integrated power systems and operate at the highest voltage level which is within the range of 330KV to 132KV. The voltages generated at the generating stations are usually between 11KV to 23KV which are stepped up to the transmission voltage via sophisticated power transformer and transmitted to transmission sub-stations where the voltages are utilized at stepped down range to sub-transmission level of voltage (132KV-33KV-11KV) depending on the desired level of voltage.

In a third world country like Nigeria, that has seen an exponential increase in population growth on the last decade, there is a serious inequality between consumers' need for power consumption and the inability of generating sources to meet the growing demand. Rivers State in Nigeria is no exception to this rule. Due to oil boom people of various ranks and class are relocating to Port Harcourt; the Rivers State capital to better their livelihood. In the last few years, Rivers State Government had intensified effort towards the installation of new power plants and associated network of conductors and other related equipment, wherefore meeting the growing request of the general populace. However, it is regrettable to state that, all these efforts have not been met with much success due the following; the transmission system is faced with the challenge of voltage regulation from the national grid; line losses on the transmission lines etc. It is quite obvious that the basic requirement for a smooth conveyance of energy is the equilibrium amid supply and demand of power.

It is obvious that in order for the oil rich Rivers State Government of Nigeria to improve on power supply to its timing populace, lots of effort are required to improve on the transmission line capacity; which is largely dependent on both ac-

tive and reactive power flow. Hence the call for improved reactive power compensation [1] of the functional power system. More effort must be made to manage and improve reactive power which plays a significant role towards the achievement of required or acceptable power efficiency. Poorly managed reactive power flow in power systems result in poor voltage regulation, increased power losses and sometimes long duration of power system outage, which altimately leads to consumer dis-satisfaction. Knowing that reactive power is proportional to the supply voltage thus it is required to improve the system bus voltages [2].

The greater the reactive power moving through a system, the lesser the capacity of the line. In other words, reactive power is proportional to voltage drop. Thus it logically follows that, the greater the reactive power flow through the transmission lines, the greater the voltage drop resulting in lower bus voltage [3]. This means that the low voltages at distribution system buses will lead to low voltage supply to consumers which is objectionable. Furthermore, reactive power can be likened to a high-way on which active power flows. That is to say, that proper reactive power in the system leads to proper real power flow in the system [4].

It is in this regard this paper seek to highlight and recommend the application of an improved technique on reactive power compensation for the 7.5MVA injection station located at A. K. Horsfall Street in Port Harcourt, to help improve power consumption and power quality for consumers within the environs.

## 2 RELATED WORKS

Many researchers have investigated the improvent on reactive

power compensation on transmission lines as well as distribution networks for different voltage levels [4], [5] and [6]. In some of these researches, the reactive power compensation improvements were achieved through placement of capacitors and the use of FACT devices such as SSSC, UPFC, SVC, D-STATCOM, STATCOM, STATCOM Plus etc. Different control strategies such as Synchronous Reference Frame theory (SRF), Instantaneous Power theory (IRP), Symmetrical Component theory (SC), and the Modified p-q theory etc. are also proposed in controlling the mentioned FACT devices [7], [8], [9], [10] and [11].

Comparative studies of the models, applications and benefits of the uses of these FACT devices for reactive power compensation are presented in [12], [13], [14] and [15]. Artificial Intelligent (AI) and Evolutionary Algorithms are extensively being use in the optimization of the sizing of reactive compensators and the optimal location techniques of placement of capacitors and FACTs devices on distribution networks to improve reactive power management [16], [17], [18], [19], [20] and [21].

### 3 METHODOLOGY

For the purpose of these work the Static Synchronous Compensator (STATCOM) under the Shunt Compensation Technique was improved by integrating the band pass filter and the Static Synchronous Compensator in to the AC transmission power system of the 7.5MVA injection substation for more efficient and effective reactive power compensation. Simulations were done using MATLAB 2016 power system tool for proper analysis.

STATCOM plus is very much analogous to a synchronous generator or condenser. The synchronous condenser depending on the excitation current can supply or absorb reactive power. STATCOM plus does this in addition to regulating the bus voltage to which it is connected. The equivalent circuit of a synchronous condenser which is a salient pole electrical machine with no prime mover is shown Figure 1. The diagram shows the equivalent circuit of a synchronous condenser (SC) with an adjustable A.C voltage point notable as (E) whose magnitude is organized by varying the excitation current. Under lossless condition, the modification in the generated voltage (E) is implicit to be zero. By changing or adjusting the magnitude of the generated voltage E, the reactive current delivered to the synchronous condenser can also be varied. When  $E = V$  i.e. generated voltage equal to bus voltage (V), the output current is equal to zero. When generated voltage (E) is greater than the bus voltage (V), then the synchronous condenser injects reactive power into the system; that is SC is in capacitive mode.

When generated voltage is less than the bus voltage, the synchronous condenser absorbs reactive power from the system; that is SC is in inductive mode. When the phase angle difference between the generated voltage and the bus voltage is zero, the reactive current drawn is given by the equations

below:

$$I_r = \frac{V-E}{X'} \tag{1}$$

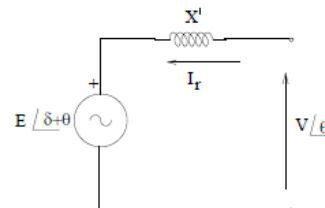


Figure 1: Synchronous Condenser Equivalent of STATCOM

There is a similarity between STATCOM plus and the synchronous condenser. One of the components of the STATCOM plus is an inverter which converts an input D.C voltage across the capacitor that is connected on the D.C side of the inverter. Figure 3.6 shows a single phase STATCOM plus. The D-STATCOM plus is a controlled reactive-power source. It provides the desired reactive power generation and absorption completely by means of electronic processing of the voltage and current waveforms in a voltage-source converter (VSC).

The D-STATCOM plus has number of advantages over conventional methods of compensation which are; less space is required since there are no bulky reactors, faster response, easily reloadable, it can function as super conductive magnetic energy storage (SMES) and connect directly to other energy sources such as battery etc.

### Equipment at Substations

Substations are very significant and integral part of the electric power systems. Substations provide the linkage amid high-voltage transmission and the low voltage distribution schemes. There are various types of substations with various ratings depending on what functional role they are playing within the system. The one line diagram for the substation under review is given in the appendix.

### Mathematical Calculation on Compensations

To improve the existing power factor to proposed or desired power factor for correction; required power equation via power triangle is used. The active (real) power is related to the apparent power and power-factor (pf) by the given equation:

$$KW = KVA \times (pf) \tag{2}$$

Where: KW = Active power; KVA = Apparent power; (pf) = power factor.

The reactive power can be used in determining the size (rating) of capacitor to be used in ( $K_{VAR}$  or  $M_{VAR}$ ); this is given as:

$$K_{VAR} \text{ (or } M_{VAR}) = KW \text{ (or } MW) \times \text{pfactor - correction} \tag{3}$$

This means, that the apparent power (MVA) is the vector sum of the active-power (MW) and reactive-power (MVAR).

The  $M_{VAR}$  capacities of the capacitor required for compensation, is obtain by using the direct relationship as:

$$Q_c = \frac{p}{pf_1} (\sin(\cos^{-1}(pf_1))) - \frac{p}{pf_2} (\sin(\cos^{-1}(pf_2))) \quad (4)$$

Where:

$Q_c$  = Reactive power compensation of the capacitor.

$p$  = Total active power load in (MW)

$pf_1$  = existing power factor of the load.

$pf_2$  = proposed/desired power-factor to be used for correction.

### Study Case: A.K. Horsfall Injection Substation

Transformer capacity = 7.5MVA

- No of units = 2 units
- Presently: only one (1) - unit is working with = 7.5MVA
- Existing power factor of load (MW) = 0.68
- Proposed/desired or design power - factor = 0.90

Obtaining the parameters needed by using equation (3);

$$7.5 \times 0.68 = 5.1 \text{ MW} \quad (5)$$

Substituting into equation (4) we have:

$$Q_c = \frac{5.1}{0.68} (\sin(\cos^{-1}(0.68))) - \frac{5.1}{0.90} (\sin(\cos^{-1}(0.90))) \quad (6)$$

Where:  $pf_1$  = existing power factor = 0.68

$pf_2$  = proposed power factor = 0.90

Also we can obtain  $Q_c$  by:

$$Q_c = 7.5 \times (\sin(\cos^{-1}(0.68))) - 7.5 (\sin(\cos^{-1}(0.90))) \quad (7)$$

$$Q_c = 7.5 \times (\sin(47.156356)) - 5.66666 (\sin(25.841932)) \quad (8)$$

$$Q_c = 3.02 \text{ MVAR}$$

$$Q_c \cong 3 \text{ MVAR}$$

Therefore, the recommend size of capacitor bank required at the A.K. HORSFALL street injection station is 3MVAR, to produce the required reactive power in order to deliver the active power (KW); while expecting the restoration of the other units of the transformer ( $1 \times 7.5\text{MVA}$ ) that is down, i.e. out of service due to overload problem.

The flow chart for obtaining the required reactive power for a substation is given in Figure 2.

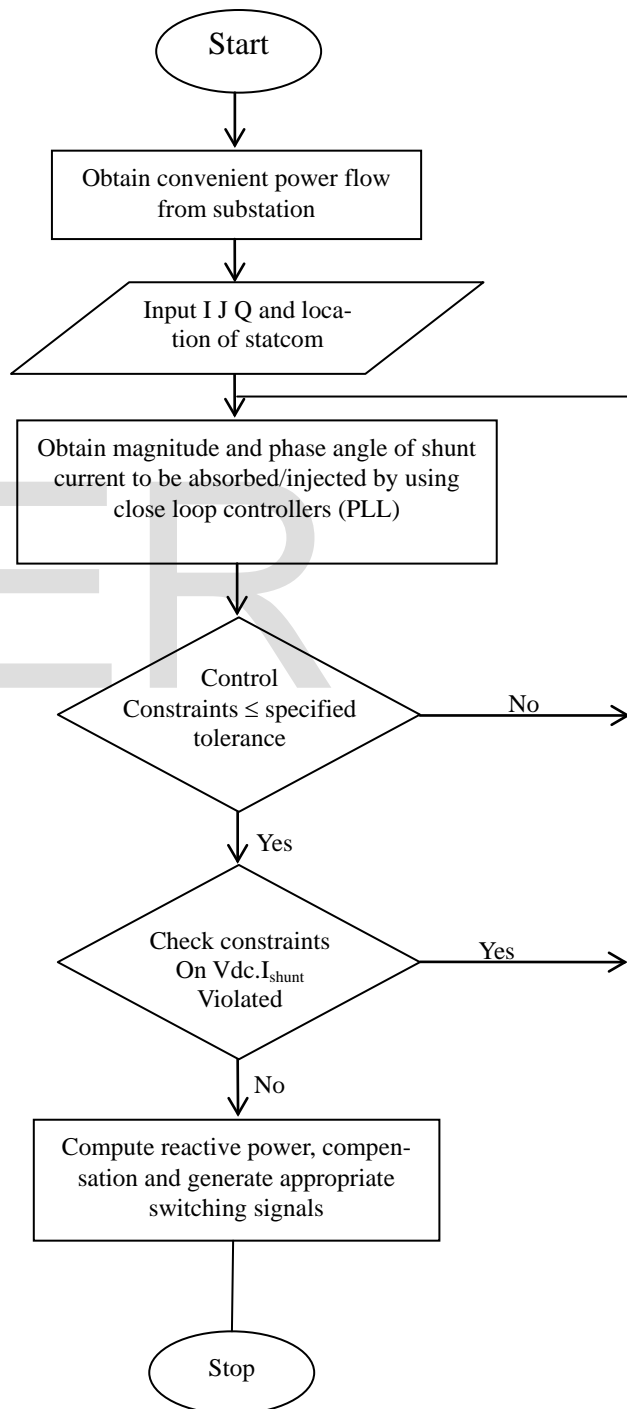


Figure 2: Flow Chart for Implementation of D-STATCOM plus

#### 4 RESULTS AND DISCUSSION

The Distribution STATCOM plus (D- STATCOM plus) dynamic response was observed for various system voltages with respect to reference set voltages. The simulations circuit has an equivalent circuit of the D-STATCOM plus connected to a domestic distribution network system which precisely loads at the Rivers State Government House. The system modelled in MATLAB has the following simulation input parameters as listed in Table 1.

Table 1  
Simulation Parameters

Number	Values	System
01	IGBT built, 3 arms, 6 pulse, carrier frequency = 1080Hz, sample period = 5us	Inverter
02	Norminal power = 7.5MVA, Frequency = 50, magnetisation resistance $R_m$ (pu) = 500, magnetisation inductance $L_m$ (pu) = 500	Three phase transformer
03	Proportional gain $K_p = 0.5$ integral gain $K_i = 500$ , sample time = 50us	Proportional integral (pi) controller
04	$R = 25.1\text{ohms}$ , $L = 400\text{e-}3\text{H}$	Load

As shown in the figure at the appendix, the test system is injecting 11kV, 50Hz signal, represented by a thevenin equivalent, feeding distribution lines through a (3) three-winding transformer connected in  $Y_g/Y_g/Y_g$ , 33/11/11kV matrix. A varying load is connected to the 11kV, secondary side of the transformer. A two-level D-STATCOM plus is connected to the 11kV tertiary winding to provide instantaneous voltage support at the load point.

The system performance is analysed for compensating reactive power on different system conditions so as to achieve rated voltage at a given load, these various cases are discussed and result as follows:

##### Case I: System Voltage Profile during a Fault Current

A three-phase short-circuit-ground fault is applied at the load point of the simulation model through a fault resistance of 0.66  $\Omega$ , the transition period for the defect is considered from 0.3

sec to 0.6 sec. The first simulation which does not contain D-STATCOM plus; it was observed that the voltage sag at the load point is 36.28% with respect to the reference voltage as illustrated in Figure 3. The second simulation was carried out with the D-STATCOM plus connected to the system, it was observed that the voltage sag was almost completely diminished, and the root mean square voltage at the sensitive load point was sustained at 97% as shown in Figure 3.

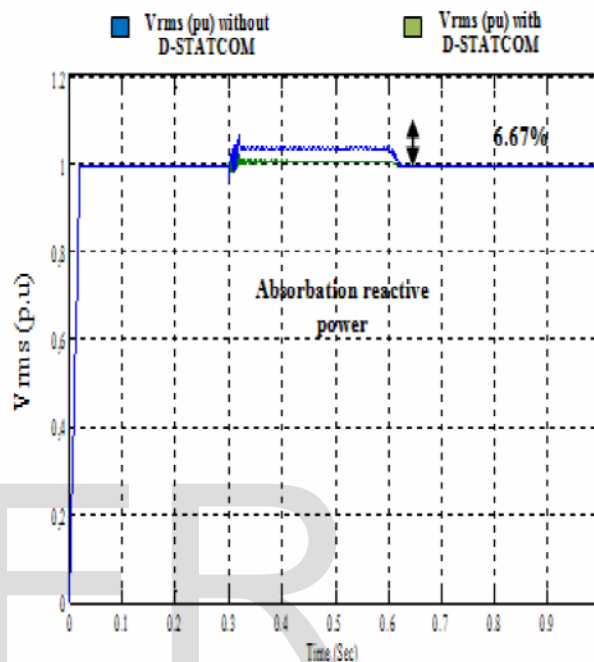


Figure 3: Voltage Profile during a Fault Current at the Load Point with and without D-STATCOM plus.

The result confirm the injection of reactive power into the AC power system by STATCOM plus and stability maintain in less than a second.

##### Case II: System Voltage less than the Reference Voltage

A capacitive motor is coupled to the high voltage side of the designed system to represent capacitive load while transition time is considered from 0.3 sec to 0.6 sec. The first simulation which does not contain D-STATCOM plus is observed and the voltage sag at the load point is 6.67% with respect to the reference voltage as Illustrated in Figure 4.3. The second simulation is carried but with D-STATCOM plus is connected to the system, then the voltage sag is diminished almost completely, and the root mean square voltage at the 3sensitive load point is sustained at 99.75% as shown in Figure 4.

The result confirm again that the D- STATCOM plus was able to stabilize and maintain the AC power system by injection reactive power in less than a second.

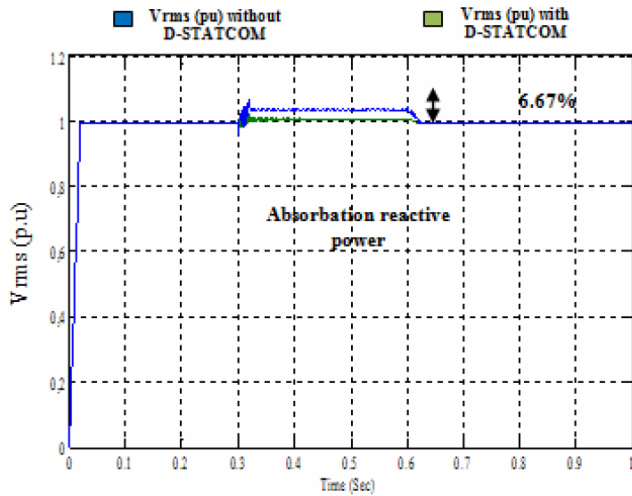


Figure 4: Voltage Profile when Load is Capacitive with and without D-STATCOM plus

**Case III: System Voltage Greater than the Reference Voltage**

An Induction motor is coupled to the high voltage side of the designed system to represent inductive load while transition time is considered from 0.3 sec to 0.6 sec. The first simulation does not contain D-STATCOM plus it was observed that the voltage sag at the load point is 17.98% with respect to the reference voltage as illustrated in Figure 5. The second simulation is performed with D-STATCOM plus connected to the system, it is observe that the voltage sag is almost diminished completely and the root mean square voltage at the sensitive load point is sustained at 99.70% as shown in Figure 5.

The result confirms that the D- STATCOM plus absorbed the reactive power from the AC power system and stabilizes the system in less than a second.

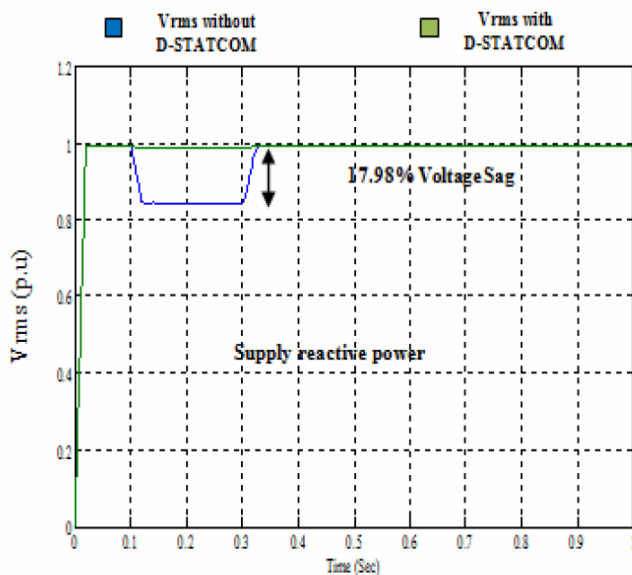


Figure 5: Voltage Profile when Load is Inductive with and without D-STATCOM plus

In Table 2 electrical motors where used as inductive loads to demonstrate the positive effects of using the D-STATCOM plus.

Table 2  
Application of D-STATCOM plus on Electrical Motors

Rated Voltage (V)	Rated power (KW)	Operating Frequency (hz)	No. of poles	Speed (RPM)	In-take current (A) before STATCOM	Power factor before STATCOM	Intake-current (A) after STATCOM	Power factor after STATCOM
415	30	50	4	1500	56	0.72	47.5	0.9
415	7.5	50	4	1500	14.2	0.86	12.7	0.96
415	15	50	4	1500	28.5	0.84	25.3	0.95
415	22	50	4	1500	41	0.83	35.1	0.97
415	25	50	4	1500	44	0.78	36.3	0.94
415	110	50	4	1500	202	0.7	178.4	0.92

As observed in Table 2, the application of D-STATCOM plus improved the power factors of the motors by supplying the necessary reactive power which also resulted in the reduction of the line current.

The D-STATCOM plus device when also applied across the secondary side of two distribution transformers increased the power factor towards unity and at the same time also decreased the current drawn from the line as shown in Table 3. Thus, allowing transformers to operate below their thermal limit, making the transformer more effective and efficiently. As the load demand on the supply system changes, the voltage at the consumer’s terminal changes correspondingly. The variations of voltage at the consumer’s terminals are undesirable and must be kept within prescribed limits of +/-6% of the declared voltage (240L-N or 415L-L).

Table 3  
Application of D-STATCOM plus on Transformers

Rated power (KW)	Connected load (KW)	Reactive power (KVA) before D-STATCOM	Power factor before D-STATCOM	Reactive power (KVA) after D-STATCOM	Power factor after D-STATCOM	Load-ing factor before D-STATCOM	Load-ing factor after D-STATCOM	Recovered capacity
1500	1000	1020	0.7	470	0.9	95%	74%	21%
750	100	135	0.73	75	0.96	87%	43%	44%

In summary, it was observed from the analysis on the A.K.



Horsfall AC power distribution network in Port Harcourt that the voltages without D-STATCOM plus are not within the acceptable voltage at some point. The voltage magnitude limits as depicted in Figures 1, 2 and 3. The drop in voltage magnitude beyond the acceptable limits experienced by consumers which have negative effect is usually caused by increased load demand on the network made by consumers, power theft and of course technical challenges.

The designed D-STATCOM plus integrated into the A. K. Horsfall AC transmission power distribution injection substation in Port Harcourt network, solved the challenge of voltage variations and minimized the heating effect on the distribution transformers, by sustaining it values to 1.0 p.u. This confirm that the reactive power compensation improvement techniques for the injection station is very active and efficient, it also ensures regularization of voltage supply to incandescent lamps, smooth operation of the Electric motor, never the less it increasing the loading factors of the distribution transformers making more power available for consumption; thus providing economic benefits for the supplier and consumers.

## 5 CONCLUSION

In this work, band pass filter and STATCOM are combined to form the D-STATCOM Plus and then integrated into the AC transmission power system at the A. K. Horsfall Street Distribution Injection Substation in Port Harcourt. The result displays a suitable efficient and effective reactive power compensation technique that is proposed to upsurge the transmittable power in AC power systems. Presently a fixed/mechanically switched capacitors and reactors are being employed to increase the steady state power transmission by controlling the voltage along the lines. However these devices do not provide high speed control. Furthermore, control cannot be initiated frequently because mechanical devices wear out quickly compared to static devices.

STATCOM plus is a better device than SVC. For a state like Rivers State having interconnected with the Nigerian grid system, the SVC is a better option from economic point of view but due to other aspects like stability margin, power factor correction, voltage improvement and power system performance, STATCOM plus is preferred.

## Recommendations

STATCOM plus should be implemented in Engineering plants, using arc incinerators that operate with large random peaks of reactive power causing undesirable effects in the plant itself and in the AC power network.

The supplier of electric power charges the consumer also for reactive power demand; I recommend STATCOM plus should be implemented in distribution system applications to reduce the reactive power demand which therefore means lesser bills for consumers.

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