A comparative Analysis of the performances of the discretely switched bulk capacitors and the PI controlled DSTATCOM

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Abstract

In this work a comparative analysis of the performance of the switched bulk capacitors against the performance of a STATCOM in the reactive power compensation of a standalone three phase reactive power load. The proportional-integral (PI) controlled is Zeigler Nicholas tuned. A set of four bulk reactive power compensating three phase capacitive VAR units are used and a single capacitor or more number of capacitors of resulting VAR values closest to the reactive power demand are connected across the three phase line at the point of common coupling. Then instead of the discrete capacitor bank a PI tuned STATCOM is connected at the point of common coupling and the performance of PI controller is observed. Then these two variants of reactive power compensation are compared and contrasted. The results of the two procedures are quantitatively analyzed. The transient and steady state behavior of the two techniques are studied. The advantages of the use of STATCOM in terms efficiency and drawback of the STATCOM in terms of degraded power quality are compared.

Keywords: Power quality, STATCOM, PI controller, stability.

1. Introduction

The reactive power compensation is a common problem in electrical power systems. Wherever there is a reactive component of the load it leads to poor source side power factor causing increased source current, increased losses and the requirement of over rating of source capacity for a given real power delivery [1]. The traditional procedure is to connect a set of capacitors across the lines close to the load. The reactive power demand of the load is supplied by the capacitor bank and the source is relieved of this burden.

Reactive power compensation can also be done using synchronous generators [2] connected across the load and the synchronous generator if run in the over excited mode of operation can be used to supply the reactive power demand of the load. The advent of modern power electronics has lead to the development of power electronic converters that could be used in electrical networks for improving the power quality of electrical distribution and utilization thereby increasing the overall system efficiency and maximizing the real use of the available power capacity.

The STATCOM or the Static Synchronous Condenser is an electronic equivalent of the conventional synchronous condenser or the synchronous generator [3]. The STATCOM is completely solid state and it does not consume as much real power that could be required for a synchronous generator while both are engaged in the activity of reactive power compensation systems.

The core of the STATCOM is a Graetz bridge power electronic converter. As a converter of electrical power it has two ports through which power in a given form can enter and leave in the desired form. The two ports of the STATCOM can be viewed as the AC side and the DC side. The advantage of the Graetz bridge realized STACOM is that simultaneously either real power or reactive power can enter and leave through any of the two ports [4].

That is real power can enter trough the AC side and charge the DC side capacitor so as to maintain the DC link voltage topped up properly and maintained at a constant value. Reactive power can be supplied from the STACOM at the AC side while the DC link voltage across the DC link capacitor is maintained at a constant DC potential level. If a renewable energy source is connected across the DC link capacitor the STACOM can be set to deliver real as well as reactive power at its AC terminals to be fed into the three phase line. Thus the Graetz bridge converter is capable of transferring both real and reactive power in either direction which can happen simultaneously.

In this work the functionality of the STACOM as a reactive power compensator alone is focused. Therefore the general requirements are that the STATCOM converter draws real power from the AC mains to charge the DC link capacitor and maintain the DC voltage at a preset value, and that the STATCOM should supply the reactive power demand of the load [5].

The main component of the STATCOM is a three phase three leg six pulse converter. Although the STATCOM has many functionalities, the only degree of freedom available is to manipulate the six On/Off power electronic switches of the SATATCOM converter in an appropriately timed manner as dictated by a three phase reference signal. It is the three phase reference signal that virtually holds all the constraints or requirements of operation in the form of the amplitude, the phase and the frequency. Since the STATCOM has to work in line synchronism the designer does not usually change the frequency of the reference signal but keep it as the line frequency with the help of a Phase Locked Loop frequency detector [6].

The challenge, therefore, is the formation of the three phase reference signal with the appropriate amplitude and phase so that when this reference signal is used for Pulse Width Modulation of the STATCOM converter, the reactive power compensation as well as the maintenance of the DC link voltage are achieved. As for reactive power compensation the three popular techniques are,

- ✓ Fixed capacitor method - where a set of fixed capacitors from an available bank of capacitors are selected and connected across the load depending upon the reactive power demand of the load. This method may be done manually or automated but its accuracy in terms of timing and magnitude of compensation is poor. Compensation could be done in discrete steps only while the demand may be of the continuous scale.
- ✓ Using the synchronous motor method - in which the excitation of the synchronous generator is increased and is adjusted manually or automatically so as to render the required reactive power demand. Compensation could be done continuously and with fairly good accuracy.
- ✓ The system has to spend some minimal mechanical power to keep the synchronous motor in the running condition. With the intention of compensating reactive power, some real power needs to be spent. Given the quantum of reactive power that can be compensated by the synchronous motor method and the relatively small real power required by the synchronous motor the method is quite feasible and is still now popular as well.

The main advantage of the STACOM is that it combines the two important features of the two traditional methods that are that the STACOM is static as the capacitor method, and that the STACOM can give continuous control as a synchronous motor.

In this work the performance of the STATCOM is compared against the fixed capacitor method for a given loading conditions with time varying load patterns. Although it is well known that the STACOM will outperform the fixed capacitor method this work presents a quantitative analysis and reveals the superiority of the STATCOM in terms of observed parametric values [7]. For this purpose the STATCOM is PI controlled. As for the fixed capacitor switching method the capacitors have been assumed to be loss less.

2. Review of Reactive Power Compensation

2.1. Basic system outline

System nominal voltage	V: 3-phase/380 V/50 Hz
Load real power demand	P: 5 kW/380 V/50 Hz
Load reactive demand	Q: 5 kVAR/380 V/50 Hz

This is a medium voltage system and therefore the compensation sub system like fixed capacitors or the STATCOM does not require any voltage matching transformers. The Fig. 1 shows the single line diagram of the proposed scheme.

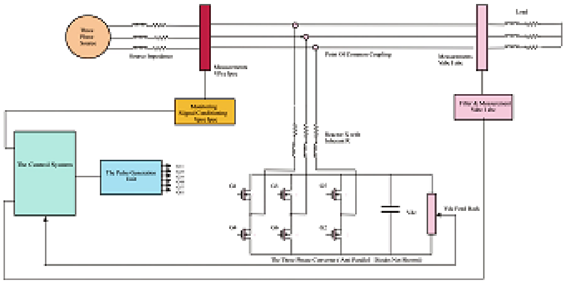


Fig. 1. The block diagram of the STATCOM

A consideration of the calculations are necessary for further investigation. In three phase systems;

Real Power P = $\sqrt{3} * Vl * Il * Cos\theta$ Watts

Reactive Power Q = $\sqrt{3} * Vl * Il * Sin\theta$ VAR

Apparent Power = $\sqrt{P^2 + Q^2}$ VA

Power factor = $\frac{Watts}{VA}$

If the P demand = 5e3 Watts and Q demand = 5e3 VAR (Inductive) the power factor of the load will be PF = 0.707. The compensating VAR required will be 5e3 VAR (Capacitive).

On connecting a three phase compensating capacitor of 5e3 VAR the source side is relieved of this reactive burden. The source side power factor moves to unity from its earlier value of 0.707 (Lagging). The value of capacitance in each phase can be calculated as follows.

VAR value;

Reactive Power Q = $\sqrt{3} * Vl * Il * Sin\theta$ VAR with V_{line} = 380 V and f = 50 Hz. Assuming Delta connected capacitor bank the current through each line will be

Il = 5e3 /($\sqrt{3} * Vl * Sin\theta$) Amps

I_{Phase} = 5e3 /($\sqrt{3} * \sqrt{3} * Vl * Sin\theta$) Amps

= 5e3 /(3 $* Vl * Sin\theta$) Amps

with power factor 0.707 $Sin\theta = Cos\theta$ and $\theta = 45\ degrees$.

I_{Phase} = 5e3/(3 $*$ 380 $*$ 0.707) Amps

= 6.203 A.

Therefore X_c = 1/(2*p_i*f*C)

= V_l/I_{phase} = 380/6.203

= 61.26 Ohms

C = 1/(2*pi*50*61.26)

= 51.98 MFD (say 52 MFD) * 3 nos.

If the load will be varied at different times with different reactive power demands, then assuming the same operating three phase line voltages the capacitive VAR requirement and the corresponding capacitance per phase will be as shown in Table 1.

2.2. STATCOM

The schematic of the STATCOM based reactive power compensation scheme is shown in Fig. 1. The system under consideration is of three phase and consists of a single source and single load. The load is assumed to be a balanced but variable kVA, kW and kVAR type. The STATCOM is supposed to deliver the required kVAR to the load that may vary from time to time. Depending upon the reactive power demand the STATCOM, in association with the switching scheme will deliver the appropriate quantity of reactive power.

The switching scheme adopted may be of any one of the popular PWM techniques like the Sinusoidal PWM or the Space vector PWM. However in this application a direct Hysteresis control scheme is adopted [8,9,10]. The hysteresis controller switches on and off the six power electronic switches of the STATCOM in accordance with a comparator and the comparator compares the reference converter current and the actual converter current.

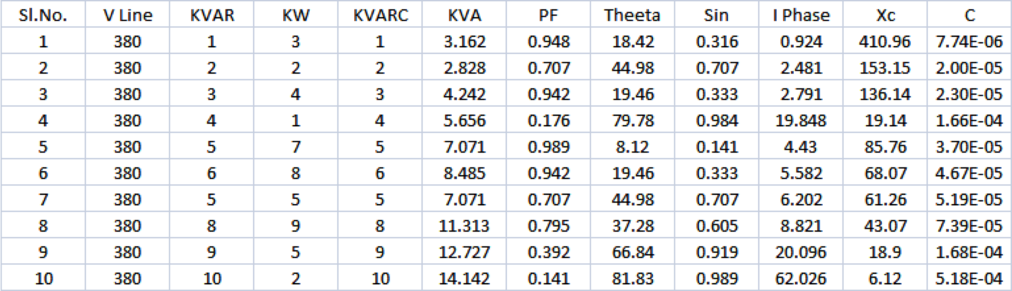
There are three hysteresis comparators, one for each phase, followed by a logical inverter corresponding to each comparator. The output of the hysteresis comparators drive the upper switches of the Graetz bridge of the STATCOM while the inverted outputs drive the respective lower arm switches [11,12]. The main task in this type of control scheme is the formulation of the reference three phase current which has to be followed by the actual three phase source current [13].

The structure of the STACOM based reactive power compensation consists of a STATCOM converter, the DC link capacitor and the reactor. The schematic of the STATCOM based reactive power compensation scheme for a standalone load is shown in Fig. 1.

3. Compensation of reactive power

The two basic operational requirements are that the voltage at the Point of Common Coupling (PCC) and the DC link voltage across the DC link capacitor are to be maintained at the preset level. As for the voltage at the PCC it is the d component of the three phase voltage at the PCC that has to be maintained at the preset level..

Table 1. Capacitive VAR requirement



Sl.No.	V Line	KVAR	KW	KVARC	KVA	PF	Theeta	Sin	I Phase	Xc	C
1	380	1	3	1	3.162	0.948	18.42	0.316	0.924	410.96	7.74E-06
2	380	2	2	2	2.828	0.707	44.98	0.707	2.481	153.15	2.00E-05
3	380	3	4	3	4.242	0.942	19.46	0.333	2.791	136.14	2.30E-05
4	380	4	1	4	5.656	0.176	79.78	0.984	19.848	19.14	1.66E-04
5	380	5	7	5	7.071	0.989	8.12	0.141	4.43	85.76	3.70E-05
6	380	6	8	6	8.485	0.942	19.46	0.333	5.582	68.07	4.67E-05
7	380	5	5	5	7.071	0.707	44.98	0.707	6.202	61.26	5.19E-05
8	380	8	9	8	11.313	0.795	37.28	0.605	8.821	43.07	7.39E-05
9	380	9	5	9	12.727	0.392	66.84	0.919	20.096	18.9	1.68E-04
10	380	10	2	10	14.142	0.141	81.83	0.989	62.026	6.12	5.18E-04

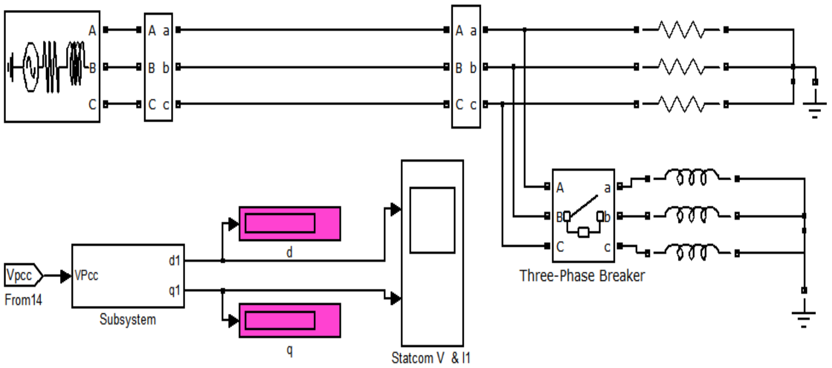


Fig. 2. The MATLAB/Simulink schematic for a simple system of load and source

Consider a single Load and source system the load is of three phase balanced nature. The load may be of any power factor as it may be demanded. The terminal voltage of the source and that of the load are one and the same and the d and q components of this voltage are as shown in the following table.

With reference to Fig. 3 the V_d and V_q quantities of V_{abc} the bus bar voltage are shown. At time 0.2 second the load is changed from a resistive load of nearly unity PF to an inductive load of 0.4 PF again at time 0.6 second the inductive load is removed and the load is resistive. The inclusion of an inductive load between times 0.2 second and 0.6 second causes the quantity of id to dip from 0.99 to 0.75.

The three phase source voltage exhibits a sudden voltage dip and this dip in voltage continues as long as the load current is highly reactive that is up to time instant 0.6 second. With reference to the voltage profile it is evident that the terminal voltage of the source depends upon the nature of the load. If there exists a mechanism that delivers the required reactive power for the load then the source voltage can be relieved of this burden and the fall in the source voltage caused by the reactive loads can be avoided.

3.1. Compensation by a fixed capacitor method

The Fixed capacitors for the compensation of inductive VAR can be used with an automatic system that continuously monitors the power factor of the load and connects the capacitor with appropriate value. Based on the knowledge of the load a set of fixed capacitors may be used. Depending upon the reactive power load that may vary from time to time the capacitors are turned On and Off automatically.

The drawback of the system is that if the reactive load is of a certain value for which there is no exact compensating value of capacitor the compensation can only be approximate. The fixed capacitor type of compensation is a discrete control scheme whereas the STATCOM offers continuous control that offers close compensation for any value of reactive power demand within the design premise.

4. Result and discussion

4.1. Case - 1: Typical results of fixed capacitor compensation

The case 1: In this case a load of P = 10 kW is initially connected from the 0 second. At time = 0.2 second and inductive load of Q = 30 kVAR is connected. At time = 0.6 second the reactive load is removed. The effect of the addition of the reactive load, on the d component of the source voltage is shown in Fig. 3. No compensation is used.

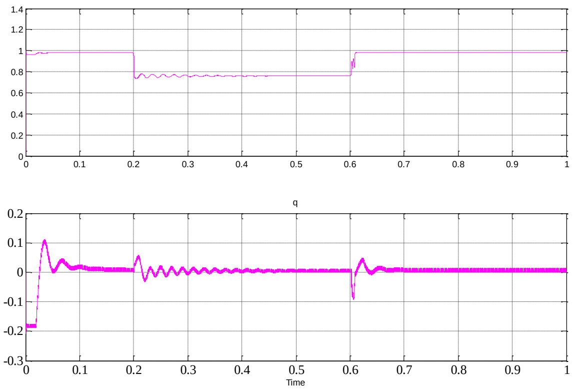


Fig. 3 The deviation of the *d* component of V_{pcc} with the inclusion of a sudden reactive load at 0.2 s. The reactive load component is removed at time 0.6 s.

4.2. Case - 2: Typical results of fixed capacitor compensation

In this case a load of P = 10 kW is initially connected from the 0 second. At time = 0.2 second an inductive load of Q = 30 kVAR is connected. The compensating capacitor bank of 30 kVAR is connected along with the inductive load. At time 0.6 second the reactive load is removed. The effect of the addition of the reactive load, on the d component of the source voltage is shown in Fig. 4.

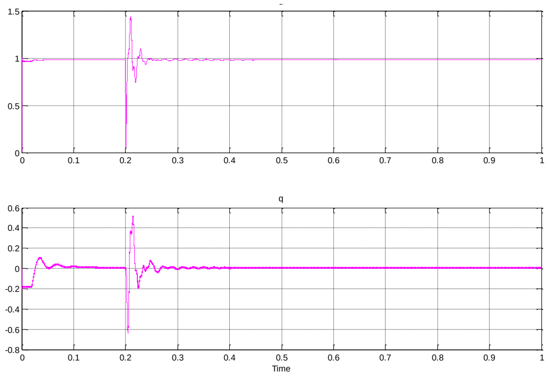


Fig. 4. The Reactive power included at 0.2 sec is compensated by a suitable capacitor.

4.3. Case - 3: Typical results of fixed capacitor compensation

In this case a load of P = 10KW is initially connected from the 0 second. At time 0.2 second and inductive load of Q = 30 kVAR is connected. The compensating capacitor bank of 30 kVAR is connected across the inductive load with a little delay of 0.1 second and at 0.3 second. At time 0.6 second the reactive load is removed. The effect of the addition of the reactive load, on the d component of the source voltage is shown in Fig. 5.

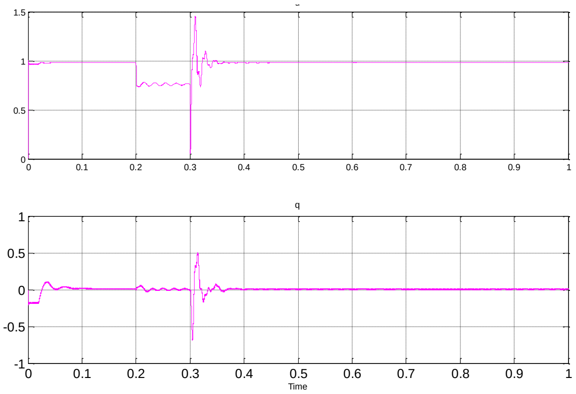


Fig. 5. The compensating capacitor is connected to the bus bar with a time delay of 0.1 s. The effect of this delay in the d component of V_{pcc}.

4.4. Case - 4: Typical results of fixed capacitor compensation

In this case a load of P = 10KW is initially connected from the 0 second. At time 0.2 second and inductive load of Q = 33KVAR is connected. The compensating capacitor bank of 30 KVAR is connected along with the inductive load. At time = 0.6 second the reactive load is removed. The effect of the addition of the reactive load, on the d component of the source voltage is shown in fig. 6.

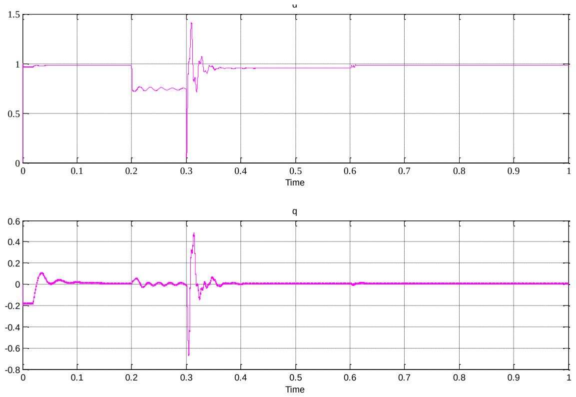


Fig. 6. The effect of connecting a capacitor that of a lower value than the requirement. The d quantity does not reach its required value of 1. (Q demand = 30 kVAR) Q_{cap} = 27 kVAR

4.4. Case - 5: Typical results of fixed capacitor compensation

In this case a load of P = 10KW is initially connected from the 0 second. At time = 0.2 second an inductive load of Q = 27KVAR is connected. The compensating capacitor bank of 30 KVAR is connected along with the inductive load. At time = 0.6 second the reactive load is removed. The effect of the addition of the reactive load, on the d component of the source voltage is shown in Fig. 7.

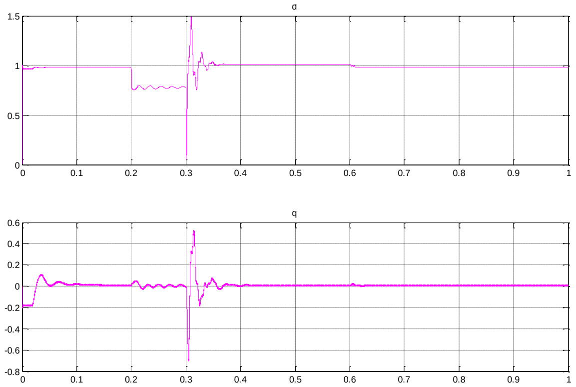


Fig. 7. The effect of connecting a capacitor that of a higher value than the requirement. The d quantity

reaches a value that is more than the required level of 1. (Q demand = 30 kVAR) Q cap = 33 kVAR

A set of five different cases have been studied with different inductive loads and in each case the fixed capacitor type of compensation has been done and the results have been recorded. In the next phase of the study a STATCOM is designed and its performance has been compared against the fixed capacitor method of compensating the reactive power.

4.5. The two controllers in association with the STATCOM.

In The two parameters of interest are the maintenance of the voltage at the point of common coupling and the maintenance of the DC link voltage on the DC side of the STTACOM converter.

It is clear by the examples demonstrated earlier in this paper that the d component of the park transformation of the three phase source voltage falls with increase in the reactive power demand. If the appropriate quantity of the reactive power is supplied by the STATCOM then the source is relieved of this burden and the fall in the d component of the Park transformed three phase source voltage can be avoided.

The indication of a drop in the d component of the voltage at the point of common coupling is an indication of the increased reactive power demand on the load side. As such a PI controller is used to check the fall of the said d component against the standard value that is nearly unity when the load is resistive and the load power factor is unity.

For the purpose of supplying reactive power from the STATCOM a sufficient DC voltage is to be maintained across the terminals of the DC link capacitor on the DC side of the STASCOM converter. This voltage should be maintained a constant one so that by controlling the modulation index of the STATCOM converter the required reactive power can be supplied.

Due to the losses occurring in the STATCOM converter switches and the internal resistance of the DC link capacitor known as the effective series resistance the voltage across the DC link capacitor may fall below the rated value. This has to be topped up appropriately by supplying the required real power from the three phase AC source. In order to maintain constant DC link voltage a PI controller is used. This PI controller manipulates the error between the set value or the desired DC link voltage and the actual DC link voltage and a control quantity is generated by this PI controller that will be used to adjust the phase angle of the reference three phase signal.

The proposed STATCOM controller has three legs and six power electronic switches. It is a six pulse converter. The switching scheme adopted is of the hysteresis controller scheme. The hysteresis controller generates the six pulses for the six power electronic switches. As for the hysteresis controller, there are three sets of hysteresis band comparators and a set of three inverters. Each hysteresis band comparator compares the reference phase current and the actual inverter current and produces a train of pulses for the upper set of three switches. The logical inverter associated with the hysteresis band comparator inverts this train of pulses and supplies the switching pulses to the corresponding complementary low level power electronic switches.

The STATCOM is a bi directional power flow controller. There can be a transaction of real power from the AC side to the DC side, or reactive power from the DC side to the AC side and as well as in the reverse direction.

While the STATCOM receives or sends reactive power the DC voltage is not affected. However if the STATCOM receives real power from the AC bus bar the DC link voltage rises and this DC link voltage falls with the STATCOM supplying real power from the DC side to the AC bus bar side.

The transaction of real and reactive power happening through a STATCOM happens as follows. Let V_{inv} be the terminal AC voltage of the STATCOM.

V_{pcc} be the bus bar AC three phase voltage.

V_{dc} be the DC link voltage.

X be the reactance between the STATCOM AC terminals and the PCC. The magnitude of reactive power supplied by the STATCOM is denoted as Q and is given by the relation. $Q = (V_{inv}(V_{inv} - V_{pcc}) \text{ Cos } \delta) / X_2$ where δ is the angle between V_{inv} and V_{pcc}. If this angle $\delta = 0$ and $\text{Cos } \delta = 1$, then the reactive power transaction will be solely decided by the difference between V_{inv} and V_{pcc}.

Since V_{pcc} is to be maintained constant, it is the STATCOM terminal voltage V_{inv} that is the only deciding factor to govern the flow of reactive power from the STACOM towards the AC bus bar and hence to the load. With reference to the equation $Q = (V_{inv}(V_{inv} - V_{pcc}) \text{ Cos } \delta) / X_2$ if V_{inv} is held more than V_{pcc} reactive power flows from the STATCOM to the AC bus bar. If V_{inv} is less than V_{pcc} then reactive power flows from the AC bus bar towards the STATCOM.

Table 2. Performances of the training phase varying the neuron number

V_{inv}	V_{pcc}	$V_{inv\ \theta}$	$V_{pcc\ \theta}$	p	Q
400	380	0	0	0	Inv to Pcc
380	400	0	0	0	Pcc to Inv
400	400	Lead by 45 Deg	0	Inv to Pcc	0
400	400	Lag by 45 Deg	0	Pcc to Inc	0
400	380	Lead by 45 Deg	0	Inv to Pcc	Inv to Pcc
380	400	Lead by 45 Deg	0	Inv to Pcc	Pcc to Inv
400	380	Lag by 45 Deg	0	Pcc to Inv	Inv to Pcc
380	400	Lag by 45 Deg	0	Pcc to Inv	Pcc to Inv

In a similar manner, the magnitude of real power supplied by the STATCOM is denoted as P and is given by the relation. P = (V_{inv}*V_{pcc}*Sin δ) / X_2 where δ is the angle between Vinv and Vpcc. If this angle δ = 0 and sin δ = 0, then the real power transaction will be zero. However if the this angle δ = 90 degrees and even if V_{inv} and V_{pcc} are equal there happens a real power flow from the leading node to the lagging node. The magnitude of real power flow and its direction are governed by the phase angle between the voltages V_{inv} and V_{pcc}.

Since V_{pcc} is to be maintained constant magnitude and treated as zero phase angle reference, it is the phase angle of the STATCOM terminal voltage V_{inv} that is the only deciding factor to govern the flow of real power from the STACOM towards the AC bus bar or in the reverse direction.

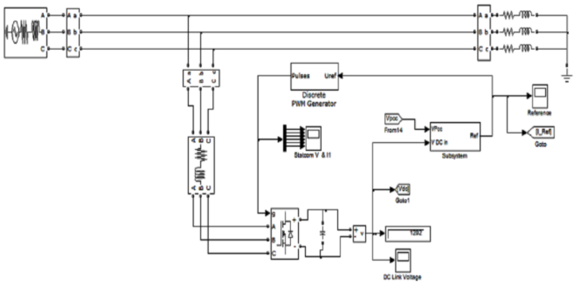


Fig. 8. The position of the DSTATCOM in the Reactive power compensation scheme

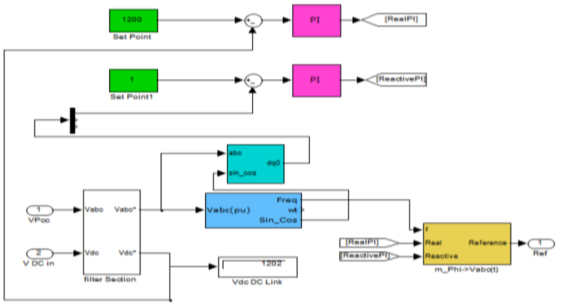


Fig. 9. The two PI controllers for regulating D component of V_{pcc} and the V_{dc} respectively

The reference current is a three phase current that encapsulates the required mode of operation. The Amplitude of the three reference sine waves and their respective phase angles will be decided by the two PI controllers. The PI controller that tracks the d component of the Vpcc will decide the amplitude of the three phase reference sine waves. The PI controller that tracks the DC link voltage will decide the phase angle of lead or lag of the three phase reference sine wave. The MATLAB SIMULINK block diagram is shown in Fig. 8.

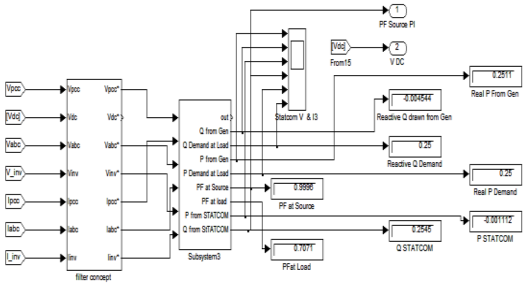


Fig. 10. The Measurement and display sub system showing the vital parameters

The results of implementation of the STATCOM with a set of PI controllers have been presented in the following waveforms.

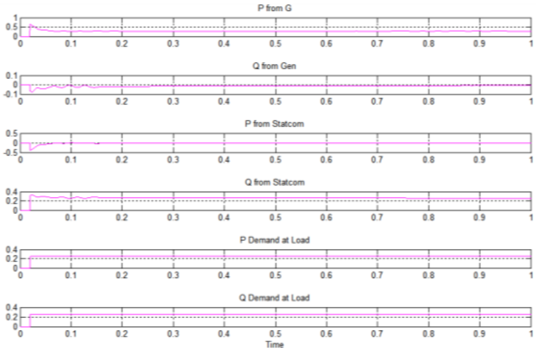


Figure 10. The various quantities associated with the reactive power compensation for a standalone load with the DSTACOM.

The real power demand of 0.25 PU KW is supplied by the main source. The reactive power demand Q of 0.25 PU KVAR is supplied by the DSTATCOM.

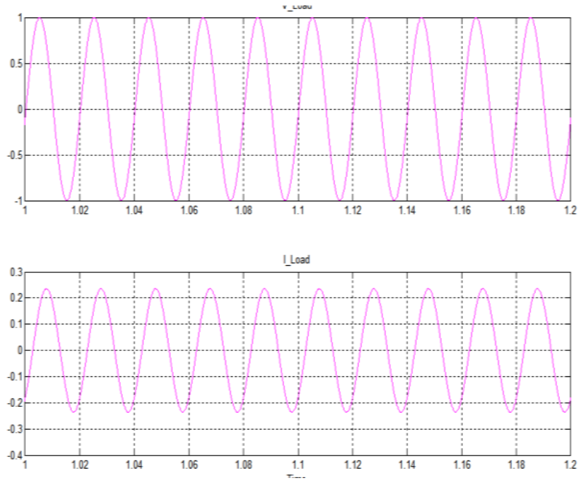


Fig. 11. The waveforms of the terminal voltage across the load and the load current.

There is phase difference between the two (for the R Phase) The Load is a reactive and hence the delay in between the V and I components.

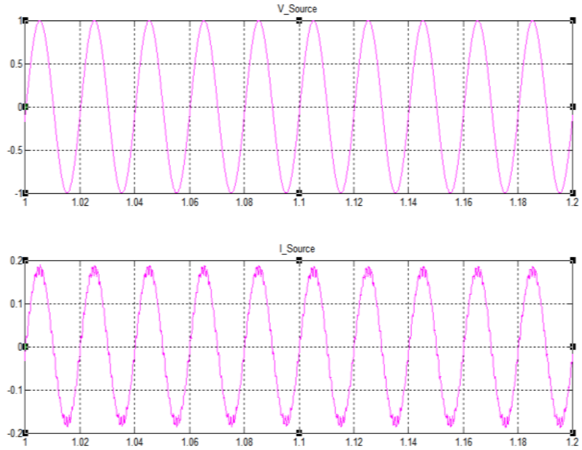


Fig. 12. The waveforms of the source voltage and the source current.

There is no phase difference between the two (for the R Phase) The DSTATCOM has compensated (in fact supplied) the reactive power demand of the load and hence there is no delay in between the V and I on the source side.

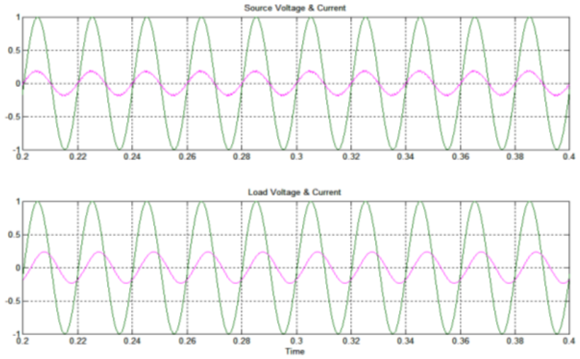


Fig. 13. Comparison of source *V* and *I* / Load *V* and *I*

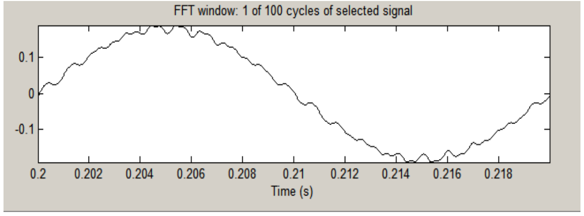


Fig. 14. The source current of the R phase (To show the waveform distortion when the DSTATCOM is in action)

The reactive power compensation using the DSTATCOM is efficient in the sense it can be used for any continuous reactive power demands within the designed rating Which a fixed capacitor bank cannot. However the quality of power is affected by the operation of the DSTATCOM by virtue of the non linear STATCOM and its high frequency switching operation. Figure 14 gives the source current waveform. Figure 15 gives the FFT of the source current waveform and it indicates a THD of about 5.01%. There is no much influence on the source voltage. Still the operation with the fixed passive Capacitor bank does not affect the power system in terms of injection of harmonics while the DSTATCOM causes the distortion in the source side voltage and current. The details of the study are further shown in Table 3.

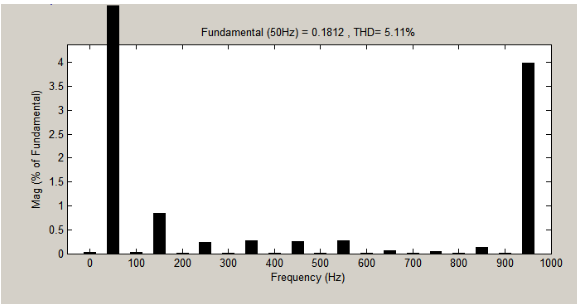


Fig. 15. The FFT of the source current. The THD is 5.11 with the DSTATCOM is in action

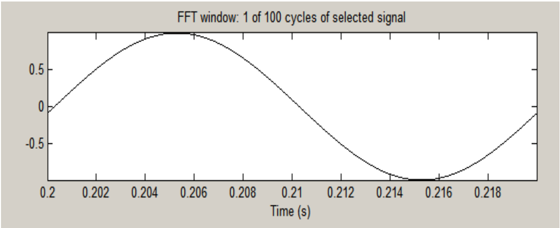


Fig. 16. The waveform of the source voltage. The source voltage is not affected much by the DTATCOM.

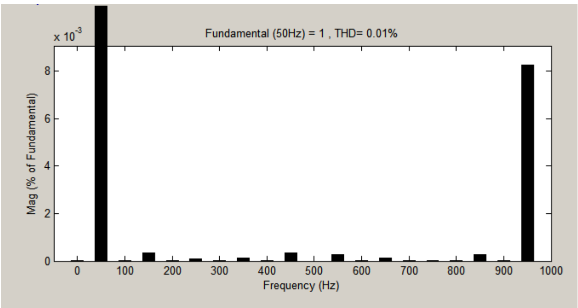


Fig. 17. The FFT of the source voltage.

Table 3.Comparison of accuracy between the models developed for validation dataset.

Sl. No.	**P_{Demand}**	**Q_{Demand}**	**PF_{Load}**	**PF_{Source}**	**THD_{Is}**	**THD_{Vs}**
Capacitor	30 kW	30 kVAR	0.707	0.99	0.04	0.01
STATCOM	30 kW	30 kVAR	0.707	0.987	5.1	0.04

Q_{cap} = 30 kVAR used for the fixed capacitor type compensation.

Sl. No.	**P_{Demand}**	**Q_{Demand}**	**PF_{Load}**	**PF_{Source}**	**THD_{Is}**	**THD_{Vs}**
Capacitor	30 kW	32 kVAR	0.683	0.92	0.04	0.01
STATCOM	30 kW	32 kVAR	0.683	0.97	5.2	0.05

Q_{cap} = 30 kVAR used for the fixed capacitor type compensation

5. Conclusion

In this work the performance of reactive power compensation schemes based on discretely switched bulk capacitors and a PI controlled DSTATCOM are compared. While the discretely switched bulk capacitors based reactive power compensation is concerned the system is less efficient in terms of effective and exact compensation in magnitude. There are no power quality issues as the capacitors do not introduce harmonics into the system. The DSTATCOM offers flexible, continuous and effective compensation by giving out the exactly required reactive power. However this method leads to poor power quality and harmonics into the system that has to be filtered out using passive filters. Frequent variations of reactive power demand can be easily addressed by the DSTATCOM while the fixed capacitors based reactive power compensation becomes helpless. It has to be noted that till date the fixed capacitor method of reactive power compensation is widely used in the national power distribution system in the Indian scenario of power distribution..

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