# Fuzzy Logic Based Window Operation of DSTATCOM for an Autonomous Asynchronous Generator

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**Abstract:** Large inductive loads require larger rating of DSTATCOM to generate the required reactive power of the load. Larger the rating of the DSTATCOM higher is the cost. Most distribution system has a base reactive power requirement. The reactive power demand at any instant varies around the base value. A window operation of the DSTATCOM is proposed in this paper. The base reactive power is provided by the TSCs and the DSTATCOM operates within a window (comprising of both inductive and capacitive reactive power) beyond the base reactive power provided by the TSCs. Thus the range of the reactive power compensation of the system is enhanced without the system being limited by the steps in which the TSCs operate. Within the window range, the DSTATCOM provides a continuous and smooth variation in the reactive power generation and can track the change in the VAr requirement very fast. To obtain optimal performance of the combined system, the TSCs are switched through a Fuzzy Logic controller. In this paper, window operation of the DSTATCOM along with Fuzzy Logic Controller operated TSCs is demonstrated for an autonomous asynchronous generator. The entire system has been simulated on MATLAB platform.

**Keywords:** Autonomous Asynchronous Generator (AAG), DSTATCOM, TSC, Window Operation, Fuzzy Logic Controller.

## 1. Introduction

The demand of electrical energy is ever increasing. The accelerated depletion of the fossil fuel and the price of petroleum crude fluctuating widely, has forced the energy planners to look for alternative resources of energy which are replenished by nature [1]-[4]. For remote and rural applications, more and more need is being felt to have off-grid systems based on asynchronous generators, using available renewable energy sources like wind, micro or pico hydro and biomass [5]-[7]. Asynchronous generators, however, require reactive power to maintain its terminal voltage under varying condition of load and speed [8]. In case of constant speed prime movers like biogas, diesel, gasoline engines, the speed of autonomous asynchronous generator (AAG) remains constant, while the voltage at the generator terminals varies with load [9]-[10]. For such applications, reactive power is compensated by means of Static VAr Compensator (SVC) and Distribution Static Compensator DSTATCOM. For small and remote applications, the cost of installing a DSTATCOM to handle the entire reactive load may become an appreciable part of the entire project cost of an autonomous generation system. In this present era of competition executing project with restrained cost has become important. Further, the situation becomes all the more stringent when the source of power is a micro hydro power plant. Most distribution system including the autonomous generation has a base reactive power requirement. This can be compensated by some fixed capacitors either connected directly to the Point of Common Coupling (PCC) or through Thyristor Switched Capacitors (TSCs). TSCs are less complex than the DSTATCOM and hence cost less. However, TSCs can provide reactive power in large steps and cannot provide dynamic control of reactive power.

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The reactive power demand at any instant varies around the base value. The dynamic load compensation is required over this small range which is over and around the base reactive power demand. A novel concept has been proposed here for window operation of a DSTATCOM over this small range, for an AAG of a micro hydro power station. A low cost solution to the compensation problem is thus made available. The reactive power compensation can be made suitable for voltage regulation at the generator terminal. At the same time the small amount of load unbalance and some extent of harmonic introduced by the load can also be compensated by the same DSTATCOM.

An on-off controller when used for switching of TSCs may not be able to predetermine the requirement of switching (on or off). If a voltage comparator is used to determine the switching requirement of the TSCs, then there could be hunting around the base reactive power demand. A Fuzzy Logic controller (FLC) [11]-[16] is proposed as solution to this problem. By monitoring the variation and the rate of variation of the terminal voltage of the generator, the FLC will be able to predict the requirement of the switching of the TSCs and avoid hunting phenomenon, resulting in efficient and fast switching of the TSCs to produce a smooth regulation of the terminal voltage with load variation.

## 2. System Configuration

Figure 1 shows the schematic of the proposed system, consisting of an asynchronous generator, the capacitor bank for it's no load excitation, the DSTATCOM, the TSC and a fuzzy logic controller (FLC).

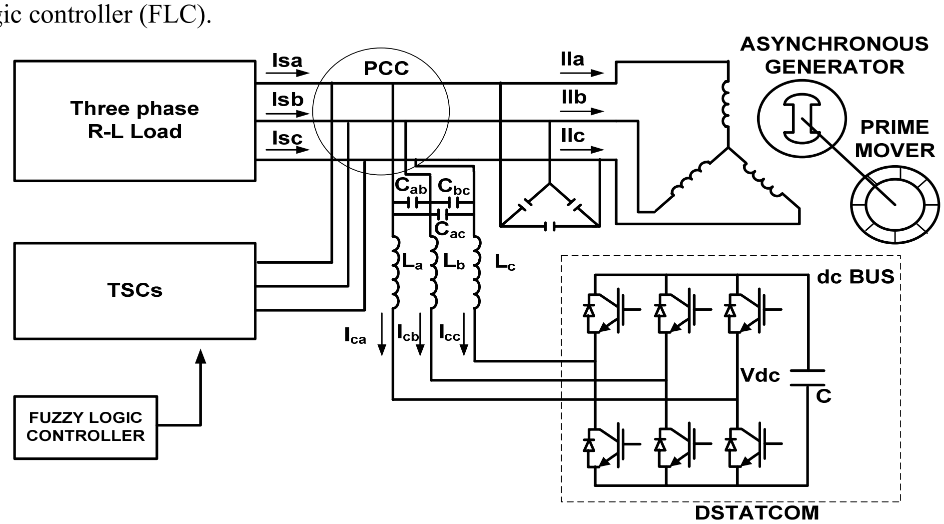



Figure 1. Schematic of the proposed Autonomous Power System

A three phase squirrel cage induction machine is used as asynchronous generator. It is driven by a constant power source like a micro hydro turbine. A delta connected capacitor bank is used to generate the required excitation for the rated voltage at no load [8]. The additional demand of reactive power is met by the proposed controller consisting of TSCs, FLC, and the DSTATCOM. The DSTATCOM has bidirectional flow capability of active and reactive power. It can source or sink reactive power. The combined controller of TSCs and DSTATCOM act as the source of lagging or leading current to maintain a constant terminal voltage with varying loads. The DSTATCOM consists of three-phase IGBT based voltage sourced inverter (VSI) bridge with a set of ac inductors (being the leakage inductance of the coupling transformer) along with a small ac shunt filter and a dc bus capacitor [17] [18].

Of the various alternatives available for reactive power compensation, it is found that the cost per kVAr is the least for TSC and the most for DSTATCOM. Depending on the customer's situation (i.e. the amount of the kVAr to be compensated) the cost of compensation, with only DSTATCOM used, may become quite high, forcing the customer to opt for some traditional solution based on installation of shunt passive capacitors. Such a solution not only lacks granularity i.e. the smallest amount of VAr compensated, but also lacks in dynamic capability resulting in poor Dynamic Reactive Power Compensation (DRPC) and terminal voltage regulation. This can result in over-voltage under light load, or under-voltage on heavy load, if proper and swift switching of the capacitors is not done.

Considering the above scenario, a mid way solution has been proposed in this paper. By proper and dynamic integration of the DSTATCOM with the conventional TSCs, the cost aspect can be brought within the reach of the project management, without the sacrifice of the granularity and the DRPC for the solution. The operation of DSTATCOM with inductive / capacitive VAr (+/- VAr) compensation with a specific base value and steps of TSCs has been named here as WINDOW operation of the DSTATCOM.

## 3. Concept of Window Operated DSTATCOM

DSTATCOM generically compensates reactive power generated by one customer, does voltage regulation and causes reduction of harmonics at the point of common coupling (PCC) so that the other customers and the supply side are not affected. The DSTATCOM can generate VAr (capacitive mode) or can absorb VAr (inductive mode). Thus a DSTATCOM of 'X' kVAr rating can provide -X kVAr to +X kVAr. In a way, it can be said that only 50 % of its capability is utilized in the inductive mode and 50% in the capacitive mode. Now if a fixed capacitor capable of providing 'X' kVAr is used in parallel with this DSTATCOM, the combined entity can provide a load compensation of zero to 100 %. The kVAr produced by a combined unit of DSTATCOM and fixed capacitor is graphically shown in Figure 2.

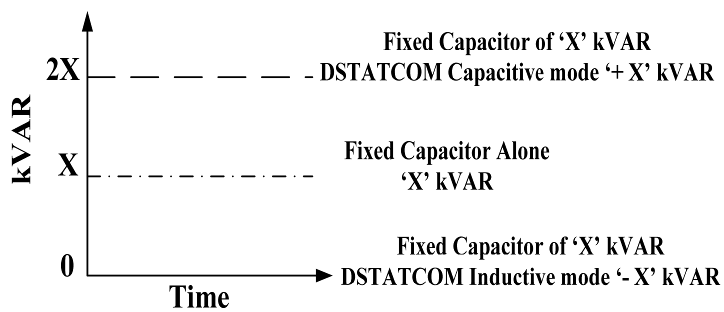



Figure 2. Graphical representation of capacity utilization of DSTATCOM & Fixed Capacitor unit.

Thus it is possible to get 200% load compensation with the same DSTATCOM when used along with a fixed capacitor. Further, the granularity or the minimum incremental value of the VAr compensation produced by the combined unit remains the same as that of DSTATCOM. Generally a constant inductive load is always present on the system. In that case this base inductive VAr is compensated by the fixed capacitor and the variable part is compensated by the DSTATCOM.

## 4. Dynamic Var Compensation

For dynamic VAr compensation, the fixed capacitor is replaced by Thyristor Switched Capacitors (TSC). The dynamic VAr compensation of the combined unit of TSCs and DSTATCOM is brought out by the following case study. Consider a case where the inductive load varies from zero to say 250 kVAr . The load compensation can be achieved with five TSCs each of capacity 50 kVAr and a DSTATCOM of just 50 kVAr rating. Depending on the customer's situation a certain number of TSCs are switched on at any instant.

If at a point of time the load has an inductive component of 100 kVAr, the compensation can be achieved with two TSCs switched on. Then the dynamic load compensation range of the TSC & DSTATCOM system will be 50 kVAr to 150 kVAr. Any value of load compensation within this window can be achieved by this combined unit. As inductive kVAr of the load increases more TSCs can be switched on. If the inductive kVAr of the load approaches the present upper window limit of 150 kVAr, another TSC can be switched on. The compensation range of the TSC & DSTATCOM system will then be 100 kVAr to 200 kVAr. On the other hand, if the inductive kVAr of the load approaches the present lower window limit, a TSC can be switched off. The compensation range of the TSC & DSTATCOM system will then be 0 kVAr to 100 kVAr. Since the small to medium consumer loads are either inductive or purely resistive, the above discussed mode of operation of the TSCs and the DSTATCOM has been graphically represented in Figure 3.

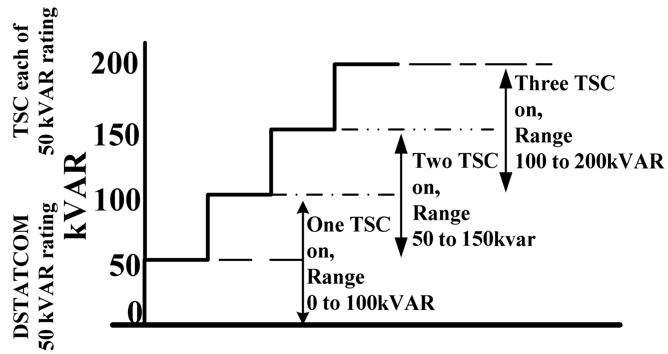



Figure 3. Steps of operation of TSCs & DSTATCOM combined unit.

There can be other possible modes for example where the rating of the DSTATCOM is half the TSC rating. However in that case, the range of operation at each step shall be reduced.

## 5. Control Architecture

The control architecture of the power system, shown in Figure 1, is configured in two parts. The first one, shown in Figure 4, controls the operation of the DSTATCOM. It has two control loops. These control loops control the ac voltage at the PCC and the voltage of the dc bus. The second part of the control system, shown in Figure 5, controls the switching of the TSCs.

## 6. Control Algorithm of DSTATCOM

The VSI of the DSTATCOM, shown in Figure 1, is modeled in discrete mode using ode23tb on MATLAB platform. The discrete-time integrator block is used to implement the PI controller. Forward Euler method is used for integration. The discrete-time integrator block approximates 1/s by T/(Z-1), which results in the following expression for the output at the $n^{th}$ step .

$$Y(n) = Y(n-1) + KT^{*} U(n-1) \qquad (1)$$

Y(n) is the output and U(n) is the input to the controller

The scheme for controlling the DSTATCOM is shown in Figure 4. Different components are modeled as follows :

(1) AC Terminal Voltage Control of AAG

The three phase voltage at the AAG terminal ($v_{sa}$ $v_{sb}$ and $v_{sc}$ ) are considered sinusoidal and hence their amplitude is computed as:

$$V_t = \sqrt{\{(2/3)\ (v_{sa} + v_{sb} + v_{sc})\}} \qquad (2)$$

The $V_t$ computed above is compared with the desired terminal voltage $V_{tref}$ . The ac voltage error $V_{er(n)}$ at the *n*th sampling instant is

$$V_{er(n)} = (V_{tref} - V_{t(n)}) \quad (3)$$

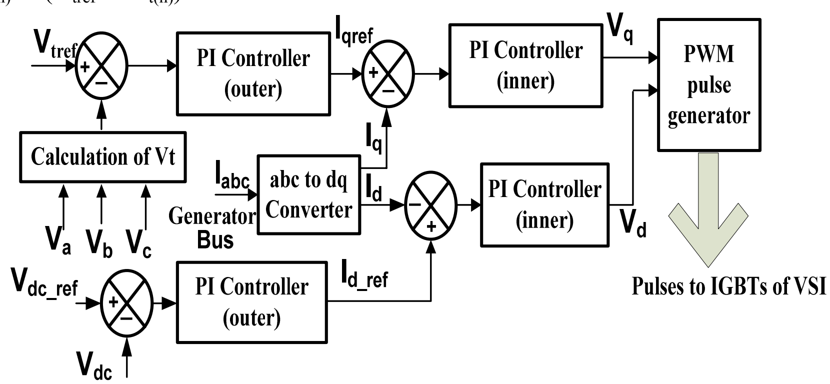



Figure 4. Schematic of the Control System of DSTATCOM.

Where $V_{t(n)}$ is the amplitude of the sensed three phase ac voltage at the generator terminal at the *n*th instant. The error $V_{er(n)}$ is fed to an outer PI controller, using discrete time integration, to generate the $I_{qref}$ .

$$I_{qref\,(n)} = I_{qref\,(n-1)} + K_{ap}\,\{V_{er(n)} - V_{er(n-1)}\} + K_{ai}\,V_{er(n)} \quad (4)$$

Where $K_{ap}$ and $K_{ai}$ are the proportional and integral gain constants of the outer PI controller of the ac terminal voltage at the PCC

The actual $I_q$ is generated by an 'abc to dq converter' using Park's Transformation over the load current. The $I_{qref}$ and $I_q$ are compared and the error is fed to an inner PI current controller to generate $V_q$ .

$$I_{qer(n)} = (I_{qref\,(n)} - I_{q(n)}) \quad (5)$$

$$V_{q(n)} = V_{q(n-1)} + K_{bp}\,\{I_{qer(n)} - I_{qer(n-1)}\} + K_{bi}\,I_{qer(n)} \quad (6)$$

Where $K_{bp}$ and $K_{bi}$ are the proportional and integral gain constants of the inner PI controller of the ac terminal voltage at the PCC

(2) Control of the Voltage at the dc terminal of the DSTATCOM

The $V_{dc}$ of the dc bus is compared with the desired dc bus voltage $V_{dc\_ref}$ . The dc voltage error $V_{der(n)}$ at the *n*th sampling instant is

$$V_{dcer(n)} = (V_{dc\_ref} - V_{dc(n)}) \quad (7)$$

Where $V_{dc(n)}$ is the sensed dc voltage at the dc bus of the DSTATCOM at the *n*th instant.
The error is then fed to an outer PI controller to generate the $I_{dref}$.

$$I_{dref\,(n)} = I_{dref\,(n-1)} + K_{ap}\,\{V_{dcer(n)} - V_{dcer(n-1)}\} + K_{ai}\,V_{dcer(n)} \quad (8)$$

Where $K_{ap}$ and $K_{ai}$ are the proportional and integral gain constants of the outer PI controller of the dc bus voltage.

The actual $I_d$ is generated by an 'abc to dq converter' using Park's Transformation over the load current. The $I_{dref}$ and $I_d$ are compared and the error is fed to an inner PI current controller to generate $V_d$

$$I_{der(n)} = (I_{dref\,(n)} - I_{d(n)}) \tag{9}$$

$$V_{d(n)} = V_{d(n-1)} + K_{bp}\{I_{der(n)} - I_{der(n-1)}\} + K_{bi}\, I_{der(n)} \tag{10}$$

Where $K_{bp}$ and $K_{bi}$ are the proportional and integral gain constants of the inner PI controller of the dc bus voltage.

(3) PWM current Controller

The $V_d$ and $V_q$ signals generated above are converted into modulation index 'm' and phase 'Φ' which are then used by the PWM modulator for producing the required pulses for triggering the IGBTs of the VSI. This causes the VSI to regulate the terminal voltage of the load by generating / absorbing the required reactive current and supplying / absorbing active power from the generator to maintain the dc side voltage of the inverter.

## 7. Control Algorithm of TSCs

The switching of the TSCs can be based on the regulation voltage at the AAG terminal. The increase of load causes the voltage at the terminal to drop. The DSTATCOM is used in the voltage control mode. The extent of control of the terminal voltage of the induction generator by the DSTATCOM is dependent on its rating. So for further enhancing the terminal voltage the TSCs are used. The control of the switching of the TSCs could have been done by a simple on-off controller. Such a control may lead to either over-correction or under-correction of the terminal voltage. However it is found that a better response is obtained by controlling the switching through a fuzzy logic controller [11]-[16]. This controller is shown in Figure 5.

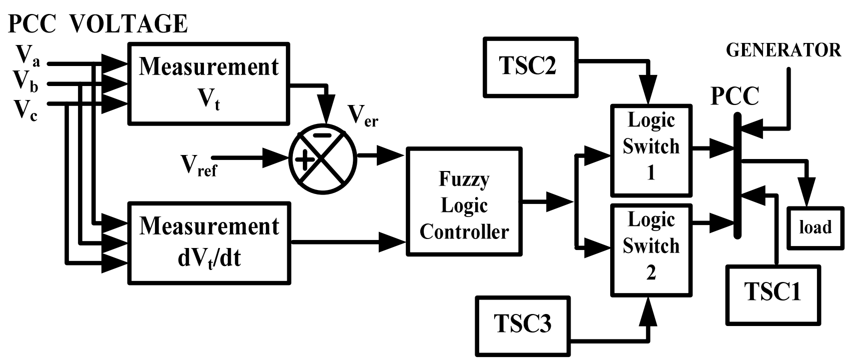



Figure 5. Control schematic for switching of the TSCs.

In a fuzzy logic controller, the control action is determined by the evaluation of a set of simple linguistic rules. This does not require the knowledge of the mathematic model of the system. Two inputs are considered for the fuzzy controller. They are the magnitude of the error $V_{er}$ of the terminal voltage and rate of change of the terminal voltage $dV_t/dt$. The amplitude of the terminal voltage of the asynchronous generator as given by (2) is:

$$V_t = \sqrt{\{(2/3)\ (v_{sa} + v_{sb} + v_{sc})\}} \tag{2}$$

$V_t$ is compared with the desired terminal voltage $V_{tref}$. The ac voltage error $V_{er}$ at any instant is given by

$$V_{er} = (V_{tref} - V_t) \quad (11)$$

$V_{er}$ computed above and the measured $dV_t/dt$ value is fed to the fuzzy logic controller, which in turn provides switching signals to the TSCs connected to the AAG terminal. The Fuzzy controller is characterized as follows:

- Fuzzification of the input variables.
- Triangular membership functions for simplicity.
- Implication using Mamdani's 'min' operator.
- Aggregation of the consequents across the rules.
- Defuzzification using the centre of gravity method.

The triangular membership functions with 50% overlap used for input and output fuzzy sets are shown in Figures 6, 7 and 8 in which the linguistic variables are represented by H(high), O(Zero), L(Low) for $V_{er}$ and N (Negative), O(Zero), P(Positive) for $dV_t/dt$, VL (Very Low), L(Low), N(Normal) for output. The Fuzzy mapping of the input variables to the output is represented by IF-THEN rules of the form given in the Table 1.

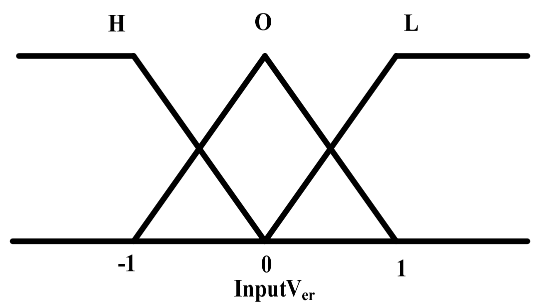



Figure 6. $V_{er}$ membership function

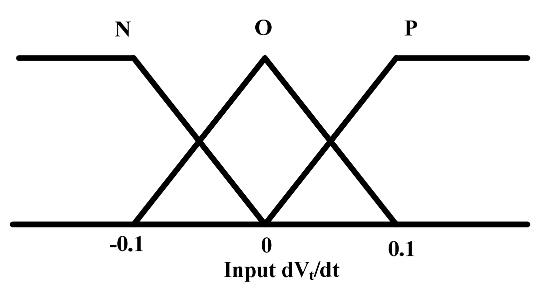



Figure 7. $dV_t/dt$ membership function

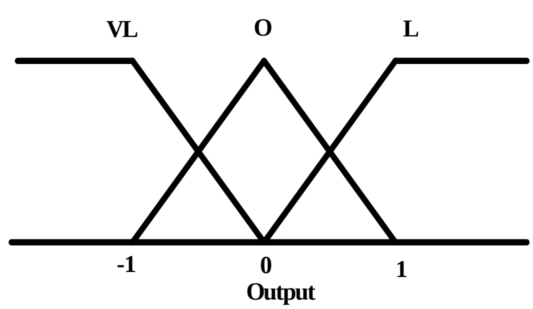



Figure 8. Output membership function.

Table 1. Rule Set for the Fuzzy Controller

| $dV_t/dt$ ↓ \| $V_{er}$ → | H | O | L |
|---|---|---|---|
| N | L | L | N |
| O | VL | N | N |
| P | VL | L | L |

3) Inference & De-fuzzification
In this work, the ‘min’ inference rule and centre of gravity de-fuzzification technique have been used [11]. The centre of gravity method gives a crisp output $Z_0$ of Z variables by taking the geometric centre of the output fuzzy value $\mu_{out}$ (Z) area, where $\mu_{out}$ (Z) is formed by taking the union of all the contribution of rules whose degree of fulfillment is greater than zero [11].

$$Z_o = \frac{\int Z\mu_{out}(Z)dZ}{\int \mu_{out}(Z)dZ} \quad (12)$$

## 8. Matlab Based Simulation

After selection of components of the proposed system, such as filtering inductor and capacitor of DSTATCOM, the proposed load and the components of TSC, the modeling and simulation is performed in the MATLAB. The modeling of the asynchronous generator is carried out using the available standard model of 7.5 kW, 400 V, 50 Hz, squirrel cage induction machine and 500 µf delta connected excitation capacitor bank is used. The simulation is carried out for single switching of an inductive load and corresponding switching of a TSC to maintain the AAG terminal voltage constant. Further switching in or out of loads can be done with corresponding switching-in or -out of the TSCs. Figure 9 shows the MATLAB based simulation model of the AAG along with its controllers. Simulation is carried out by MATLAB version 7.1 in discrete mode at 5e-7 step size with ode 23tb (stiff / TR – BDF-2) solver. The various parameters selected for simulation of the proposed power system are given in the Annexure.

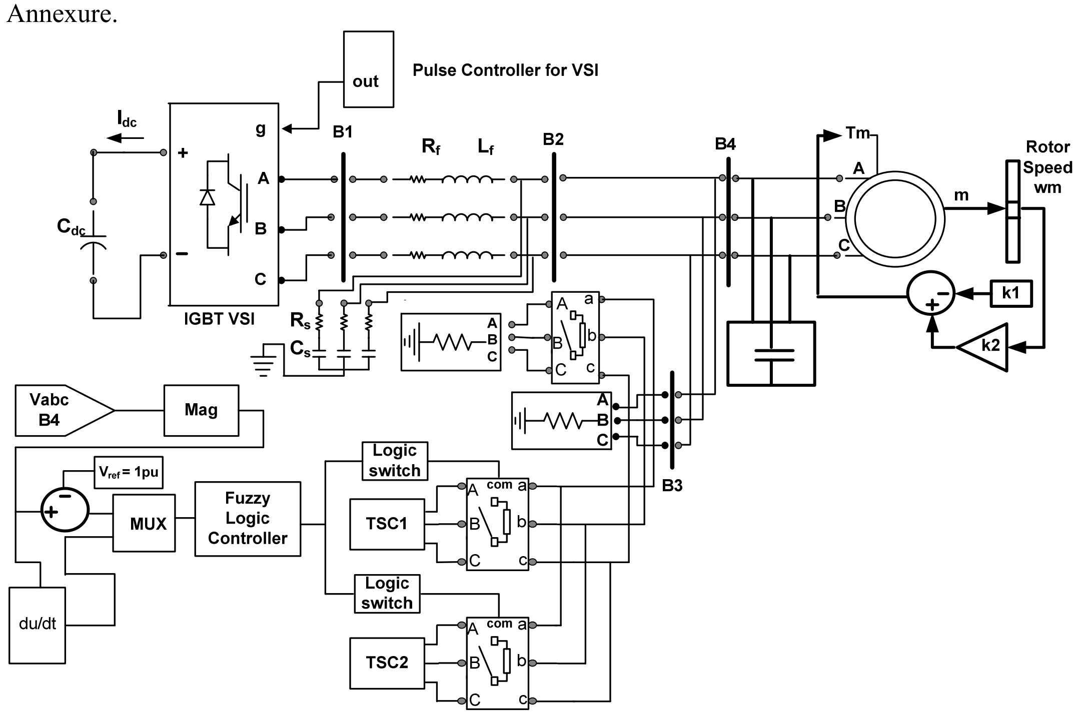



Figure 9. Simulation model of the proposed Autonomous System

## 9. Results and Discussions

The performance of the proposed controller for the window operation of DSTATCOM is demonstrated for an asynchronous generator. Simulated transient waveforms of the AAG terminal voltage (Vabc B4), generator current (Iabc B4), voltage at the terminal of the VSI (Vabc B2), VSI current (Iabc B2), total harmonic distortion of voltage at the AAG terminal (THD B4), current carried by linear load ( Iabc B3), rotor speed of the generator $\omega_m$, are shown in Figure 10 and in Figure 11. Figure 10 demonstrates the Window operation of the DSTATCOM with manual switching of the TSCs. Figure 11 demonstrates the Window operation of DSTATCOM with the Fuzzy logic controller controlling the switching of the TSCs. Parameters of the asynchronous generator and the components used in the simulation of the TSC and DSTATCOM system are given in the Appendix.

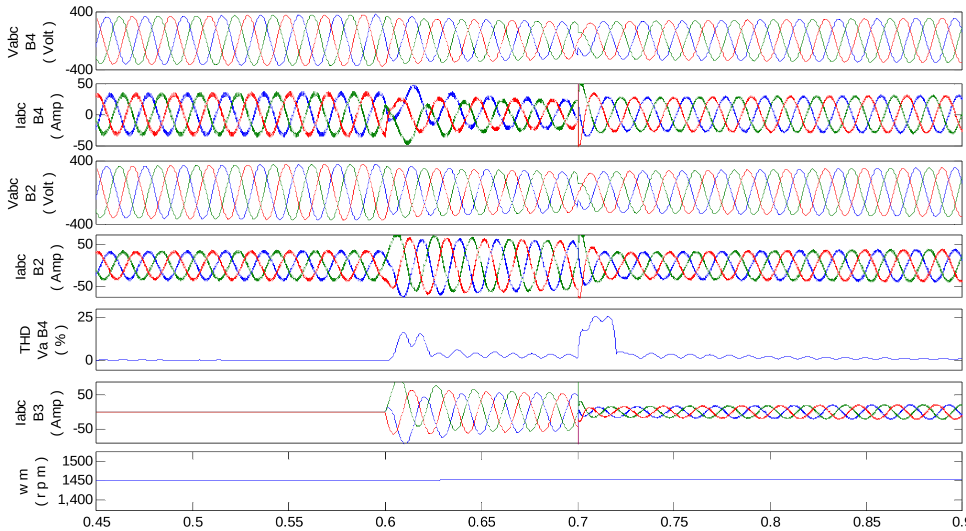



Figure 10. Simulation of Window operation of DSTATCOM manual operation of TSC.

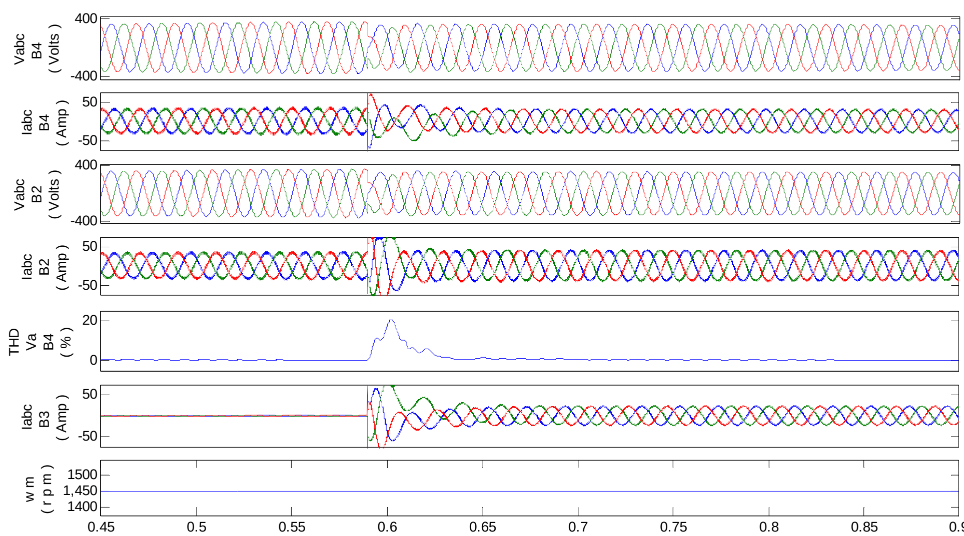
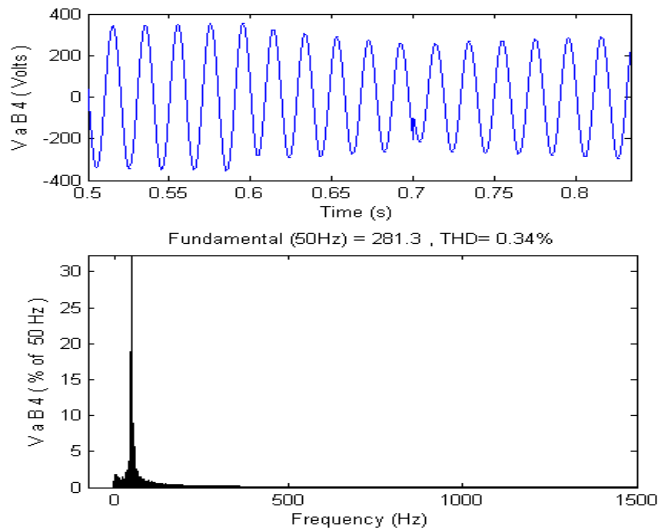
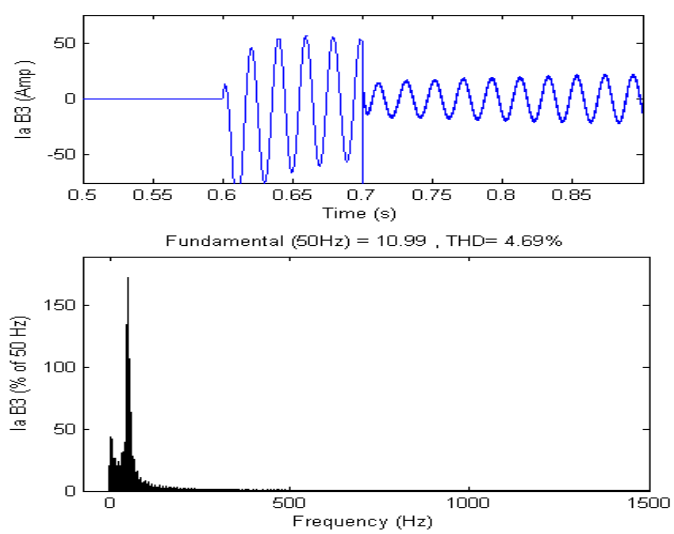



Figure 11. Simulation of Window operation of DSTATCOM with FLC control of TSC.

The reactive power requirement of the unloaded generator is provided by the delta connected fixed capacitors. In Figure 10 the simulation begins with a load of 1kW connected to the AAG, with the additional reactive power requirement of the AAG being met by a TSC and the DSTATCOM. The load is increased by addition of 1kW and 60 kVAr at 0.6s. The terminal voltage of the AAG falls due to further increase in reactive power requirement of the AAG because of the increased load. The DSTATCOM current increases from 30Amp to around 75Amps. Since this is more than the capacity of the DSTATCOM, the terminal voltage of the generator falls. Excess amount of harmonic, shown by the values of THD Va B4 in Figure 10, is injected into the PCC. One TSC is manually switched on at 0.7s. The terminal voltage of the AAG gradually recovers to the rated value.



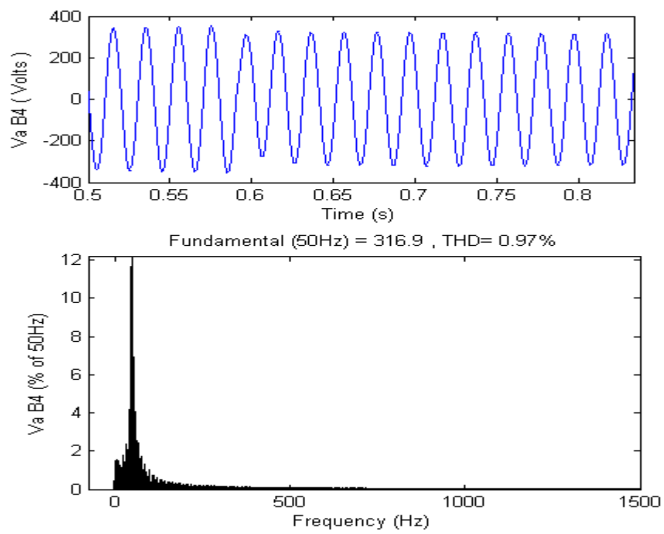

a.



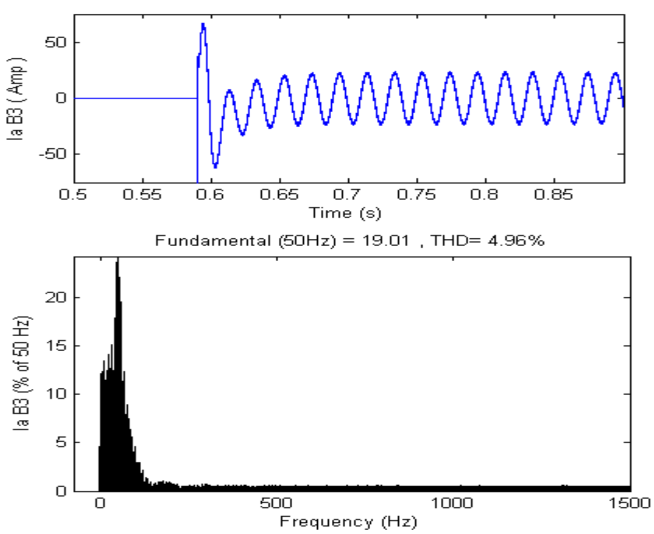

b.

Figure 12: a. Harmonic spectrum of source voltage with manual switching of TSCs
b. Harmonic spectrum of load current with manual switching of TSCs

Next, the performance of the TSC with FLC switching, along with the DSTATCOM is shown in Figure 11. The FLC is allowed to identify the switching-in of the additional load and thereby an increase of the reactive power requirement of the AAG. The load is again increased by 1kW and 60 kVAr at 0.6 s. The FLC promptly identifies the additional reactive power requirement and generates signal for switching on the second TSC. The terminal voltage is restored to the rated value in around 1½ cycles. The harmonics injected into the PCC is much less as shown by the values of THD Va B4 in Figure 11.




a.




b.

Figure 13: a. Harmonic spectrum of source voltage FLC switching of TSCs
b. Harmonic spectrum of load current with FLC switching of TSCs

Figures 12a and 12b demonstrate the harmonic spectrum of terminal voltage (Va B4) of the AAG and the load current (Ia B3) with manual switching the TSCs. Figure13a and 13b demonstrates the harmonic spectrum of terminal voltage (Va B4) of the AAG and the load current ( Ia B3) with FLC switching the TSCs. The total harmonic distribution of the source voltage at the PCC is very small and is within the Power Quality requirements. This shall cause minimal disturbance to the other loads connected to the PCC. Further, it is seen that load current suffers minimum disturbance when FLC switching is used.

**Conclusion**

The proposed integrated dynamic reactive power compensation of load for an autonomous asynchronous generator using FLC to control the switching of the TSCs along with a small rating DSTATCOM, has been shown to work effectively and provide quality power to the customer. The harmonic distortion of the supply at the AAG terminal is found to be within the Power Quality limits. Further, the integrated compensator works out to be an economical solution and can be easily used with mini / micro autonomous asynchronous generation systems. This integrated controller optimizes the cost versus dynamic response between the use of the commercially available only TSCs system and the most desirable, compensation with the only DSTATCOM, without the loss of granularity of the system. By monitoring the variation and the rate of variation of the terminal voltage, the FLC predicts the requirements of the switching of the TSCs and avoids hunting phenomenon, resulting in efficient and fast switching of the TSCs to produce a smooth regulation of the terminal voltage with load variation. The use of the FLC enhances the response of the integrated controller to the dynamic changes of the load and regulates the terminal voltage in a smooth and fast manner.

**ANNEXURE**

Asynchronous Generator:
7.5 kW, 400 V, 50 Hz, rpm = 1440, Squirrel cage, Pole Pair = 2, Inertia J = 0.0343 kg.$m^2$
No load excitation capacitors each of 550μF, delta connected, k1 = 2, and k2 = 2910.

**TSCs:**

3nos Thyristor Switched Capacitor, each with active power of 10 W and capacitive reactive power of 80 kVAr, Delta connected

**DSTATCOM parameters :**

Capacity $\pm$10 kVAr
$L_f$ = 800μH, $R_f$ = 0.004 Ω, and $R_s$ = 1 Ω, $C_s$ = 30 μF, $C_{dc}$ = 1500 μF, $K_{ap}$ = 0.5, $K_{ai}$ = 2
$K_{bp}$ = 5, $K_{bi}$ = 20.

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