International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 3 (2015) pp. 7517-7535

http://www.ripublication.com

Application of Fuzzy Controller in Phase Shift Controlled D-STATCOM for Voltage Sag Mitigation

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Abstract

Power quality is of major concern in the power distribution systems. The increase in use of sensitive and susceptive electronic and computing equipments and other non linear loads affects the quality of power delivered which leads to severe economical impacts on both utilities and customers in distribution system. The application of custom power devices offers fast response and reliability to the electric utilities. The Distribution Static synchronous compensator (D-STATCOM) which has been emerging as a promising custom power device is selected in this work for the mitigation of voltage sag. The D-STATCOM with a suitable control strategy is capable of mitigating the voltage sag in a very fast manner and this feature of phase shift controlled D-STATCOM can be exploited to improve the power quality. Three different control strategies namely PI Controller, Fuzzy Logic Controller, Fuzzy-PI Controller have been developed for phase shift controlled D-STATCOM to mitigate the voltage sag. Proposed controllers of D-STATCOM are implemented under MATLAB/SIMULNK environment. The effectiveness of the control schemes with immediate voltage generation to mitigate the voltage sag in three phase system due to the system faults is proved with the comparative assessment of the graphical results using MATLAB / SIMULINK software.

Keywords— Power Quality, Distributed Static Compensator (D-STATCOM), voltage sag, PI Controller, Phase shift control, Fuzzy logic Controller, Fuzzy PI Controller

I. INTRODUCTION

Today, there is a great need for improving and maintaining power system security and reliability in highly complex and inter connected power system. Due to under loading and overloading of lines, power flow in the system is affected. As a result of this, there arises a problem of deteriorating voltage profile and power system stability. So finally power quality (PQ), which is one of the most important concerns nowadays, is affected. PQ becomes especially important with the insertion of sophisticated devices, whose performance is very sensitive to the quality of power supply. Power quality is a very important issue due to its impact on electricity suppliers, equipment manufactures and customers. According to the IEEE defined standard (IEEE Std. 1100, 1999), power quality is “The concept of powering and grounding electronic equipment in a manner suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment”. Therefore, a power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure or a mis-operation of end user equipments.

Modern industrial processes are mainly based on electronic devices such as PLC’s, power electronic devices, drives etc., and since their controls are sensitive to disturbances and less tolerant to power quality problems such as voltage sag, swell and harmonics. Among the different disturbances affecting power quality, Voltage sag is the most important power quality problem. It contributes more than 60% of the power quality problems that exist in power systems. By definition, voltage sag is an *rms* (root mean square) reduction in the AC voltage at the power frequency, for duration from a half-cycle to a few seconds. Voltage sag is caused by a fault in the utility system, a fault within the customer’s facility or a large increase of the load current, like starting a motor or transformer energizing. Usually, voltage sags cause the malfunction of the modern process control, programmable logic control, and variable speed drives; in addition, sags can initiate significant tripping off for voltage-sensitive loads [1]. Voltage sags are not tolerated by sensitive equipments used in modern industrial plants.

Hence, various methods have been applied to mitigate voltage sag. The conventional methods are by using capacitor banks, introduction of new parallel feeders and by installing uninterruptible power supplies (UPS) [2]. But, these are not efficient due to uncontrollable reactive power compensation and high costs of new feeders and UPS. So Nowadays, FACTS based Power electronic controllers for distribution systems, namely custom power devices, are able to enhance the quality of power that is delivered to customers. Among them, D-STATCOM has been emerged as a promising device to provide solution not only for voltage sags but a host of other power quality solutions such as voltage stabilization, flicker suppression, power factor correction and harmonic control. The problem of voltage sags and swells and its severe impact on sensitive loads are mitigated using D-STATCOM was proposed in [3] [4] [5]. The control technique based on a proportional integral controller was proposed in [6] [7]. But, the PI controller which is a linear control method is used widely due to simple control structure but suffers a disadvantage of fixed gains i.e., it cannot adopt itself to the varying parameters and conditions of the system. To cope with this disadvantage some non linear methods like differential algebra theory, exact linearization with feedback were followed [8]. Such control methods need exact mathematical model and parameters of controlled system. As an advanced technology, intelligent controllers like Fuzzy Logic Controller (FLC) have been used in the control of D-STATCOM [9] [10] 11]. To obtain desired reference voltage, Fuzzy PI Controller is used [12]-[15].

This paper introduces D-STATCOM with Fuzzy logic controller. The proposed control techniques overcome the disadvantages of the control circuit proposed in [6] [7]. Some of them are they do not need an accurate mathematical model, they can work with precise inputs, can handle non-linearity, and they are more robust. At the end, MATLAB/SIMULINK model based simulated results were presented to validate the effectiveness of the proposed control method of D-STATCOM over conventional methods.

II. DISTRIBUTED STATIC COMPENSATOR

Distributed Static Compensator (D-STATCOM) is the most efficient and effective modern custom power device used in power distribution networks. D-STATCOM is a three phase shunt connected solid state device that injects current into the system in order to regulate the load side voltage. It is normally installed in a distribution system between the supply and the critical load feeder at the point of common coupling (PCC). Other than voltage sags and swells compensation, D-STATCOM includes other features like: line voltage harmonics compensation, reduction of transients in voltage and fault current limitations.

A. Basic Configuration of D-STATCOM

A D-STATCOM, which is schematically depicted in Fig.1 consists of a voltage source converter (VSC), dc energy storage device, an injection transformer, harmonic filter and a control strategy connected in shunt with the distribution network. By controlling the magnitude and the phase angle of the output voltage of the VSC, both active and reactive power can be exchanged between the distribution system and the D-STATCOM.

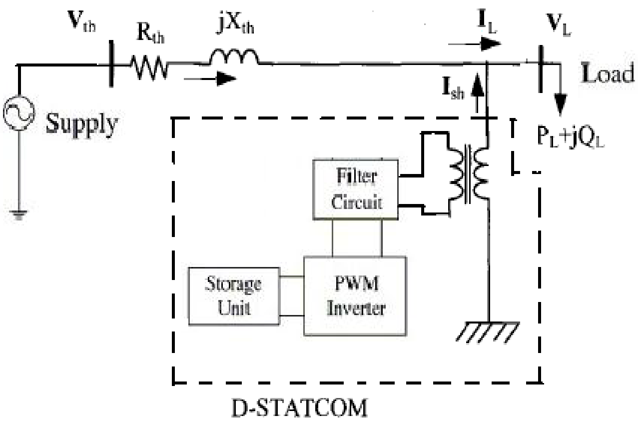


Fig.1. Block diagram of a D-STATCOM

The VSC converts the dc voltage across the storage device into the three phase AC voltage which is coupled with the system voltage through the reactance of injection transformer. The VSC is used to either completely replacing the voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual voltage. The main function of the filters used with the D-STATCOM power circuit is to filter out the unwanted harmonics generated by the VSC and hence, keep the harmonic level within the permissible limit. In this work, an IGBT is used as the switching device in the voltage source converter. The VSC switching strategy is based on a sinusoidal Pulse width Modulated technique (SPWM) which offers simplicity and good response. Since custom power is a relatively low power application, PWM methods offer a more flexible option than the Fundamental Frequency Switching (FFS) methods favoured in FACTS applications. The injection transformers connect the D-STATCOM to the distribution network via the high voltage windings. They transform and couple the injected compensating current generated by the VSC to the incoming supply voltage. The high voltage side of the injection transformer is connected in shunt to the distribution line, while the low voltage side is connected to the D-STATCOM power circuit. The energy storage unit supplies the required power for compensation of load voltage during voltage sag. The controller of D-STATCOM continuously monitors the load voltage and determines the amount of compensation required by the AC system for various disturbances. The D-STATCOM can be seen as a current source since it is connected in shunt with the distribution system and the load.

B . Modelling of D-STATCOM

In Fig.1, the shunt injected current I_{sh} corrects the voltage sag by adjusting the voltage drop across the system impedance Z_{th}. The value of I_{sh} can be controlled by adjusting the output voltage of the converter. The shunt injected current I_{sh} can be written as

$$I_{sh} = I_L - I_S \tag{1}$$

$$I_{sh} = I_L - \frac{V_{th} - V_L}{Z_{th}} \tag{2}$$

where

I_{sh} - Output current

I_s - Source current

I_L - Load current

V_{th} - Thevenin's voltage

V_L - Load voltage

Z_{th} - System Impedance

The shunt injected current by the D-STATCOM is also given by

$$I_{sh}\angle\eta = I_L\angle-\theta - \frac{V_{th}}{Z_{th}}\angle(\delta-\beta) + \frac{V_L}{Z_{th}}\angle-\beta \quad (3)$$

η, δ, β are the angles of I_{sh}, V_{th}, Z_{th} respectively, and θ is the load power factor angle.The complex power injection of the D-STATCOM is expressed as

$$S_{sh} = V_L I_{sh}^{*} \quad (4)$$

Thus, the effectiveness of the DSTATCOM in correcting voltage sag depends on the value of Z_{th} or fault level of the load bus. Referring to equation 1, the output current will correct the voltage sags by correcting the voltage drop across the system impedance.

The importance and functions of various components are discussed below:

Voltage Source Converter (VSC)

VSC is the core component of the D-STATCOM. During voltage sag, VSC generates proper voltages and introduces a voltage difference between the VSC and the point of connection with the power system. This voltage difference results in proper current that is injected into the power system. Active and reactive power can be injected independently in the power system.

Energy storage

The purpose of energy storage is to maintain the DC side voltage of VSC. It can be capacitor or DC source, e.g. battery. Traditional D-STATCOM only has DC capacitor. Thus, only reactive power can be injected to the power system by D-STATCOM, whereas both active and reactive power can be injected to the power system by D-STATCOM if DC source is used.

Filter

As the Pulse-Width Modulation (PWM) technique is used in VSC, the output voltage of VSC has switching ripple, which bring harmonics into the current injected to the power system. These harmonics will affect the voltage quality of the power system. Therefore, a relatively small reactor is installed between VSC and the point of the system, with which the D-STATCOM is connected, to filter those harmonics in the current. The filter can be small if high switching frequency is used. A shunt transformer also can filter this harmonic content in the current.

Injection Transformer

It provides electrical isolation & voltage boost to the system. In a 3-phase system, either 3 single phase units of isolating transformer or 3-phase isolating transformer can be employed for the purpose of current injection to the D-STATCOM. While selecting the injection transformer, the determination of expected maximum output voltage is prime significance, both economically & technically.

Control Block

Control block is the heart of the D-STATCOM. Control block is used which switch

Pure Wave DSTATCOM modules as required. They can control external devices such as mechanically switched capacitor banks too. These control blocks are designed based on the various control theories and algorithms like instantaneous PQ theory, synchronous frame theory etc.

III. CONTROL STRATEGY OF D-STATCOM

The D-STATCOM can be controlled by controlling its inverter. The control unit gives information on required current to be inserted and its duration during sag. Three control strategies are proposed for the D-STATCOM in this paper.

A. Proportional-Integral Controller

Here, the conventional PI controller is implemented along with the phase shift control. The control system only measures the *rms* voltage at the load point, i.e., no reactive power measurements are required. The VSC switching strategy is based on a sinusoidal PWM technique which offers simplicity and good response. The controller input is an error signal obtained from the reference voltage and the value *rms* of the terminal voltage measured. Such error is processed by a PI controller the output is the input signal to the D-STATCOM, which is provided to the PWM signal generator. The modulated signal is compared against a triangular signal in order to generate the switching signals for the VSC valves. But the conventional PI controller suffered from certain disadvantages such as it could not respond to various operating conditions of the system efficiently.

In this control algorithm the voltage regulation is achieved in a D-STATCOM by the measurement of the rms voltage at the load point and no reactive power measurements are required. Fig 2 shows the block diagram of the implemented control technique.

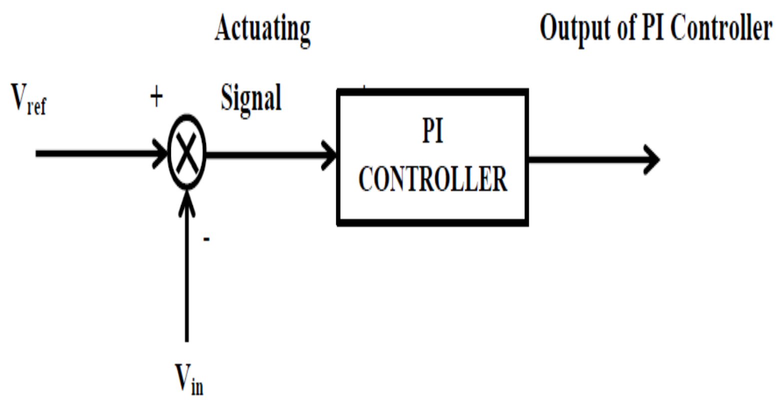


Fig 2 Block diagram of the implemented controller technique

Here, the Proportional-Integral controller is implemented along with the **phase shift control**. The aim of the controller is to maintain constant voltage magnitude at the point where a sensitive load is connected, under system disturbances. The control system only measures the *rms* voltage at the load point, i.e., no reactive power measurements are required. The controller input is an error signal obtained from the reference voltage and the value *rms* of the terminal voltage measured. Such error is processed by a PI controller which generates the angle which decides the necessary phase shift between the output voltage of the VSC and the AC terminal voltage.

The output of error detector is V_{ref} - V_{in}

V_{ref} equal to 1 p.u. voltage

V_{in} voltage in p.u. at the load terminals.

This angle is summed with the phase angle of the balanced supply voltages, assumed to be equally spaced at 120 degrees, to produce the desired synchronizing signal required to operate the PWM generator.

Here, the Proportional-Integral controller is implemented along with the **phase shift control**. This Control technique is to generate correct reference signals to the PWM generator with respect to the error processed by the PI controller. So that correct magnitude of current could be injected to compensate the voltage sag. The controller input is an error signal obtained from the reference voltage and the value *rms* of the terminal voltage measured. Such error is processed by a PI controller the output is the angle δ, which is provided to the PWM signal generator. The sinusoidal signal $V_{control}$ is phase-modulated by means of the angle δ. That is

$$V_A = \sin(\omega t + \delta) \tag{5}$$

$$V_B = \sin(\omega t + \delta - \frac{2\pi}{3}) \tag{6}$$

$$V_c = \sin(\omega t + \delta + \frac{2\pi}{3}) \tag{7}$$

The modulated signal $V_{control}$ is compared against a triangular signal in order to generate the switching signals for the VSC valves. The main parameters of the sinusoidal PWM (SPWM) scheme are the amplitude modulation index of the signal (M_a), and the frequency modulation index of the triangular signal (M_f).

The amplitude modulation index M_a is kept to 1 p.u. That is

$M_a = \frac{V_{control}}{V_{tri}}$ (8) where $V_{control}$ = Peak amplitude of the control signal

V_{tri} = Peak amplitude of the triangular signal

The frequency modulation index is given by

$$M_f = \frac{f_s}{f_1} \tag{9}$$

where f_s is the Switching frequency

f_1 is the fundamental frequency

The VSC switching strategy is based on a sinusoidal PWM technique which offers simplicity and good response. Sinusoidal Pulse Width Modulation (SPWM) technique is used which is simple and gives a good response. In the SPWM, as the switch is turned on and off several times during each half cycle, the width of the pulses is varies to change the output voltage. Lower order harmonics can be eliminated or reduced by selecting the type of modulation for the pulse widths and the number of pulses per half-cycle. Higher order harmonics may increase but it can be easily eliminated by filters. The SPWM aims at generating a sinusoidal inverter output voltage without lower order harmonics. This is possible if the sampling frequency is high compared to the fundamental output frequency of the inverter. Since custom power is a relatively low power application, PWM methods offer a more flexible option than the Fundamental Frequency Switching (FFS) methods favored in FACTS applications. Besides, high switching frequencies can be used to improve on the efficiency of the converter, without incurring significant switching losses.

B. Fuzzy Logic Controller

The Fuzzy Logic is a mathematical tool for dealing with uncertainty. It offers to a soft computing partnership 'the important concept of computing with words'. It provides a technique to deal with imprecision and information granularity. In general, the fuzzy logic provides an inference structure that enables appropriate human reasoning capabilities. In fuzzy logic, basic control is determined by a set of linguistic rules which are determined by the system. Since numerical variables are converted into linguistic variables, mathematical modelling of the system is not required. The fuzzy logic control is being proposed for controlling the inverter action. FLC is incorporates a simple, rule based IF X AND Y THEN Z approach to a solving control problem rather than attempting to model a system. The block diagram of the proposed control method is shown Fig.3. The error is calculated from the difference between supply voltage data and the reference voltage data. The error rate is the rate of change of error. The error and error rate are defined as:

$$Error = V_{ref} - V_s \quad (10) \quad Error \quad rate = error(n) - error(n-1)$$

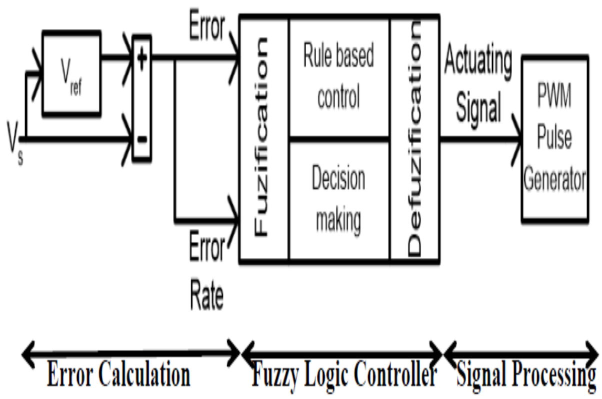


Fig.3 Block diagram of proposed control model

Table. I Specifications of the Fuzzy logic Controller

1	Input Variables	Error & Error Rate
2	Output Variable	Input Signal to the D-STATCOM
3	Membership Function	Triangular Membership Function
4	Fuzzy inference Method	Mamdani Inference method
5	Defuzzification method	Centroid Method
6	No. of Rules	7*7=49 Rules

Fuzzification is the process where the crisp quantities are converted to fuzzy. Thus fuzzification process may involve assigning membership values for the given crisp quantities. This unit transforms the non-fuzzy (numeric) input variable measurements into the fuzzy set (linguistic) variable that is a clearly defined boundary, without a crisp (answer). The input variables to the FLC namely, the error and error rate are defined by linguistic variables such as negative big (NB), negative medium (NM), negative small (NM), zero (Z), positive small (PS), positive medium (PM) and positive big (PB) given by membership functions. Fuzzy process is realized by Mamdani method. Mamdani inference method has been used because it can easily obtain the relationship between its inputs and output. The set of rules for fuzzy controller are represented in Table II. There are 49 rules for fuzzy controller. The output membership function for each rule is given by the Min (minimum) operator. The Max operator is used to get the combined fuzzy output from the set of outputs of Min operator .The output is produced by the fuzzy sets and fuzzy logic operations by evaluating all the rules.

Table. II FAM (Fuzzy Associated memory) Table

e/δe	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	Z
NM	NB	NM	NM	NS	NS	Z	PS
NS	NM	NM	NS	NS	Z	PS	PS
Z	NM	NS	NS	Z	PS	PS	PM
PS	NS	NS	Z	PS	PS	PM	PM
PM	NS	Z	PS	PS	PM	PM	PB
PB	Z	PS	PS	PM	PM	PB	PB

Defuzzification is the process of converting the controller outputs in linguistic labels represented by fuzzy set to real control (analog) signals. Defuzzification means the fuzzy to crisp conversions. The fuzzy results generated cannot be used as such to the applications, hence it is necessary to convert the fuzzy quantities into crisp quantities for further processing. This can be achieved by using defuzzification process. Centroid method is used for defuzzification in the present studies. The outputs of FLC process are the control signals that are used in generation of switching signals of the PWM inverter by comparing with a carrier signal.

C. Fuzzy PI Controller

When D-STATCOM is implemented with Fuzzy Logic Controller, It could not able to mitigate the Voltage Sag effectively i.e., the magnitude of the Voltage at the Load Point is not equal to 1 p.u which is the Reference Voltage. So the combination of PI controller and Fuzzy Logic Controller is implemented. PI controller is very common in the control of D-STATCOM. However, one disadvantage of this conventional controller is the fact that by using fixed gains, the controller may not provide the required control performance, when there are variations in the system parameters or operating conditions. To overcome this problem, the PI controller using fuzzy logic is proposed. The controller is composed of fuzzy controller and PI controller. According to the error and error rate of the control system and fuzzy control rules, the fuzzy controller can online adjust the two parameters of the PI controller in order to be adapted to any variations in the operating conditions.

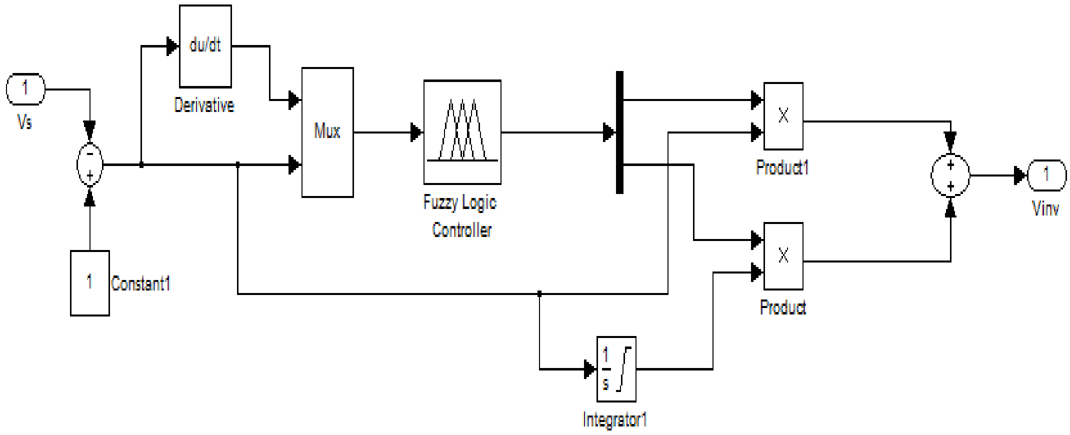


Fig 4 Implementation of the Fuzzy PI Controller for D-STATCOM

Fig.4 is the block diagram of the D-STATCOM's fuzzy PI controller. The inputs of the Fuzzy PI Controller of the D-STATCOM are the error (e) between the reference voltage at the coupling point and the actually measured value, as well as the deviation (Δe) of them. Given error and error rate as the inputs, then we can get ΔK_P and ΔK_i at that moment through fuzzy computing so as to realize the best regulation of the PI parameters.

This fuzzy adjuster is used to adjust the parameters of proportional gain K_P and integral gain K_i.

$$K_P = K_P^* + \Delta K_P \quad (11)$$

$$K_i = K_i^* + \Delta K_i \quad (12)$$

Where K_P^* and K_i^* are the reference values of fuzzy-PI based controllers

When the deviation appears, the controller will function to prevent it from increasing.

The actual operation is as follows:

1. If error is big, then the value of ΔK_P is maintained at a high value to give the system a fairly good fast-tracking performance, at the same time set the value of ΔK_i =0 to avoid a big over-shoot of the system's response.
2. If error is medium, then choose to make ΔK_P smaller and ΔK_i larger accordingly to avoid a big over-shot of the system's response.
3. If error is small, then ΔK_P is to further decrease as designed, and ΔK_i should be of a suitable value and will increase as error is getting smaller, so that the system will soon be stabilized, its stationary deviation will be removed, and the accuracy of control will be greatly improved.

Δe is taken into account simultaneously: when Δe is in the same direction as e and the input is deviating from the stable values.

As the input e and Δe reach the equivalent language values, we can get the fuzzy values of the two corrected parameters through fuzzy formula calculation applying the tuning rules. The input membership functions are given in Fig 5 & Fig 6.

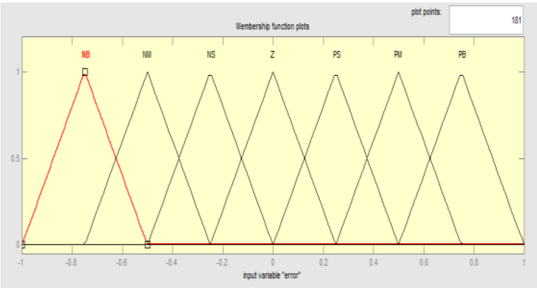


Fig.5 Input membership function of 'Error'

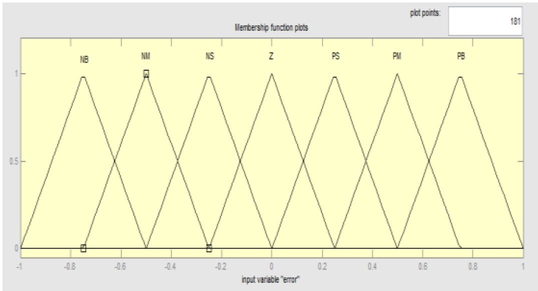


Fig.6 Input membership function of 'change in error'

The membership functions for the output variables are shown in Fig 7 & 8.

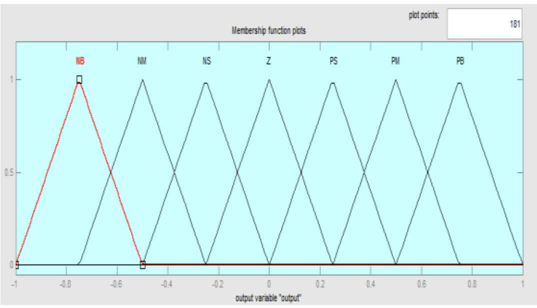


Fig.7 Output membership function 'ΔK_P'

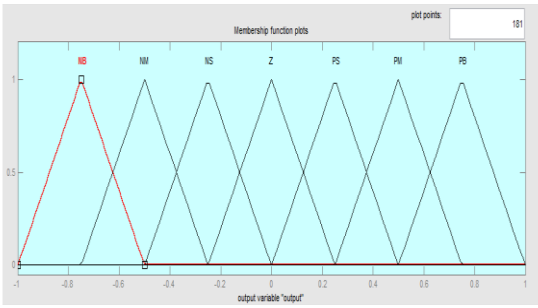


Fig.8 Output membership function 'ΔK_i'

Rule based table on which Fuzzy-PI controller for D-STATCOM installed on proposed test system for Voltage Sag mitigation is designed as given in Table III & IV.

Table III Rule base table for ΔK_P

e/ δe	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	NB	PM	PS	PS	Z
NM	PB	PB	NM	PM	PS	Z	Z
NS	PM	PM	NS	PS	Z	NS	NM
Z	PM	PS	Z	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NB
PM	Z	Z	NS	NM	NM	NB	NB
PB	Z	NS	NS	NM	NM	NB	NB

Table IV Rule base table for ΔK_i

e/ δe	NB	NM	NS	Z	PS	PM	PB
NB	Z	Z	NB	NM	NM	Z	Z
NM	Z	Z	NM	NM	NS	Z	NS
NS	Z	Z	NS	NS	Z	NS	NS
Z	Z	Z	NS	NM	PS	NM	Z
PS	Z	Z	Z	PS	PS	NM	Z
PM	Z	Z	PS	PM	PM	NM	Z
PB	Z	Z	PS	PM	PB	NB	Z

As the input e and Δe reach the equivalent language values, we can get the fuzzy values of the two corrected parameters through fuzzy formula calculation applying the tuning rules.

Where

NL	-	Negative Large	PS	-	Positive Small
NM	-	Negative Medium	PM	-	Positive Medium
NS	-	Negative Small	PL	-	Positive Large
Z	-	Zero			

After the above fuzzy deduction, defuzzification is done (including the maximum recognition approach, centre of gravity method, etc) the two corrected parameters regulated by the fuzzy-PI controller and choose its accurate value to calculate the amount of output control.

IV. SIMULATION AND RESULTS

Simulations are performed on the D-STATCOM test system using MATLAB/SIMULINK to study the efficiency of proposed control strategies. The system specifications are listed in Table V. It is assumed that the voltage magnitude of the load bus is maintained at 1 p.u during the voltage sags condition. The proposed system configuration of D-STATCOM is composed by 11kV, 60Hz generation system, feeding two transmission lines through a 3 – winding transformer connected in Δ/Δ/Δ, 33/ 25/25kV. Such transmission lines feed two distribution networks through two transformers connected in Y/Δ, 25/11kV. To verify the working of D-STATCOM for voltage compensation a fault is applied before the injection transformer with the fault resistance of 0.70Ω for time duration 0f 0.2-0.4s.

Table V System Parameters

S.No	System Parameters	Ratings
1	Source	3-phase,33KV
2	Inverter Parameters	IGBT based, 3 arms,6 pulse
3	Three winding transformer	Y/Δ/Δ, 33/25/25 kV
4	Two winding transformer	Δ/Y,25/11 KV
5	RL load	Active power=50e3W
6	Carrier frequency	1080 Hz
7	Nominal frequency	50Hz
8	Fault resistance	0.70 Ohm

The system performance is analyzed for compensating the load voltage in distribution system. Three different cases were considered to show the effectiveness of the control schemes of the D-STATCOM. In each case, three types of simulations were carried out. The first type of simulation is carried out without D-STATCOM with a fault applied with a fault resistance of 0.70 ohm. The second set of simulations are carried out under same condition but in the presence of PI controlled D-STATCOM. The third sets of simulations are carried out under same condition but in the presence of fuzzy controlled D-STATCOM. The next set of simulations are carried out under same condition but in the presence of fuzzy PI controlled D-STATCOM

Case 1: Single line to Ground fault

Here, single line to ground fault is applied with a fault resistance of 0.70 Ω, during the period 0.2–0.4 seconds. And it initiates the voltage sag of about 0.5973 p.u. The above simulation is carried out without D-STATCOM and the voltage sag at the load point is found to be 0.5973 p.u with respect to the reference voltage as shown in Fig 9. In addition, the FFT analysis was also carried out and the THD was calculated. The effect of harmonics without D-STATCOM when the single line to ground fault is applied which is shown in Fig.10.

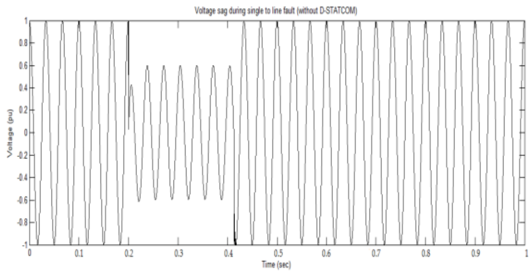


Fig.9 Voltage sag at the load point during single line to ground without D-STATCOM

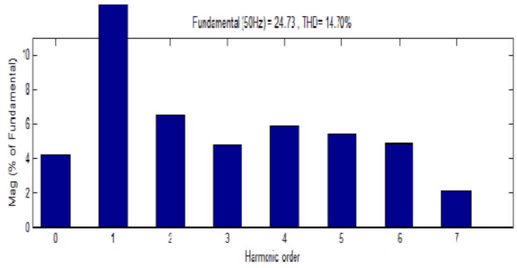


Fig. 10 Effect of Harmonics during single line to ground fault without D-STATCOM

In order to mitigate the voltage sag, the D-STATCOM was introduced with the PI Controller and the simulation was carried out under the same operating condition as mentioned in the first type of simulation which is shown in Fig. 11 and the load voltage at the terminal point was found to be 0.7535 p.u. The FFT Analysis was also carried out when the D-STATCOM was implemented with PI Controller. The THD was found to be reduced as 9.92% which is shown in Fig. 12.

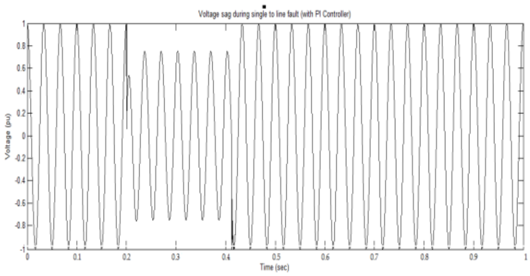


Fig.11 Voltage sag at the load point during single line to ground fault with PI Controlled D-STATCOM

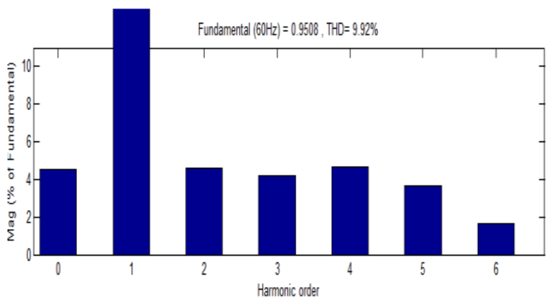


Fig. 12 Effect of Harmonics during single line to ground with PI Controller

The above simulation was carried out in the presence of Fuzzy logic controlled D-STATCOM and the load voltage at the terminal point was found to be 0.9228 p.u. as shown in Fig.13. The FFT Analysis was also carried out when the D-STATCOM was implemented with Fuzzy Logic Controller. The THD is found to be 4.43% as shown in Fig. 14.

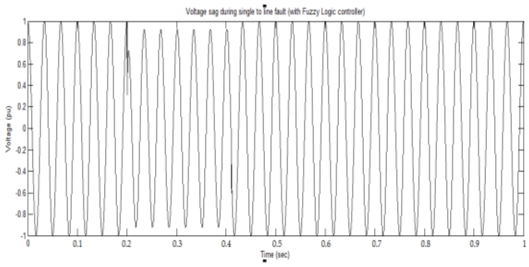


Fig.13 Voltage sag at the load point during single line to ground with Fuzzy Logic Controller

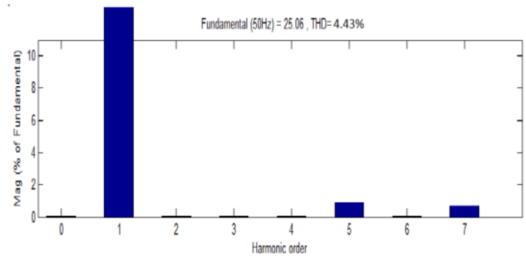


Fig. 14 Effect of Harmonics during single line to ground fault with Fuzzy logic Controlled D-STATCOM

Though the voltage sag has been mitigated through the implementation of PI and Fuzzy logic controlled D-STATCOM, the reference voltage i.e., 1 p.u could not be reached. In order to attain this, the D-STATCOM was implemented with Fuzzy PI Controlled D-STATCOM. Finally, the simulation was carried out with the implementation of Fuzzy-PI Controlled D-STATCOM and the load voltage at the terminal point was found to be 0.9968 p.u. as shown in Fig. 15 which is approximately equal to the reference voltage. The FFT Analysis was also carried out when the D-STATCOM was implemented with Fuzzy PI Controller. The THD was found to be 2.37% as shown in Fig. 16. A comparative study has been carried out for the three type of controllers which is shown in Fig.17. From the graphical results, it is observed that fuzzy based PI controller reduces the voltage sag at load end maintains at 0.9968 p.u and the THD has been reduced to 2.37%.

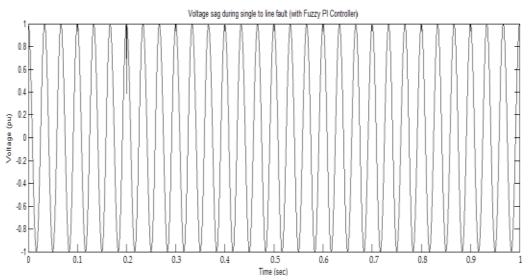


Fig.15 Voltage sag at the load point during single line to ground with Fuzzy- PI Controller

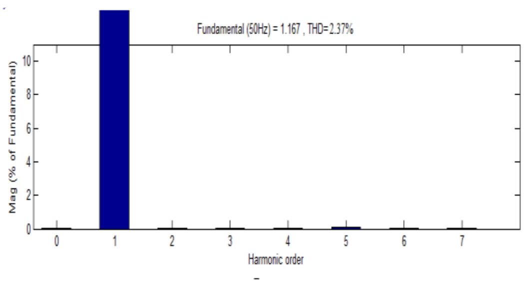
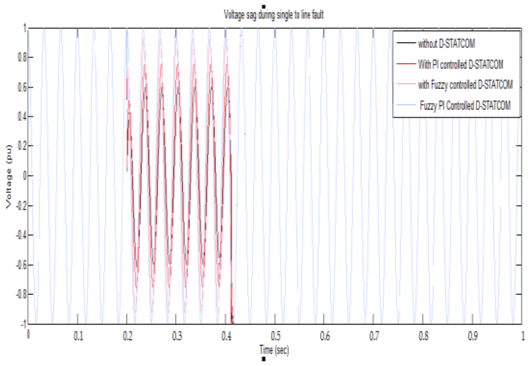


Fig. 16 Effect of Harmonics during single line to ground fault with Fuzzy - PI Controlled D-STATCOM

Case 2: Double line to ground fault

A double line to ground fault is applied with a fault resistance of 0.70 Ω, for a period 0.2 seconds has been simulated with the voltage sag of about 0.6095 p.u without D-STATCOM. With the PI Controller based D-STATCOM, with the fuzzy logic controlled D-STATCOM and with the presence of Fuzzy logic controlled D-STATCOM, the load voltage at the terminal point was found to be 0.7609 p.u, 0.8995 p.u and 0.9982 p.u respectively and the comparative results are shown in Fig.18. The FFT Analysis with Fuzzy PI Controlled D-STATCOM was reduced to 4.61%.



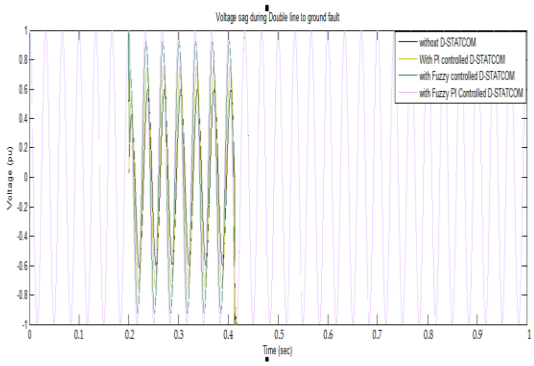


Fig. 17 Comparative Analysis of the PI, Fuzzy and PI-Fuzzy Controllers Based D-STATCOM in mitigating voltage sag (Single line to gnd fault)

Fig. 18 Comparative Analysis of the PI, Fuzzy & PI-Fuzzy Controllers Based D-STATCOM in mitigating voltage sag (Double line to gnd fault)

Case 3: Line to line Fault

A line to line fault is applied with a fault resistance of 0.70 Ω, for a period 0.2 seconds has been simulated with the voltage sag of about 0.5982 p.u without D-STATCOM. With the PI Controller based D-STATCOM, with the fuzzy logic controlled D-STATCOM and with the presence of Fuzzy logic controlled D-STATCOM, the load voltage at the terminal point was found to be 0.7531 p.u, 0.8632 p.u and 0.9233 p.u respectively and the comparative results are shown in Fig.18. The FFT Analysis with Fuzzy PI Controlled D-STATCOM was reduced to 5.09%.

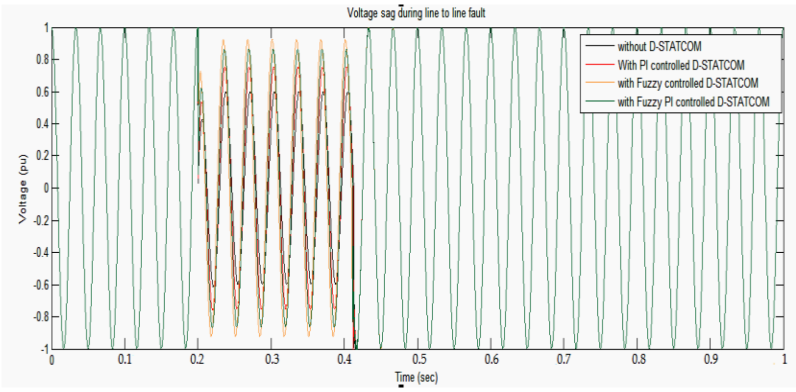


Fig.19 Comparative Analysis of the PI, Fuzzy and PI-Fuzzy Controllers Based D-STATCOM in mitigating voltage sag (Line to line Fault)

7.4 COMPARISION BETWEEN THE CONTROLLERS

From the comparative study of voltage sag analysis shown in Table V, with different controllers, Fuzzy PI control scheme is found to be a better methodology for voltage mitigation under different fault conditions. From the table VI, it is proved that with Fuzzy based PI Controller, the THD has been reduced to a minimum level compared to other controller techniques.

Table V Voltage Sag Analysis

Conditions	SLG fault	DLG fault	LLG fault
Voltage Sag mag. (without D-STATCOM)	0.5973	0.6095	0.5982
Voltage Sag mag. (with PI controller)	0.7535	0.7609	0.7531
Voltage Sag mag. (with Fuzzy controller)	0.9228	0.8995	0.8632
Voltage Sag mag. (with Fuzzy PI controller)	**0.9968**	**0.9982**	**0.9233**

Table VI THD Analysis

Conditions	SLG fault	DLG fault	LLG fault
THD (without D-STATCOM)	14.70	11.53	22.51
THD (with PI controller)	9.92	8.95	16.83
THD (with Fuzzy controller)	4.43	6.62	10.41
THD (with Fuzzy PI controller)	**2.37**	**4.61**	**5.09**

V. CONCLUSION

This paper has proposed the modelling and simulation of D-STATCOM using MATLAB/SIMULINK with PI, Fuzzy Logic controller and Fuzzy PI Controller. The performance of D-STATCOM is studied under voltage sag during different fault conditions. From the simulation results, it is clear that the Fuzzy PI controller shows good performance rather than conventional PI controller under various short circuit fault conditions and in addition generate low THD (<5%). As a result, the D-STATCOM mitigates the voltage sag and harmonics and thus improving the power quality efficiently.

ACKNOWLEDGEMENT

The authors thank the management of Velammal College of Engineering & Technology, Madurai for the work to be carried out in their premises. This work has been carried out under the funded project from Research Promotion Scheme (RPS) under AICTE, India. **Ref. No" AICTE/ RIFD / RPS (POLICY – III) 110 / 2012 - 13.**

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