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FUZZY LOGIC BASED SINGLE PHASE ACTIVE VOLTAGE QUALITY REGULATOR FOR VOLTAGE SAG COMPENSATION

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Abstract— Voltage sag has always been a huge threat to sensitive industrial and commercial electrical consumer and deep sag with long duration are usually more intolerable. In this paper, a single phase active voltage quality regulator for mitigation of long duration deep sag is proposed. Control technique used for previous study was PI-controller. However, the dynamic response of PI-controller is low and harmonic distortion is high. To overcome this limitation, a fuzzy logic controller is used instead of PI-controller, which is based on rule base. A fuzzy logic toolbox in MATLAB/Simulink software is used to design fuzzy interface system with two inputs, one output and 25 rules. Simulation of AVQR with PI and Fuzzy logic controller is performed by MATLAB/Simulink software.

Keywords- Active Voltage Quality Regulator (AVQR), PI-Controller, Fuzzy Logic Controller, Total Harmonic Distortion (THD), MATLAB/Simulink software.

I. INTRODUCTION

Power Quality (PQ) issues have obtained increased attentions in today's industrial practice [1]. As the up gradation of modern science and technology, various sophistically types of equipment and sensitive load that required a higher power quality are widely used. The industrial or commercial system contains power electronic or semiconductor device like variable speed drive are used which are very sensitive to the change in current and voltage. So they are affecting on power quality of supply system. Generally the voltage dip, momentary interruption and transient comprise 92% of all the Power Quality problems that take place in power system [2]. In fact a voltage dip has always been a danger to the industry and voltage dips with 0.25sec is leads to interrupt a manufacturing process resulting in huge financial losses [3]. In voltage sag is nothing but drop of RMS voltage between 0.1 and 0.9 per unit for duration time of half cycle to 1 min [4]. It is most serious problem of power quality and it is caused by fault in the power system or by starting a large motor. Now days, there are different technique are proposed to mitigate voltage sag. The most of the voltage regulator topology can generally categorized into two groups, first one is the inverter based regulator and another is direct ac-ac converter[6]-[9]. A series connected devices are voltage source inverter based regulator like ac-ac cuk converter, ac-ac buck converter, Dynamic voltage restorer, Dynamic sag corrector and compensate the voltage sag by injecting voltage in series with the grid.

A performance of the existing system like DVR, Dynamic sag corrector is good but some drawback in terms of cost, there feasibility and effectiveness. Generally the voltage dip, swell events usually last for less than 1sec and impress voltage dips up to 50% of rated voltage, but in industry long duration deep sag events results. So the DVR, dynamic sag corrector does not feasible for long interval deep sag, so because of that new topology which is single phase active voltage quality regulator is proposed and which is able mitigate a long interval deep voltage sag[1]. A DC link voltage adaptive control technique is applied for proposed AVQR topology to improve its operation efficiency.

It is necessary to analyze the performance of AVQR by applying new algorithm. The conventional method is based on PI controller, but there are restrictions related with this method. A common drawback is seen, it has restricted bandwidth at high frequency and also THD is high. There are different control algorithms to overcome this drawback of the conventional PI control method. Fuzzy logic control method is one of the new algorithms for controlling the output of AVQR. So this paper is based on implementing fuzzy logic control method for AVQR.

II. TOPOLOGY AND WORKING PRINCIPLE

A. Proposed Topology

The Proposed AVQR topology is shown in Fig.1 contain five main component, including an IGBT Switches (V1, V2), a bypass switch (VT1, VT2), shunt converter (VT3, VT4), a storage capacitor (C1, C2), and a low-pass filter (Lf, Cf) are the main part. Under normal condition, a bypass switch is in ON state and the normal supply voltage applied to load through that switch. When fault occurred on utility side, then voltage sag is detected, so the bypass s/w will turn OFF and converter is controlled to introduce the preferred missing voltage in series with supply voltage [11].

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B. Working Principle

Working of single phase active voltage quality regulator is depend proper operation of switches (V1 and V2), firing angle of thyristor (VT1, VT2, VT3 and VT4) shown in fig.3 [1]. For simplicity to understand working principle, thyristor switches are replaced with diode (D1, D2). The difference between these two is only that with thyristor, it is controllable and with diode, it is uncontrollable.

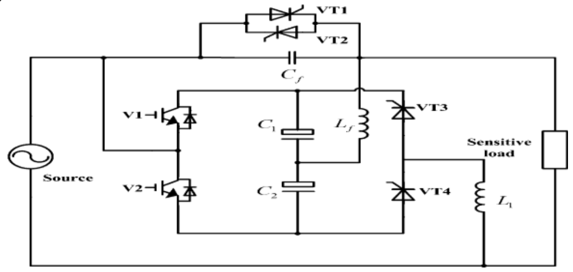

Fig.1 Proposed AVQR topology

So the DC link voltage with diode connection represent higher limit of dc voltage in the proposed topology. Switches V1 and V2 as shown in fig.2 and fig.3 are provides main operation of AVQR due to switching V1 or V2, ON or OFF dc link capacitor are charged or discharged, so dc link voltage will vary with ON or OFF status of switches[1]. Operating condition for positive and negative half cycle is shown in Fig.2 and fig.3, and dark line indicates direction of flow of current.

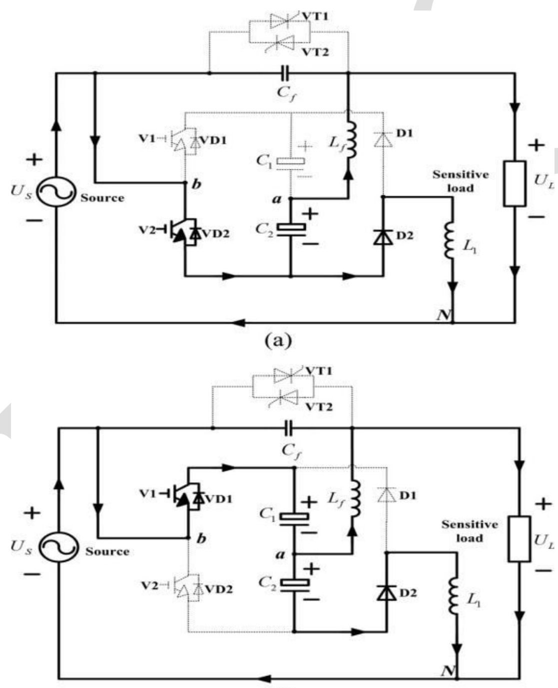

Fig.2 operation during positive half-cycle. (a) When V2 is ON (b) When V2 is OFF.

In positive half cycle, shown in fig.2 (a) V2 is switched ON and this switching generally depends on gate pulse provided to switch through control circuit. This control circuit designed such that, when measured voltage is less than supply voltage the pulse is provided to switch for specific period. Due to this, inductor L1 charges from grid through D2 and capacitor C2 will discharge to compensate the load voltage. Then switch V2 will OFF shown in fig.2 (b) charged inductor discharged and capacitor C1and C2 will charged through VD1. Similarly in negative half cycle, shown in fig.3 (a) switch V1 is ON, the inductor L1 is charges and capacitor C1 discharge to compensate load voltage. Then V1 will OFF as shown in fig.3 (b) charged inductor will discharged and capacitor C1and C2 charged through VD2 [1].

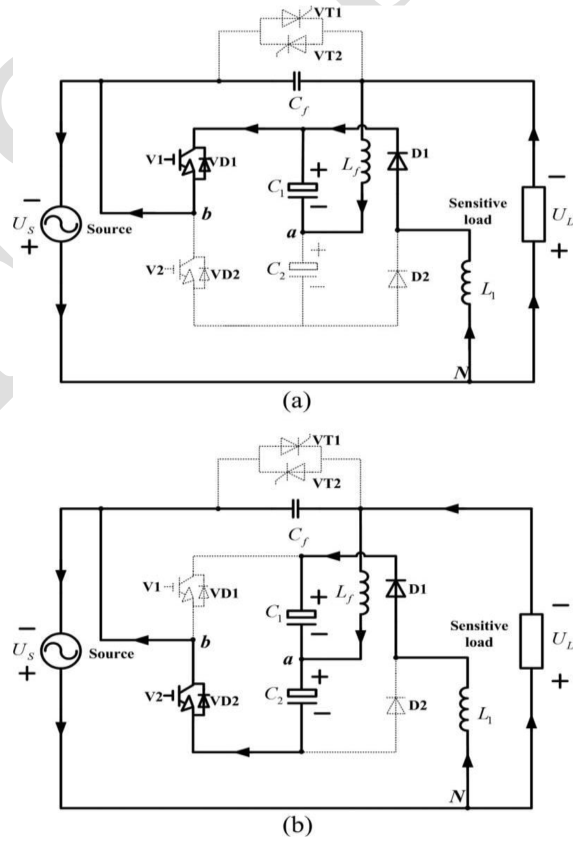

Fig.3 operation during negative half-cycle. (a) When V1 is ON (b) When V1 is OFF.

III. Modelling And Theoretical Analysis

As can be seen from fig.2 and fig.3 the working principle of AVQR for positive and negative half cycle, then it is important to evaluate the dc link voltage. In order to verify the compensation of the AVQR and to assess its ability to mitigate deep sag for a long duration that mild, DC link voltage will be resulting from the relationship based on operating condition

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aforementioned. In-Phase voltage sags compensation control strategy is applied, so in one-half cycle the energy required to maintaining output voltage which can be given as:

$$E0 = \frac{T0\Delta V}{2Vref} * P0 \quad (1)$$

Where T0 is initial time period of grid voltage, ΔV is the missing voltage in RMS, Vref is reference voltage or rated RMS voltage, and P0 is the rated load power. Required energy for compensation of voltage sag in steady state condition should completely be provided through residual grid [1]. So during T0/2 (in half cycle), the charging energy E1 and E0 both are equal.

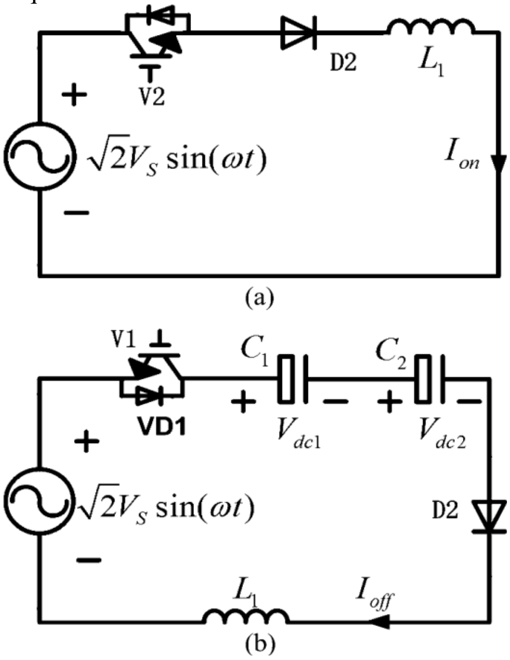

Fig.4 circuit model (a) When V2 is ON (b) When V2 is off.

Fig.4 shows the simplified circuit of fig.2 in this Vs is the RMS value of supply voltage, so from circuit that is for turn ON or turn OFF condition following equation are obtained:

$$L1\frac{dIon}{dt} = \sqrt{2}Vs\sin(wt) \quad (2)$$

$$L1\frac{dIoff}{dt} = \sqrt{2}Vs\sin(wt) - Vdc1 - Vdc2 \quad (3)$$

Then equation (2) and equation (3) can be discredited, based on two assumptions: C1 and C2 are well designed so that Vdc1 and Vdc2 both are equal excluding their ripple voltages; the line frequency is much lower than, so for nth switching cycle [1]:

$$L1\Delta Ion = \sqrt{2}Vs\sin(wnTs)tonn \quad (4)$$

$$L1\Delta Ioff = [\sqrt{2}Vs\sin(wnTs) - 2Vdc]toffn \quad (5)$$

Where, $t_{on\ n}$ and $t_{off\ n}$ are ON time and OFF time of switch V2 at n^{th} switching cycle. Actually $t_{on\ n}$ and $t_{off\ n}$ are inverter duty cycle and expressed as follows:

$$tonn = \frac{Ts}{2}[1 + \frac{\sqrt{2}\Delta V\sin(wnTs)}{Vdc}] \quad (6)$$

$$toffn = \frac{Ts}{2}[1 - \frac{\sqrt{2}\Delta V\sin(wnTs)}{Vdc}] \quad (7)$$

Combining equation (4)-(7) we get current at end of nth switching cycle

$$Ioffn = Ioff(n-1) + \frac{Ts}{L1}[\sqrt{2}Vref\sin(wnTs) - Vdc] \quad (8)$$

$$\Delta Ionn = \frac{\sqrt{2}TsVs\sin(wnTs)}{2L1} *[1 + \frac{\sqrt{2}\Delta V\sin(wnTs)}{Vdc}] \quad (9)$$

The stored energy in inductor is associated with current for switching ON or OFF condition of V2. Then for nth switching cycle:

$$Einn = \frac{1}{2}L1\Delta I^2onn + L1Ioff(n-1)\Delta Ionn \quad (10)$$

The futures of charging current are 1) the charging current always greater than zero because in diode current flows unidirectional. 2) After increasing 1-half cycle of the supply voltage the charging current always decreases.
So non zero charging current is expressed as:

$$Ioff(n-1) = \sum_{k=n0}^{n-1}\frac{Ts}{L1}[\sqrt{2}Vref\sin(wkTs) - Vdc] \quad (11)$$

Where n0 = initial superposition instant and is expressed as

$$n0 = ceil(\frac{T0\arcsin(Vdc/Vref)}{2\pi Ts}) \quad (12)$$

Substituting equation (9) and equation (11) into equation (10) we get energy which is provided through supply which is provided through supply in nth switching cycle is:

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$$Einn = \frac{Ts^2Vs^2A^2}{4L1}(1+\sqrt{2}BA)^2 + \frac{\sqrt{2}Ts^2VsA}{2L1Vdc} \cdot$$

$$*(Vdc+\sqrt{2}\Delta VA)\sum_{k=n0}^{n-1}(\sqrt{2}VrefC - Vdc) \qquad (13)$$

Where,

$$A = \sin wnTs$$

$$B = \frac{\Delta V}{Vdc}$$

$$C = \sin wkTs$$

So energy required for compensation E1is evaluated if equation (13) is added with 'n' ranges from 1 to T0/2Ts:

$$E1 = \frac{Ts^2Vs^2}{4L1}\left(\sum_{n=1}^{\frac{T0}{2Ts}}A^2 + 2\sqrt{2}B\sum_{n=1}^{\frac{T0}{2Ts}}A^3 + 2B^2\sum_{n=1}^{\frac{T0}{2Ts}}A^4\right) +$$

$$\frac{Ts^2\sqrt{2}Vs}{2L1}\sum_{n=n0}^{ne}\left[(A+\sqrt{2}BA^2)\sum_{k=n0}^{n-1}(\sqrt{2}VrefC - Vdc)\right]$$

$$= \frac{T0\Delta V}{2Vref}P0 = E0 \qquad (14)$$

Peak value of charging current Imax is expressed as

$$\mathrm{Im}ax = \frac{\sqrt{2}TsVs\sin(wn\max Ts)}{2L1}[1+\sqrt{2}B\sin(wn\max Ts)]$$

$$+\sum_{n=n0}^{n\max}\frac{Ts}{L1}(\sqrt{2}VrefC - Vdc) \qquad (15)$$

Where,

$$n\max = ceil\left(\frac{T0(\pi - \arcsin(\frac{Vdc}{Vref}))}{2\pi Ts}\right) \qquad (16)$$

So from the equation (14) and equation (15) the dc link voltage is depends on the supply voltage, switching frequency, charging of inductance and load power. A dc link voltage which evaluated from mathematical point of view but it does not give accurate value of dc link voltage. For that, iterative algorithm is adopted to compute the accurate value of dc link voltage. Flowchart required for this algorithm is shown in fig.5. In this Ts, Vs, T0, Vref, L1, P0 are constant and from that change in supply voltage ΔV and initial value of voltage required for compensation is calculated.

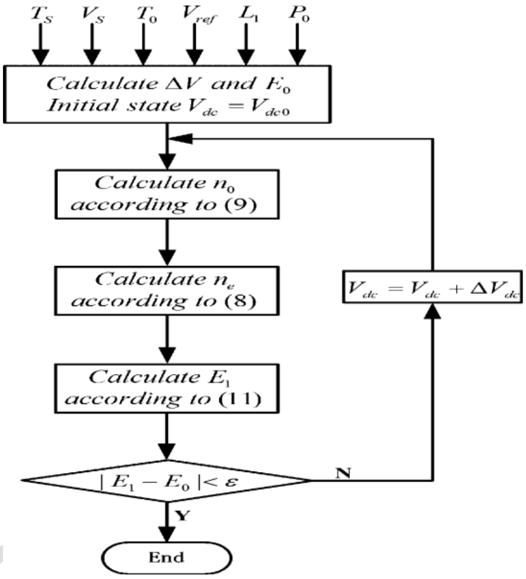

Fig.5 Flow chart for calculating Vdc

IV. Introduction to Fuzzy Logic Controller

The fuzzy logic control was first invented in 1965 by Prof. L. A. Zadeh of University of California. This innovation was not well accepted until Dr. E. H. Mamdani, applied the fuzzy logic in a practical application in 1974. Fuzzy logic is refers to study of method and principle of human reasoning. Fuzzy logic idea is similar to the human's being feeling and interference process. The schematic representation of fuzzy logic controller is shown in fig. and it consists of four primary components like fuzzification, interface mechanism, fuzzy knowledge base, and Defuzzification.

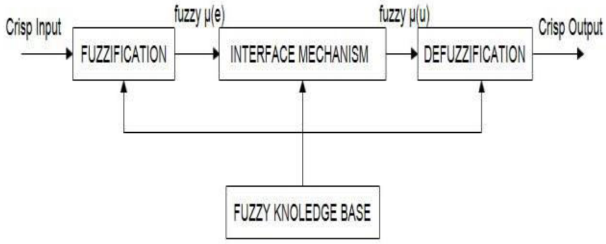

Fig. 6 schematic representation of fuzzy logic controller

1. Fuzzification – In this crisp input is converted into suitable linguistic variables using membership function.
2. Fuzzy knowledge base – The rule base and the data base are together referred as the knowledge base. A rule base containing a number of fuzzy IF–THEN rules; a data base which defines the membership functions of the fuzzy sets used in the fuzzy rules.
3. Interface Mechanism – Using If-Then type fuzzy rules converts the fuzzy input to the fuzzy output.

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4. Defuzzification – Converts the fuzzy output of the inference mechanism to crisp using membership functions analogous to the ones used by the fusilier.

A. Fuzzy logic membership function

The structure of the Fuzzy logic controller used in simulation is shown Fig.7. It has two inputs and one output. Inputs of fuzzy controller are error and change in error signal. Also an integrator is used after the fuzzy logic controller to reduce the steady state error in output of fuzzy logic controller.

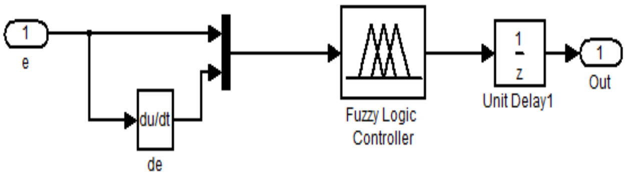

Fig.7 structure of fuzzy logic controller

There are different types of membership function in practice like trapezoidal mf, triangular mf, Gaussian mf, bell-shaped mf, s-curve mf and sigmoidal mf. The exact type of membership function depends on application. In this study, trapezoidal membership function and triangular membership function are preferred for input (error and change in error) and output variable as shown in fig.8-10.

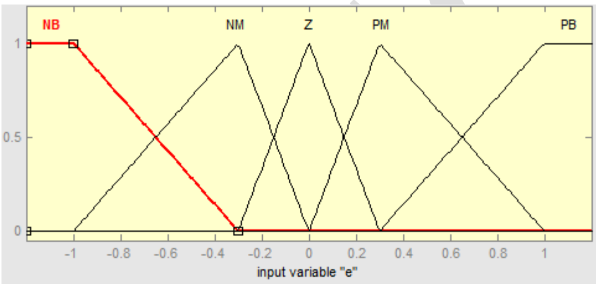

Fig.8 the membership function plots of error.

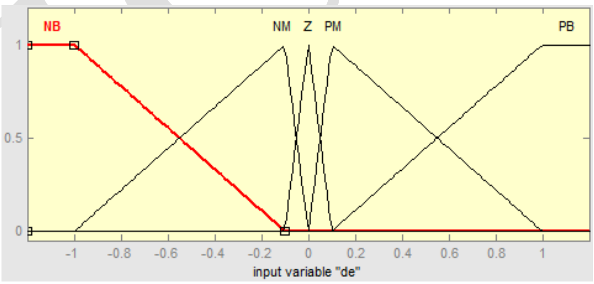

Fig.9 the membership function plots of change in error.

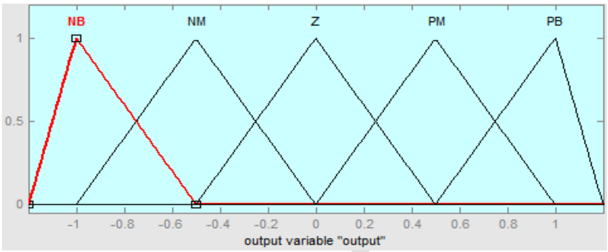

Fig.10 the membership function plots of output

B. Fuzzy logic rules

The error signal of output voltage and change in error will be input to the fuzzy logic controller. These two inputs and output are divided into five groups: 1. NB: Negative Big, 2. NM: Negative Medium, 3. Z: Zero, 4. PM: Positive Medium, 5. PB: Positive Big and its parameter. Fuzzy controller with Rule base consists of 25 rules and is given in Table 1.

TABLE I
RULE FOR ERROR AND CHANGE IN ERROR

e/Δe	NB	NM	Z	PM	PB
NB	NB	NB	NB	NM	Z
NM	NB	NB	NM	Z	PM
Z	NB	NM	Z	PM	PB
PM	NM	Z	PM	PB	PB
PB	Z	PM	PB	PB	PB

V. MATLAB / SIMULATION RESULT

Simulation result for AVQR with PI and Fuzzy logic controller along with FFT analysis is shown in figs.11-18. In this simulation supply voltage is √2*220V, 50Hz and 2KW resistive load is used. The simulation time is 0.8sec and voltage sag is produced for 70% (0.7*√2*220V) at 0.1sec and 50% (0.5*√2*220V) at 0.4sec. Required dc link voltage and KVAR for compensation of voltage sag is also shown in simulation result. System parameters required for simulation are given in table II.

TABLE II. SYSTEM PARAMETER

Description	Parameter	Real value
R.M.S. voltage	Vrms	220V
Line frequency	F0	50Hz
Switching frequency	Fs	5KHz
DC-link capacitor	C1/C2	4700µF
Filter inductor	Lf	1.5mH
Filter capacitor	Cf	20µF
Charging inductor	L1	2mH

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A. Simulation result of AVQR with PI-controller

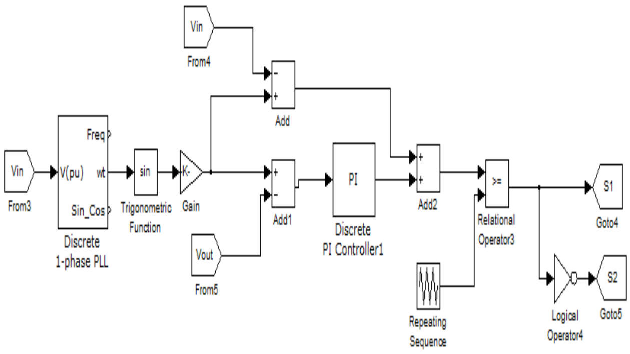

Fig.11 simulink design for controller with PI.

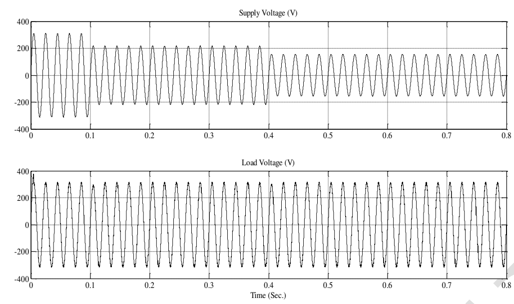

Fig.12 waveform of supply voltage and load voltage with PI controller.

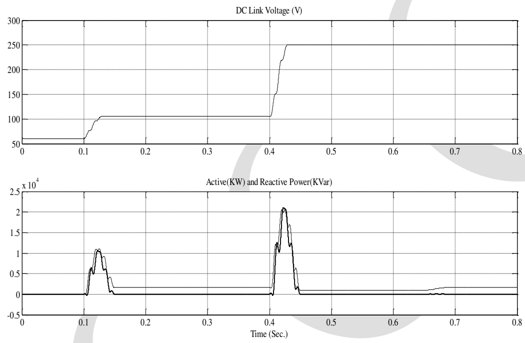

Fig.13 waveform of dc-link voltage and P-Q power with PI controller.

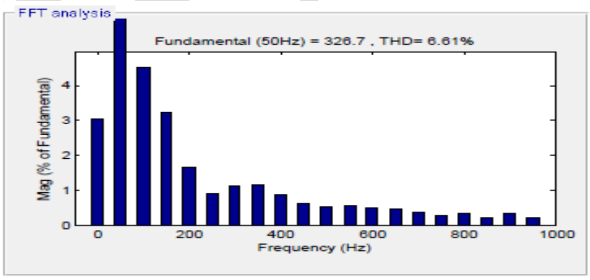

Fig.14 FFT analysis of load voltage with PI controller

B. Simulation Result Of AVQR With Fuzzy Logic Controller

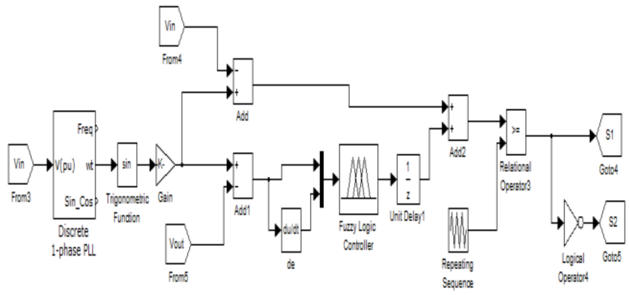

Fig.15 simulink design for controller with fuzzy controller.

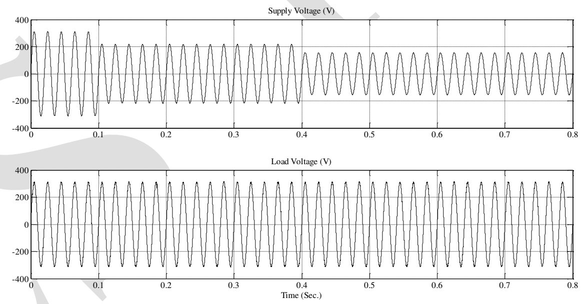

Fig.16 waveform of supply voltage, Load voltage with fuzzy controller.

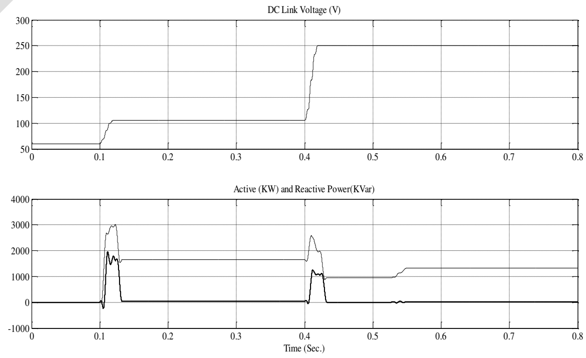

Fig.17 waveform of dc-link voltage and P-Q power with fuzzy controller.

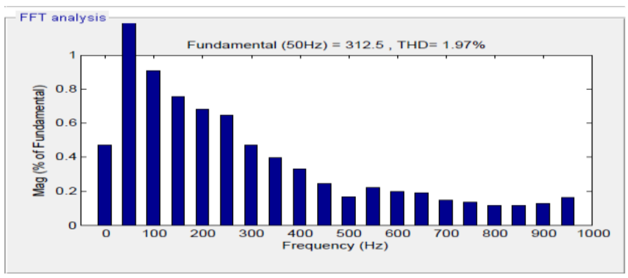

Fig.18 FFT analysis of load voltage with fuzzy controller

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For the comparative analysis of PI and fuzzy logic controller based AVQR following two steps are investigated.

1) Dynamic response of PI controller and fuzzy logic controller: It can be seen from the results that the dynamic response of the AVQR can be improved much more by utilizing fuzzy logic controller.

2) Hormonic Analisis: From fig.14 and fig.18 it can be seen that THD is considerable reduced in case of fuzzy controller. Following table shows the comparison of THD level.

TABLE III
COMPARISON OF THD LEVEL

PI / Fuzzy controller	THD
With PI controller	6.61%
With Fuzzy controller	1.97%

VI. CONCLUSIONS

This paper has presented fuzzy logic based single phase active voltage quality regulator for mitigation of long duration deep voltage sag. The compensation performance of the proposed AVQR is highly improved. A fuzzy logic control is one of the new control technique is used for controlling the output voltage of AVQR. A fuzzy logic toolbox in MATLAB/Simulink software is used for designing fuzzy interface system. Simulation of AVQR with PI and fuzzy logic controller is performed and results are compared. In a conclusion, fuzzy logic based AVQR topology provide solution for long interval deep voltage sag and harmonic distortion is low as compared with PI-controller.

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