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Fuzzy Logic Based VCM and CCM Controlled DSTATCOM for Improved Power Quality

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Abstract: *Power Quality problems in distribution systems can be solved by providing suitable shunt compensation, one such device is Distribution static compensator (DSTATCOM). Power quality issues generally arise due to high-energy demand loads such as pulse loads. In this paper, a new algorithm is proposed to generate reference voltage for a distribution static compensator (DSTATCOM) operating in voltage-control mode. To eliminate high-frequency switching components, three filter capacitors, one for each phase are to be connected in parallel with the DSTATCOM. Dead-beat controller is used to control and maintain the voltage across filter capacitor at the AC bus voltage. The magnitude of the bus voltage is chosen as nominal value, i.e., 1.0 p. u. To maintain the voltage across the DC storage capacitors constant, the required phase angle is obtained through a feedback loop. The proposed scheme ensures unity power factor (UPF) across the load terminals during nominal operation which is not possible in the traditional method. The compensator injects small currents thereby reduces the losses in the feeder and also in the voltage source inverter. The state-space model of DSTATCOM is incorporated with the deadbeat predictive controller for fast load voltage regulation during voltage disturbances. DSTATCOM here proposed provides power factor correction, harmonic elimination and thus tackles power-quality issues. The simulation results in MATLAB /SIMULINK platform are presented for the load balancing and voltage regulation of the same using the fuzzy logic controller.*

Keywords *—Current control mode, power quality (PQ), voltage-control mode, voltage-source inverter.*

I. INTRODUCTION

Power Quality (PQ) is the key to successful delivery of quality product and operation of the power industry. The increased application of electronic loads and electronic controllers which are sensitive to the quality of power make serious economic consequences and loss of revenues each year. Poor PQ can cause malfunctioning of equipment performance. Voltage imbalance, Sag, Swell, Harmonics and flicker problems, standing waves and resonance – are some of the issues that adversely affect production and its quality leading to huge loss in terms of product, energy and damage to equipment. Thus, it becomes imperative to be aware of quality of power and the deviation of the quality parameters from the norms such as IEEE-519 standard [1] to avoid damage of the equipment.

In present day distribution systems (DS) major power consumption is due to electronic devices which are reactive loads. Such typical loads are fans, pumps, refrigerators, computer loads, small rating adjustable speed drives (ASD) in air conditioners, lighting ballasts, other domestic and commercial appliances generally behaves as nonlinear loads. These loads draw lagging power-factor currents and therefore give rise to reactive power burden in the DS. The presence of unbalanced and non-linear loads affect the quality of source currents to a large extent. It affects the voltage at point of common coupling (PCC). This has adverse effects on the sensitive equipment connected to PCC and may damage the equipment appliances. Excessive reactive power demand increases feeder losses and reduces active power flow capability of the DS whereas unbalancing affects the operation of transformers and generators [2-3].

In this paper, a 5-level cascaded H-bridge inverter based DSTATCOM configuration has been presented. Inverter circuit is the heart of the DSTATCOM and various inverter topologies can be utilized in applications of DSTATCOM such as: cascaded h-bridge, neutral point clamped (NPC) and flying capacitor (FC) [4]. Among these topologies, CHB inverters are being widely used because of their modularity and simplicity. There are various modulation methods that can be applied to CHB inverters. Here phase shift modulation is used in this paper. CHB inverters can also increase the number of output voltage levels easily by increasing the number of H-bridges cells [5]. This paper presents a DSTATCOM with a PI controller based 5-level CHB multilevel inverter for the current harmonic voltage flicker and reactive power mitigation of the nonlinear load.

II. PROPOSED CONTROL SCHEME

Circuit diagram of a DSTATCOM –compensated distribution system is shown in Fig.1. It uses a 3-phase, 4-wire,2-level, neutral clamped VSI. This structure allows independent control to each leg of the VSI [6].The single phase equivalent representation of Fig.1 is shown in Fig.2. Filter inductance and resistance are L_f and R_f respectively. High switching frequency components can be eliminated by shunt capacitor. First, discrete modeling of the system is presented to obtain a discrete voltage control law, and it is shown that the PCC voltage can be regulated to the desired value with properly chosen parameters of the VSI. Then, a procedure to design VSI parameters is presented. The dc capacitor voltage is maintained at a reference value using a proportional integral (PI) controller [7]. The overall block diagram of the controller to control the DSTATCOM in a distribution system is shown in Fig. 3

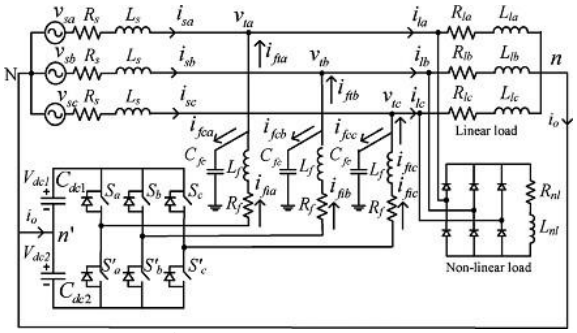


Fig.1 Circuit Diagram of the DSTATCOM compensated distribution system

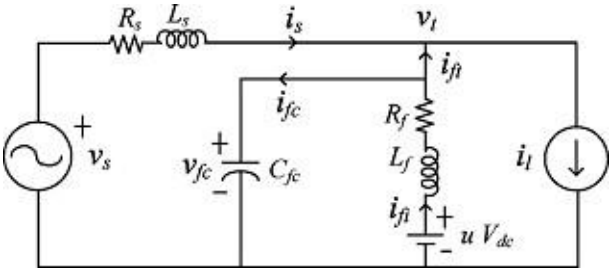


Fig.2 Single-phase equivalent circuit of DSTATCOM

II)A. Capacitor Voltage Control

The state-space equations for the circuit shown in Fig. 2 are given by

$$\dot{x} = Ax + Bz \qquad (1)$$

where

$$A=\begin{bmatrix} 0 & \frac{1}{cf_c} & 0 \\ -\frac{1}{L_f} & 0 & 0 \\ -\frac{1}{L_s} & 0 & -\frac{R_S}{L_s} \end{bmatrix}$$

$$B=\begin{bmatrix} 0 & -\frac{1}{cf_c} & 0 \\ \frac{V_{dc}}{L_f} & 0 & 0 \\ 0 & 0 & 1/Ls \end{bmatrix}$$

The capacitor voltage can be given as

$$v_{fc}(k+1) = G_{11}\, v_{fc}(k) + G_{12}\, i_{f1} + H_{11} u(k) + H_{12}\, i_{f1}(k) \qquad (2)$$

Where

$G_{11} = 1-T_d^2/2L_Fc_{fc}$

$G_{12} = T_d/c_{fc}-T_d^2R_f/2L_Fc_{fc}$

$G_{13} = 0$

$H_{11} = T_d^2v_{dc}/2L_Fc_{fc}$

$H_{12} = -T_d/c_{fc}$

$H_{13} = 0$

As seen from (2), the terminal voltage can be maintained at a reference value depending upon the VSI parameters v_{dc}, c_{fc}, L_F, R_F, and sampling time T_d. Therefore, VSI parameters must be chosen carefully. Let v_t^* be the reference load terminal voltage. A cost function J is chosen [8] as follows:

$$J = [v_{fc}(k+1) - v_t^*(k+1)^2 \quad (3)$$

The deadbeat voltage-control law from equation (2) can be given as

$$u_t^*(k) = \frac{v_t^*(k+1) - G_{11}v_{fc}(k) - G_{12}i_{f1}(k) - H_{12}i_{ft}(k)}{H_{11}} \quad (4)$$

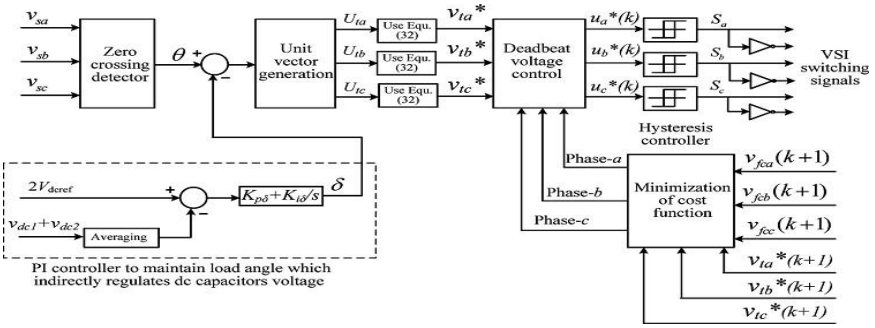


Fig.3 Overall controller Block diagram to control the DSTATCOM

The future reference voltage $v_t^*(k+1)$ in (4) is unknown. One-step-ahead prediction of this voltage is done using the following second-order Lagrange extrapolation formula

$$v_t^*(k+1) = 3\,v_t^*(k) - 3\,v_t^*(k-1) + v_t^*(k-2). \quad (5)$$

The term $v_t^*(k+1)$ is valid for a wide frequency range and when substituted in equation (4), yields to a one-step-ahead deadbeat voltage-control law. Finally $u_t^*(k)$, is converted into the ON/OFF switching command to the corresponding VSI switches using a deadbeat hysteresis controller [9].

II) B. Design of VSI Parameters

Terminal voltage can be regulated by DSTATCOM in a desirable manner by proper design of VSI parameters. The main parameters of the design procedure are as follows:

DC Capacitance (C_{dc}): Based on the period of swell/sag and change in dc bus voltage during transients, the value of dc capacitor is chosen. Let the total load rating be S KVA, means the load power varies from 0 to S kVA. The exchange of real power during transient is necessary to maintain the load power demand and it will result in the deviation of capacitor voltage from its reference value. The decrease in voltage will continue until the capacitor voltage controller comes into action. Let us assume that the controller takes a ρ cycle that is ρT, seconds to act, where T is the system time period.

Hence, maximum energy exchange takes place by the compensator during transient. This energy will be ρ S T equal to the change in the capacitor stored energy. Therefore

$$\tfrac{1}{2}\,C_{dc}\,(V_{dcref}^2 - V_{dc}^2) = \rho ST \quad (6)$$

Where V_{dcref} and V_{dc} are the reference dc bus voltage and maximum permissible voltage during transients, respectively.

From equation (6), the value of dc capacitor can be obtained by

$$C_{dc} = 2\,\rho ST/(V_{dcref}^2 - V_{dc}^2) \quad (7)$$

Voltage across DC bus (v_{dc}): For satisfactory performance, the dc bus voltage is to be taken twice of the peak of the source phase voltage. Hence, for a line voltage of 400V, the dc bus voltage is taken as 650V.

Here, S=10 kVA, V_{dcref} = 650 V, ρT=2 or 1, and $V_{dc} = 0.8V_{dcref}$ or $1.2V_{dcref}$. Using equation (7), capacitor values are found to be 2630 and 2152μF. The capacitor value 2600 is chosen to achieve satisfactory performance at all operating conditions.

Filter Inductance L_f: Suitable high switching frequency and a required rate of change of current can be provided by Filter inductance L_f so that VSI currents are in desirable range, the inductor dynamics is as follows:

$$L_f \, di_f/dt = -v_{fc} - R_f i_{fi} + V_{dc} \quad (8)$$

The inductance L_f is designed to provide good tracking performance at a maximum switching frequency (f_{max}) which is achieved at the zero of the source voltage in the hysteresis controller. Neglecting R_f, L_f is given by

$$L_f = 2V_m / (2h_c)(2f_{max}) = 0.5V_m / h_c f_{max} \quad (9)$$

Where the ripple in the current is 2 h_c. The value of L_f using (9) is found as 21.8 mH with ripple as 5% of the rated current i.e., hc=0.75A & fmax= 10 KHz. So,L_f is chosen as 22 mH here

Shunt Capacitor ***(C_{fc}):*** The value of the shunt capacitor should be chosen such that it should not cause resonance with the inductance of the feeder at the fundamental frequency (ω_0) .At resonant frequency the value of Capacitance is given as

$$C_{fcr} = 1/ \omega_0^{\,2} L_c \quad (10)$$

For proper operation, $C_{fc} << C_{fcr}$.

At ω_0 , in order to see that capacitor does not draw significant fundamental reactive current, it is chosen as 5 µF and that provides an impedance of 637 ohm.

III. INTRODUCTION TO FUZZY LOGIC CONTROLLER

Fuzzy set theory has been widely used in the area of control of dc-to-dc converter system. A simple fuzzy logic control can be built up by a group of rules based on the human knowledge of system behavior. A simulation model can be built by using MATLAB/Simulink to study the dynamic behavior of dc-to-dc converter and performance of proposed controllers. Moreover, fuzzy logic controller can also provide desirable control for both small signal and large signal at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has potential ability to improve the robustness of dc-to-dc converters. The block diagram of FLC with a dc-dc converter is shown in Fig.5.The fuzzy logic controller performs its operation in four stages:

i) Fuzzification: It converts input data into suitable linguistic values
ii) Knowledge base: It consists of a data base with necessary linguistic definitions and the set of control rules.
iii) Decision Making: This is a logic which simulates a human decision process and infers the control action using definitions of knowledge base
iv) Defuzzification: It is an interface which gives non fuzzy control action from the output of decision making logic [10]

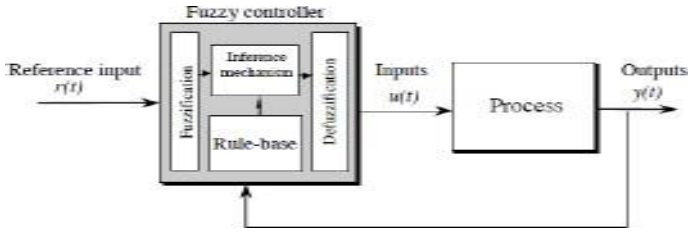


Fig.4 Fuzzy Logic controller in a closed loop system

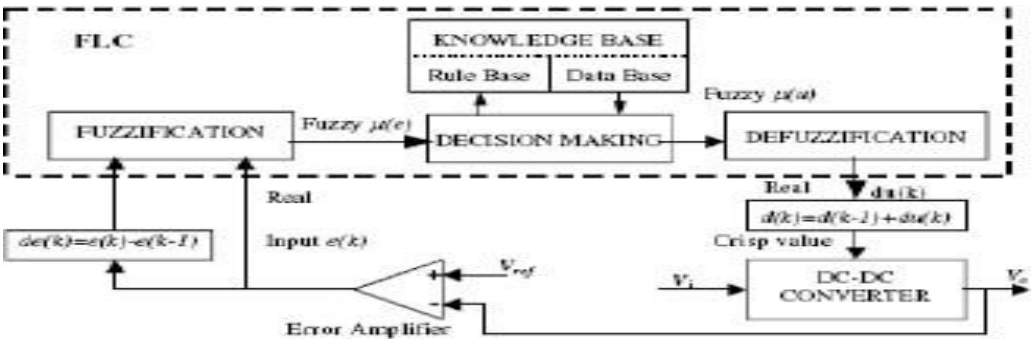
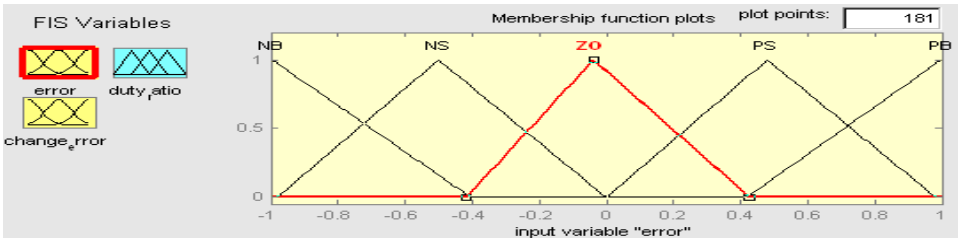


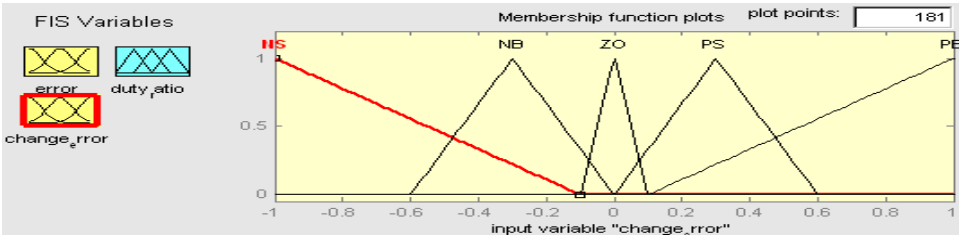
Fig.5 .DC-DC converter with Fuzzy Logic controller

III) A. Fuzzy Logic Membership Functions:

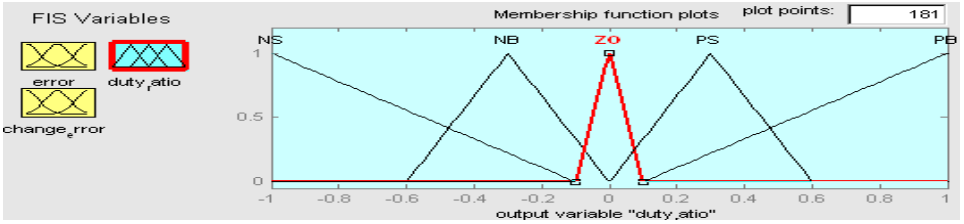
A mathematical model is not required for the Fuzzy controllers rather they can be designed based on the general knowledge of the plant. Fuzzy logic controllers can be adapted for variable operating points. Fuzzy logic Controller here is designed to control the output of dc-dc boost converter using Mamdani style of fuzzy inference system. Error (e) and change of error (de) are used as two input variables here in this fuzzy logic system. The duty cycle of PWM output will be the single output variable(u).



Plots of membership functions for error



Plots of Membership functions for change of error



Plots of membership function for duty ratio

III) B. Fuzzy Logic Rules:

The objective of this paper is to control the output voltage of the boost converter. The error and change of error of the output voltage will be the inputs to the fuzzy logic controller. These 2 inputs are divided into five groups; "NB: Negative Big, NS: Negative Small, ZO: Zero Area, PS: Positive small and PB: Positive Big "[10]. These fuzzy control rules for error and change of error can be referred in Table I.

Table I
FUZZY RULES FOR ERROR & CHANGE OF ERROR

(de) \ (e)	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

V. SIMULATION RESULTS

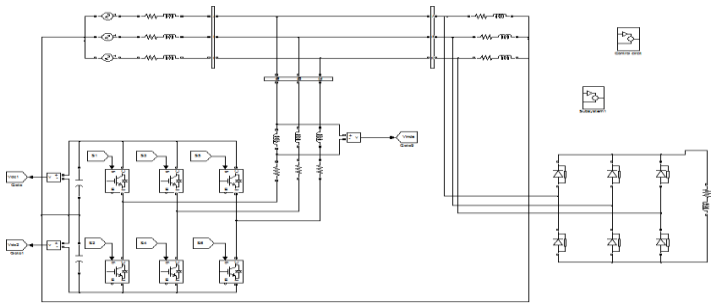


Fig.6 Simulink model for conventional system

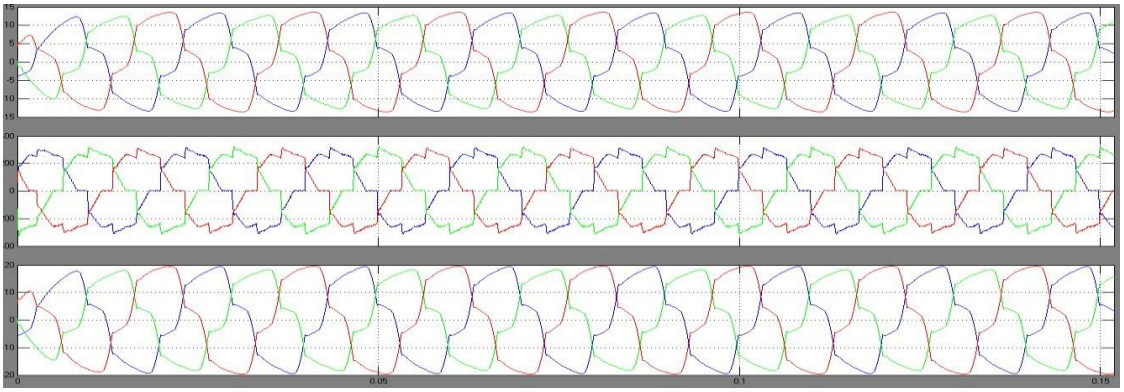


Fig.7 Results of the proposed model without DSTATCOM

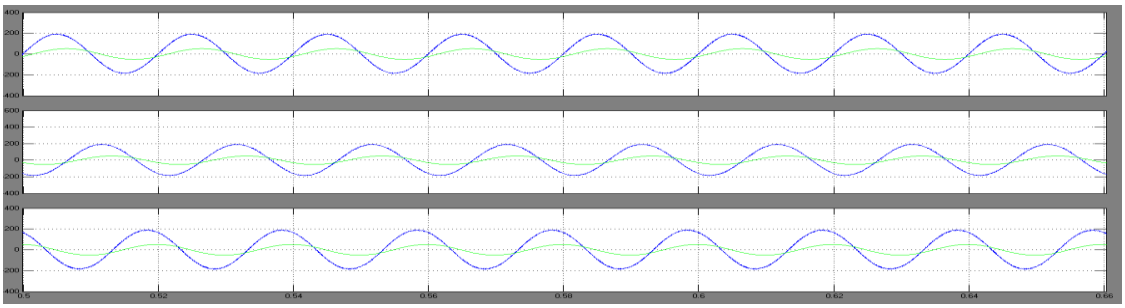


Fig.8 Terminal Voltages and source currents using the conventional method (a) Phase a (b) Phase b (c) Phase c

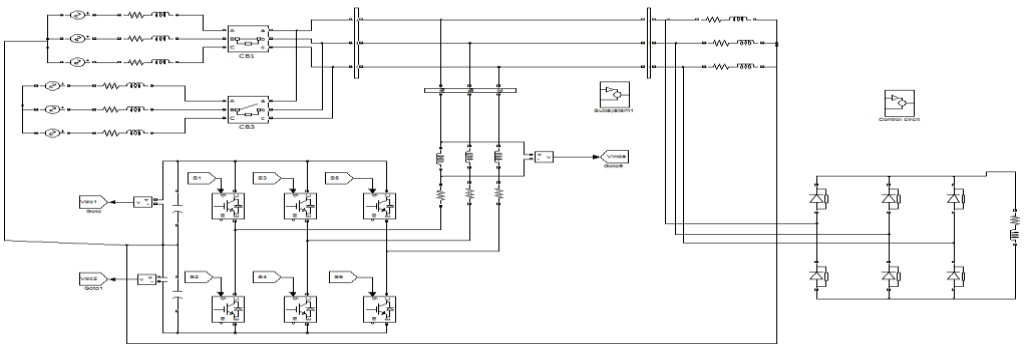


Fig.9 Simulink model for proposed system with PI controller

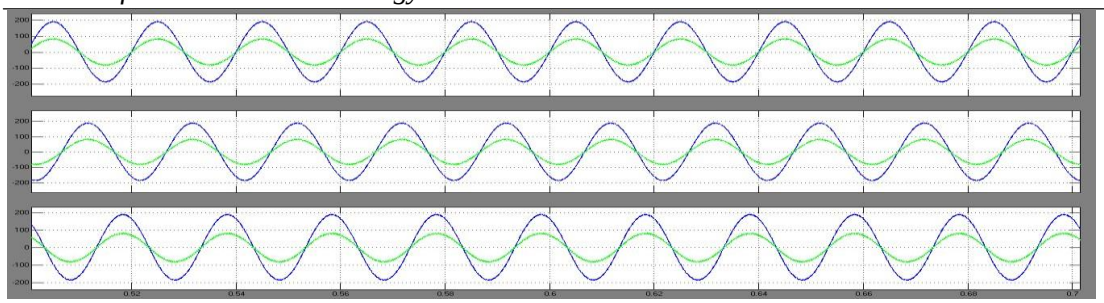


Fig.10 Terminal voltages and source currents in the proposed method using PI controller: Phase a, Phase b, Phase c

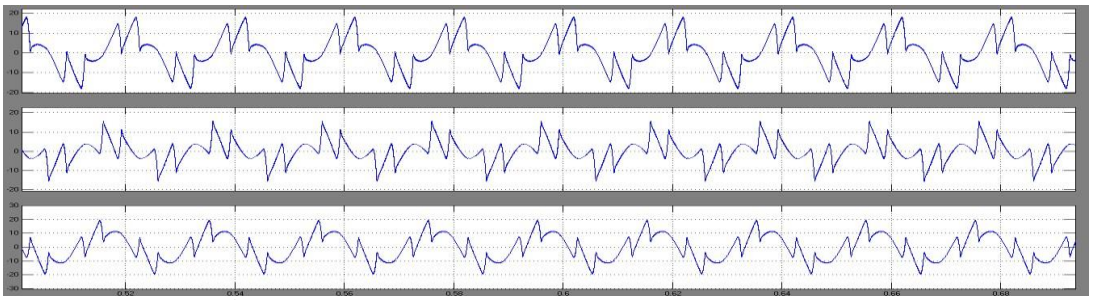


Fig.11. Simulation results for compensation currents

Fig. 12. Load reactive power, compensating reactive power, and reactive power at PCC for the Proposed method with PI controll er

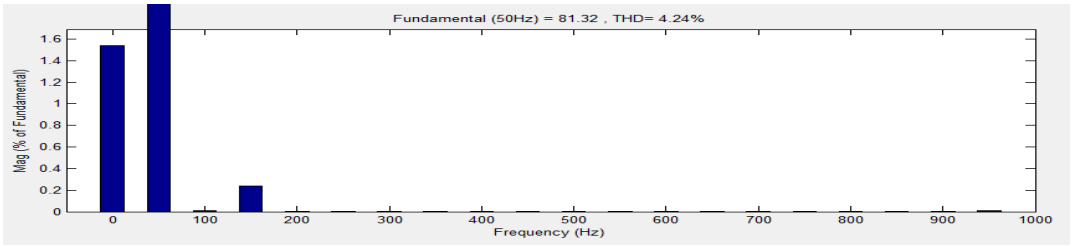


Fig.13. FFT analysis of source current with PI controller

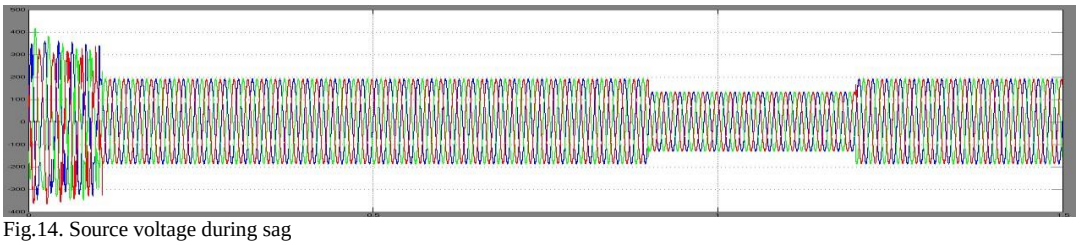


Fig.14. Source voltage during sag

Fig.15. RMS value of source voltage during sag

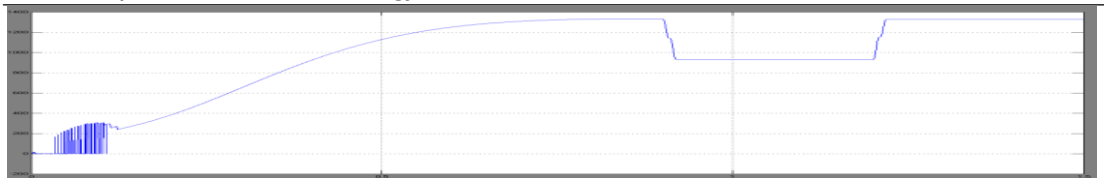


Fig.16.DC link voltage

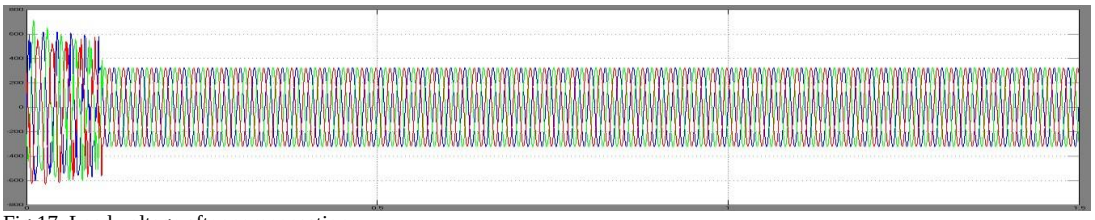


Fig.17. Load voltage after compensation

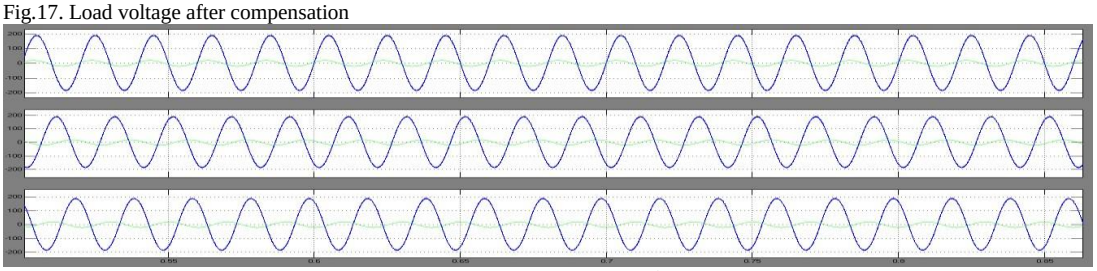


Fig.18 Terminal voltages and source currents in the proposed method using fuzzy controller (a) Phase a (b) Phase b (c) Phase c

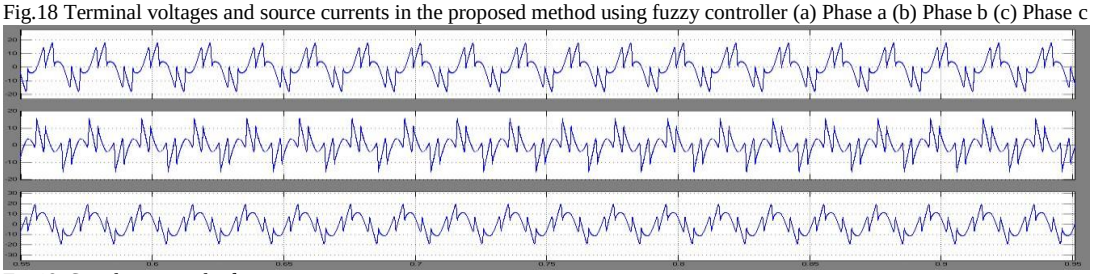


Fig.19. Simulation results for compensation currents

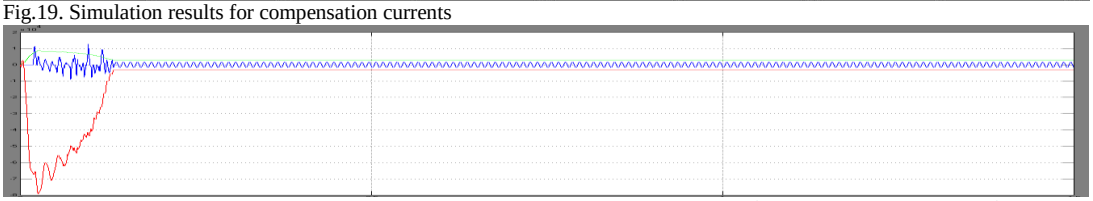


Fig.20. Load reactive power, compensator reactive power, and reactive power at PCC of the proposed method with fuzzy controller

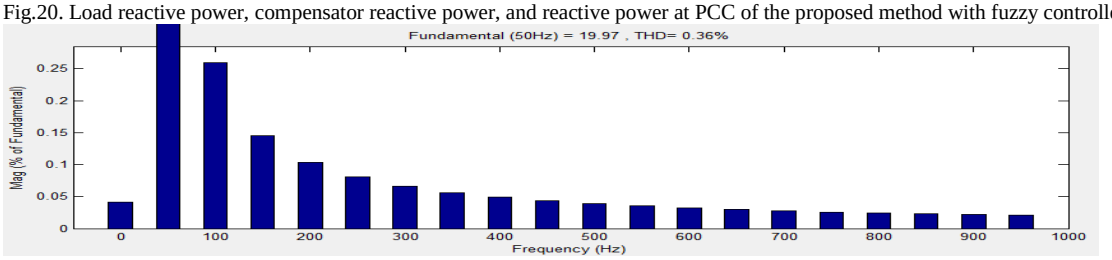


Fig.21. FFT analysis of source current with fuzzy controller

VI. CONCLUSION

In this paper, a new control algorithm has been proposed for the generation of reference load voltage to a voltage-controlled DSTATCOM. The performance of the proposed scheme is compared with the traditional scheme. The proposed method provides the following advantages:

i) The compensator injects reactive and harmonic components of load currents at nominal load and results in UPF.
ii) Unity Power Factor is nearly maintained for a variable load.
iii) Losses are considerably reduced both in the VSI and the feeder and provide better sag supporting capability with the same VSI rating compared to the traditional scheme.
iv) Better voltage regulation has been achieved during large voltage disturbances.

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