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PERFORMANCE EVALUATION OF FUZZY LOGIC BASED SINGLE-PHASE ENHANCED PHASE-LOCKED LOOP (EPLL) CONTROL ALGORITHM FOR REACTIVE POWER CONTROL USING DSTATCOM

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ABSTRACT

In this paper performance of Enhanced Phased locked loop technique in each phase is evaluated for reactive power control using DSTATCOM by Fuzzy logic Controller is investigated. DSTATCOM is a promising current controlled active shunt compensator for power quality enhancement, as seen in literature various control algorithms are proposed for reference current generations. In this paper EPLL scheme is implemented with fuzzy logic controller for finding out reference currents over conventional PI controller. Simulation is implemented using simulink model designer of MATLAB for validity of algorithm. Investigation is also carried out over conventional controller towards power factor adjustment, load compensation and harmonic minimization for linear, Non-linear and variable loads. Fuzzy controller for stabilisation of voltage across DC link capacitor is an added feature for EPLL over PI controller. Results substantially proves that reactive power maintenance i.e., UPF operation of DSTATCOM and reduction in THD of source currents using proposed method over PI based controller are noteworthy in power quality management.

KEYWORDS-- *EPLL Algorithm, VSC, Power Quality, Fuzzy Logic Controller, DSTATCOM.*

I. INTRODUCTION

Modern power system is huge complex network where hundreds of generating stations connected with thousands of transmission lines and lacks of distribution lines. The common loads encountered in the distribution system are 3-phase Induction motors, Fans, geysers and air conditioners etc. These loads require reactive power for their operation and more over due to the existence of unbalanced load on the system makes the situation worse [1]. Hence, common issues encountered in Power distribution system are poor Power Quality and also severity attributed by non-linear and dynamically varying loads is by many folds. With the new innovations in technology, power electronic converters are widely used for management of appliances which hampers the power quality at the load end. This necessities the utilities and the consumers to strive for good quality of power indeed by using power conditioner devices like SVC, DSTATCOM, etc., [1]-[7].Reactive power needs of the load, leads to poor voltage regulation and will enhances the losses within the system that necessities the whole power grid to be operated at higher MVA than as per load requirements. At the outset, Reactive power management at load end supports entire the system for power factor improvement , voltage regulation, harmonics and unbalance neutral current and which in turn minimises the losses in system. Reactive power management at the load end is governed by a promising shunt connected current controlled active custom power compensating device DSTATCOM [16], [25]-[27]. DSTATCOM (Distribution static compensator) consists of VSC, Interfacing inductor and DC bus capacitor, a series arrangement of resistor and a capacitor are used in parallel with the load at PCC is connected for removal of high frequency switching noise generated in the system by DTATCOM. As a result of several useful features, DSTATCOM has becomes a superior controller comparative to the line commutated static volt-ampere compensator (SVC). Various DSTATCOM control strategies have been reported in the literature towards VSC configurations, control algorithms and switching phenomena's like PWM, SVM and Hysteresis which are attributed to fast response, operational flexibility and dynamic characteristic behaviour.

The effectiveness of the DSTATCOM depends on the strategy employed for finding of reference signal [13], [24]. Various control schemes are proposed in the literature [3], [16]–[23]. PLL control strategies are applied under distorted utility and for as suggested in literature .In this methodology of EPLL based scheme of control algorithm is engaged for reference current extraction and for stabilisation of DC bus voltage near to the capacitor, Fuzzy logic controller is used and performance is evaluated over conventional PI controller and EPLL scheme involves in computation of synchronous phasor by phasor measurement and it is designed by using three components. They are phase detector for finding phase angles, loop filter for filtering harmonics, and a voltage controlled oscillator. It takes the input signal and derives corresponding fundamental signal, frequency difference in the signal, phase angle deviation, and other time derivatives by online assessment. Internal coefficients provided in EPLL scheme are valid for any precise application of specific range as proposed in literature [3], [21]. In this methodology, the control process for execution of enhanced phase-locked loop (EPLL) scheme is as shown in Figure 1 is realized for compensation of required reactive power, minimization of harmonics, compensation of load currents, PFC and ZVR operation modes of DSTATCOM and simulated using Simpowersystem tool block sets of MATLAB over diverse situation of source and load .The EPLL technique is employed as the elementary configuration for finding harmonics as well as inter harmonic assessment, the foremost advantages associated with the EPLL scheme are [3]

- It can be easily employable in practical applications with DSP and embedded controller is simple.
- Its response is very faster in disturbance conditions also and is very accurate, and its performance isn't unaltered because of noise and distortions in the input signals.
- It can be easily adaptable in nature and accepts the deviations in magnitude, phase angle difference and any frequency variations in the inputs.
- Its performance isn't affected due to the presence of double frequency current ripples in the control circuit.

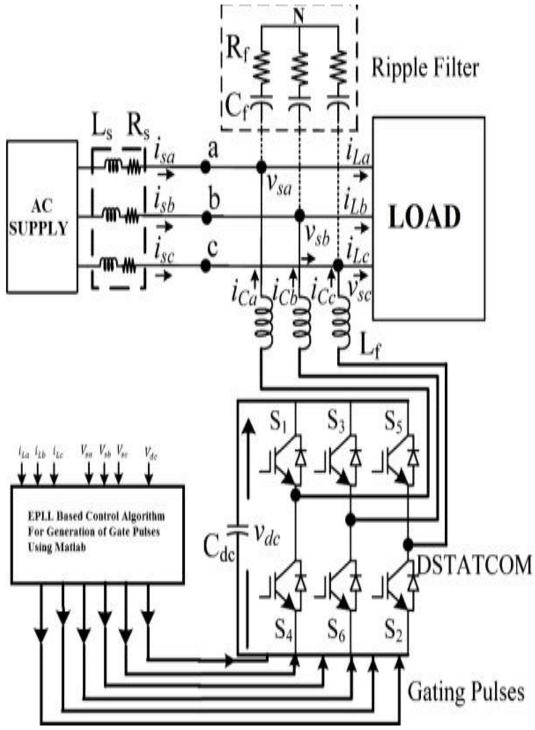


Figure 1.The schematic diagram for implementation of power module of distribution system with DSTATCOM in MATLAB.

II. FUZZY LOGIC CONTROLLER

PI controller based supervision is the most universally adopted controllers for industrial process applications and basically suited for the process with known and less parametric variations and provides satisfactory performance towards this end. As power utility system is highly complex, Non-linear and dynamic results in continuous variations in operating condition, as said PI controller will not give satisfactory operation for such variation, therefore Fuzzy controller have found to be a good alternative [14]-[17].

Figure 2 demonstrates the schematic block diagram for implementation of FLC. The operational mechanism involves in various stages as noticed from block diagram i.e., Identification of inputs for the process control, Fuzzification techniques, Rule base and finally Defuzzification techniques. The inputs given to FLC are Error in the DC bus voltage and it's Rate of change in error. Depending upon range of input values some linguistic values are defined to each input value. Since FLC doesn't understand the natural analogue values we need to convert these inputs into fuzzy values. The process of converting these input crisp values into some fuzzy values is called fuzzification process.

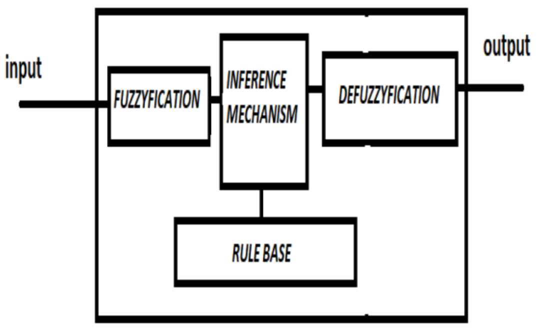


Figure 2. Schematic block diagram of Fuzzy Logic Controller

Development of fuzzy rules play a dynamic part in designing the fuzzy supervisor and relays on the human intelligence and expertise for stabilisation of voltage across the DC bus capacitor. Each input to the fuzzy interface mechanism is accounted with 7 membership functions. These membership functions will divide each input into several ranges based on its magnitude. Membership functions assigned with some linguistic values accounted for considered two inputs are Z- Zero; NL- Negative large; NM- Negative medium; NS- Negative small; PS- positive small; PM- Positive medium; PL- Positive large as respectively for each input. For two inputs we get atmost 7*7 = 49 rules as shown in Table 1. Hence, considering the information defined in the rule base, its rule and its sureness is evaluated by the fuzzy inference mechanism as given in the table. In the final stage again we need to convert the fuzzy values into crisp values to control the given system. The mechanism of converting the fuzzy values into normal crisp values is called the process of Defuzzification.

TABLE 1: FLC RULE - BASE

$\dot{e}(t)$ / $e(t)$	NL	NM	NS	Z	PS	PM	PL
PL	Z	PS	PM	PL	PL	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PS	NM	NS	Z	PS	PM	PL	PL
Z	NL	NM	NS	Z	PS	PM	PL
NS	NL	NL	NM	NS	Z	PS	PM
NM	NL	NL	NL	NM	NS	Z	PS
NL	NL	NL	NL	NL	NM	NS	Z

The most common Defuzzification technique used is Centre of Gravity method in which the output crisp value is based on the approximate weight of the fuzzy value. And the membership functions considered in this FLC are of triangular wave form type. Since FLC takes inputs in terms of lower magnitudes and it should give output in terms of higher magnitudes due to this reason we can use scaling factors at both input and output sides of the FLC.

III. DSTATCOM CONTROL ALGORITHM

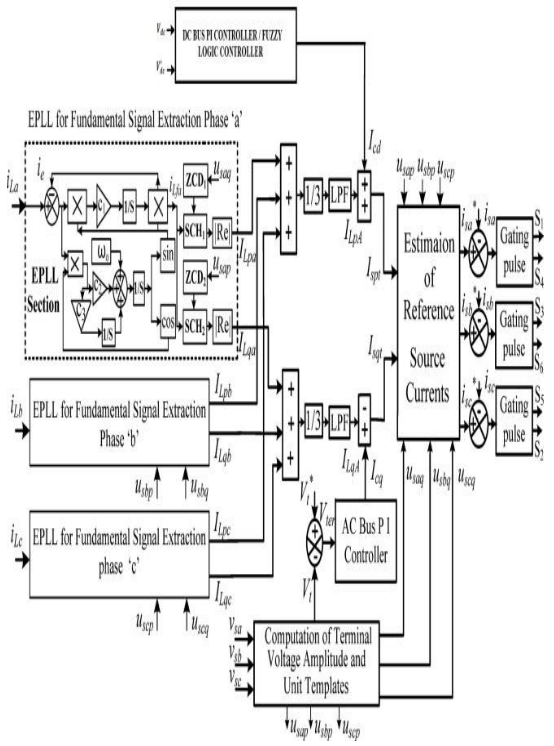


Figure 3. The schematic diagram for extraction of reference source currents and gate pulses by EPLL based control scheme for implementing in MATLAB for simulation study.

Figure 3 illustrates schematic block diagram for extracting accurate reference currents by EPLL based control scheme for execution in MATLAB simulink for simulation study. There are various stages of operation mechanism involved in the process of getting accurate output values to generate required gate pulses using this algorithm is described above.

Stage 1: In this stage the magnitude of In-phase voltage unit templates as well as Quadrature voltage unit templates are assessed by using the magnitudes of Sensed PCC voltages V_{sa}, V_{sb}, V_{sc}.These voltages are to be processed by passing them through BPF filters to remove the harmonics. In phase unit templates and quadrature unit templates are derived through the PCC voltage, which are useful in the process of generating reference currents.

The magnitude of in phase unit templates voltages at PCC voltages are calculated by below equations

$$U_{sap} = \frac{V_{sa}}{V_{ta}},\ U_{sbp} = \frac{V_{sb}}{V_{tb}},\text{and } U_{scp} = \frac{V_{sc}}{V_{tc}} \quad (1)$$

Where V_{ta}, $V_{tb}, V_{tc}$are the processed voltages of PCC voltages through LPF filters in order to eliminate any unbalance in the voltage.

The magnitude of quadrature unit templates are evaluated as shown by below equation

$$U_{saq} = \frac{(-U_{sbp}+U_{scp})}{\sqrt{3}},$$
$$U_{sbq} = \frac{(3U_{sap}+U_{sbp}-U_{scp})}{2\sqrt{3}},$$
$$U_{sbq} = \frac{(-3U_{sap}+U_{sbp}-U_{scp})}{2\sqrt{3}} \quad (2)$$

The magnitude of voltage at PCC is assessed as given by below equation

$$V_t' = \sqrt{\frac{2(V_{sa}^2+V_{sb}^2+V_{sc}^2)}{3}} \quad (3)$$

Stage 2: In this stage the fundamental components of active as well as reactive power load currents are assessed through EPLL algorithm for each phase. At this stage Enhanced Phase Locked Loop designed in the phase 'a' takes the input from the sensed load current i_{La} and the error between the currents i_{La} and i_{Lfa} becomes the total deviation (i_e) in the input signal. The fundamental load current component $i_{Lfa}$of phase 'a' is associated in phase with the load current i_{La} and is travels with some phase dissimilarity when compared to the reference in-phase unit template voltage (U_{sap}). Hence, for extracting the magnitude of i_{Lpa} is in phase with the corresponding input voltage at PCC, therefore by placing a zero crossing detector named as ZCD_1 is arranged at quadrature unit voltage template (U_{saq}) , and it is shifted from the in-phase unit template voltage U_{sap} by an angle of 90 degrees. The input to SHC1 block is taken from assessed fundamental load current and the output of Zero Crossing detector (O_{ZCD_1}) is given as triggering pulse to this block. The output given by the SHC block(O_{SHC_1}) is to be taken as magnitude of the fundamental active power load current component (I_{Lpa}) of respective phase 'a'. In same manner, the fundamental active power load current components of other two phases I_{Lpb}andI_{Lpc} will be extracted.

And now for assessment of fundamental reactive power load current component i_{La} of respective phase 'a', one more zero crossing detector ZCD_2 is to be placed at in-phase unit template voltage (U_{sap}) . The input to the second SHC block is taken from the signal i_{Lfa} and the output from second ZCD block (O_{ZCD_2}) is given as triggering pulse to this block. The output from second SHC block (O_{SHC_2}) is considered to be magnitude of the fundamental reactive power load current component $(I_{Lqa})$of respective phase 'a'. In the same way, the other two phases fundamental reactive power load current components denoted by $I_{Lqb}$and I_{Lqc} of 'b' and 'c' phases respectively are assessed.

Stage 3:In this stage average magnitude of both active and reactive power components fundamental load currents of all 3 phases are assessed through magnitudes of load current components of respective active and reactive powers are given by

$$I_{LpA} = \frac{I_{Lpa}+I_{Lpb}+I_{Lpc}}{3}$$

$$I_{LqA} = \frac{I_{Lqa}+I_{Lqb}+I_{Lqc}}{3} \quad (4)$$

Stage 4:In this stage the magnitude of active power component of reference source current is assessed by using both PI and fuzzy logic supervisor individually based on our requirement, here the reference dc link capacitor voltage is defined as a constant value as calculated from load ratings and is compared with detected dc link capacitor voltage magnitude of the DSTATCOM. The dc link voltage is controlled by using either PI controller or by fuzzy controller. And the output of these controllers is signified as I_{cd} . The addition of DC link capacitor's active power component current of the DSTATCOM and average value of the active power load current component will gives the required require source current and given by

$$I_{spt} = I_{cd}+I_{LpA} \quad (5)$$

Stage 5**:** In this stage the magnitude of reactive power reference source current components at PCC point is evaluated from an ac voltage PI controller across the PCC voltage $V_t$and the considered reference value of V_t^* . The difference between these voltages called as voltage error and is denoted as $V_{terr}$of the voltage at r^{th}sampling point and is given by

$$V_{terr}(r) = V_t^*(r) - V_t(r) \quad (6)$$

The resultant output value at PI controller is denoted by I_{cq} in order to control PCC voltage magnitude at r^{th} sample point is defined by

$$I_{cq}(r) = I_{cq}(r-1) + k_{pt}\{V_{ter}(r) - V_{ter}(r-1)\}V_t^*(r) + k_{it}V_{ter}(r) \quad (7)$$

The magnitude of reactive power reference source current component (I_{sqt}) can be calculated by finding the deviation in the output value of the PI controller(I_{cq}) and the average magnitude of reactive power load current components (I_{LqA}) and is given by

$$I_{sqt} = I_{cd}-I_{LqA} \quad (8)$$

Stage 6:In this stage the amplitude of 3-phase reference source currents of each phase is calculated by multiplying the evaluated value of reference source current with the magnitude of unit templates of their respective phases and is given by

$$i_{sap} = I_{spt}U_{sap}, i_{sbp} = I_{spt}U_{sbp},$$

$$i_{scp} = I_{spt}U_{scp} \quad (9)$$

$$i_{saq} = I_{sqt}U_{saq}, i_{sbq} = I_{sqt}U_{sbq},$$

$$i_{scq} = I_{sqt}U_{scq} \quad (10)$$

Then the total magnitude of reference source currents are evaluated by adding the active and reactive power source current components of each phase is given by

$$i_{sa}^* = i_{sap} + i_{saq}, i_{sb}^* = i_{sbp} + i_{sbq},$$

$$i_{sc}^* = i_{scp} + i_{scq} \quad (11)$$

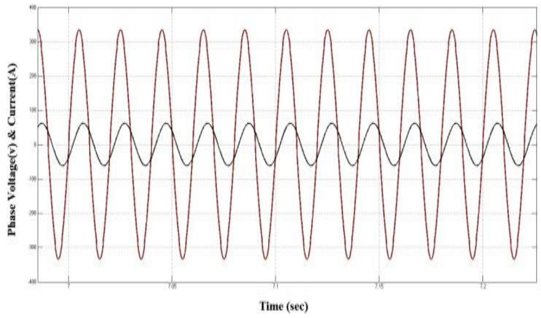
Hence, these calculated 3-phase reference source currents (i_{sa}^{*}, i_{sb}^{*}, i_{sc}^{*}) are related with noticedi_{sa}, i_{sb} ,i_{sc} to determine for any current deviations in the reference signals. These current errors are then amplified and outputs are compared with carrier signals using PWM technique to generate pulses to turn on IGBTs ($S_1$to S_6) used in the voltage source converters to inject required reactive power into the distribution system.

IV. RESULTS AND DISCUSSION

The Performance of Fuzzy logic based Single-phase EPLL algorithm for compensating Reactive power is compared with the PI controller performance is examined in this paper by using MATLAB simulation study with the data considered in Appendix. The results pertaining EPLL based DSTATCOM are described below for various loading conditions viz., Linear, Non-linear and Dynamic with PI controller and as well as FLC controller.

A. *Performance analysis of EPLL based DSATCOM for control of reactive power with PI and FLC for linear load*

Figure 4(a) show the load phase voltage and current relationship of a-phase and which clearly shows that they are out of phase, as a result source has to delivers active along with reactive power as needed by the load this is due to inductive requirements by the load and it can be noticed from Table 2 From Figure 4(b) we can observe that Source phase voltage and phase currents are become in phase this is because of compensation provided by the DSTATCOM, which concludes that source only delivers the active power required by the load and some active power losses in the system and the amount of reactive power required by the load is injected from the shunt connected DSTATCOM at the load end. From Figure 4(c) it can be noticed that the required reactive power of the load to certain extent has been supplied from the source with PI control strategy and the source is relived from reactive power requirements, which is clearly accessible through Figure 4(g) where with fuzzy the completely demanded reactive power was supplied from the source only. Figure 4(d) indicates that with PI the response of the system is slow in comparison with Fuzzy controller as noticed from Figure 4(h).Also from table 2. It is noticed clearly that the source current before compensation is 42.73A and after compensation it is found to be about 35.45A and with fuzzy 30.92A. Also reactive power required by the load 17690 VAR of which source delivers 18790 VAR without DSTATCOM and source delivers 2112 VAR after compensation with PI and 260.2 VAR with fuzzy controller. From results it is clearly understood that fuzzy based controller performance is satisfactory over PI controller.



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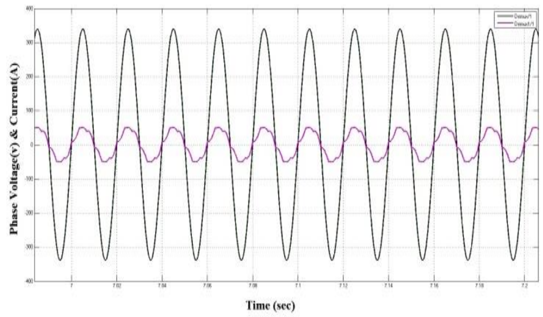

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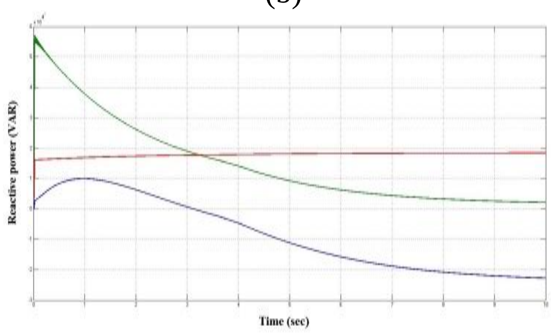

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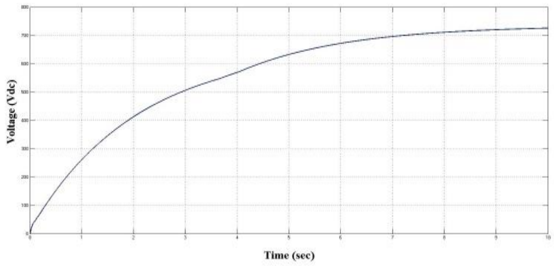

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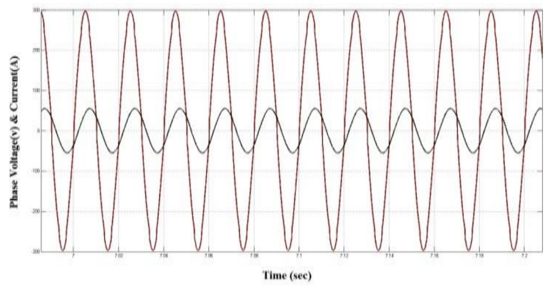

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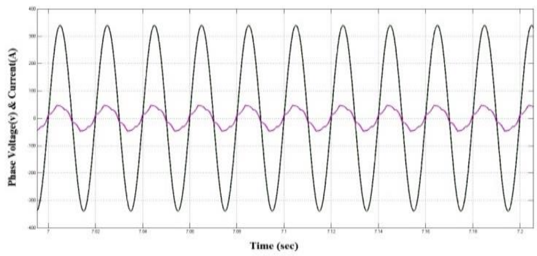

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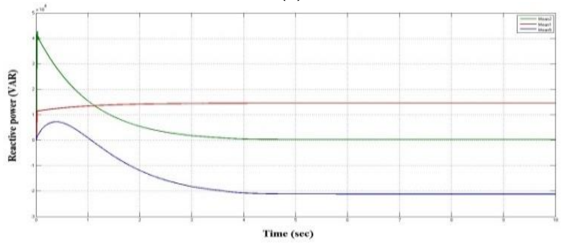

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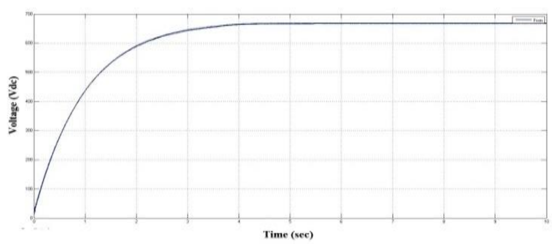
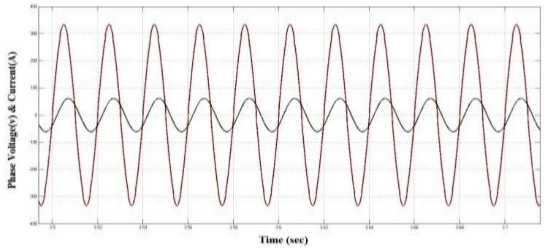


(h)

Figure 4.(a) Load Voltage and load Current signals with PI controller (b) Source Voltage and source Current waveforms with PI controller(c) Reactive Power delivered by The DSTATCOM with PI controller (d) DC Link Capacitor Voltage DSTATCOM with PI controller (e) Load Voltage and load Current waveforms with Fuzzy based controller (f) Source Voltage and source Current waveforms with Fuzzy based controller (g) Reactive Power delivered by The DSTATCOM with Fuzzy based controller (h) DC Link Capacitor Voltage DSTATCOM with Fuzzy based controller.

B. Performance analysis of EPLL based DSATCOM for control of reactive power with PI and FLC for Dynamic load

The following figures show the performance of DSTATCOM with a linear balanced, unbalanced and variable load condition. Figure 5(a) show the phase voltage and current relationship of load current of a-phase and which clearly shows that they are out of phase, as a result source has to along with reactive power as needed by the load this is due to inductive requirements by the load and it can be noticed from Table 2. From Figure 5(b) we can observe that Source phase voltage and phase currents are become in phase this is because of compensation provided by the DSTATCOM, which concludes that source only delivers the active power required by the load and some active power losses in the system and the amount of reactive power required by the load is injected from the shunt connected DSTATCOM at the load end .From Figure 5(c) it can be noticed that the required reactive power of the dynamically varying load has been supplied by the DSTATCOM while the reactive power supplied by the source is less and which is almost proportional to load variations. And the obtained results proves that the better response is observed through the proposed control algorithm under the condition of unbalanced as well as dynamically loaded condition and also Figure 5(d) we can notice that the PI controller works satisfactory but its response time is somewhat slower. From Table 2 At a particular instant of load It is noticed clearly that source current before compensation is found to be 42.89A and after compensation it is found to be about 35.47A and with fuzzy 30.94A.Also reactive power required by the load 17820 VAR of which source delivers 18930 VAR without DSTATCOM and source delivers 2386 VAR after compensation with PI and 307 VAR with fuzzy controller. From results it is clearly understood that fuzzy based controller performance is satisfactory over PI controller.



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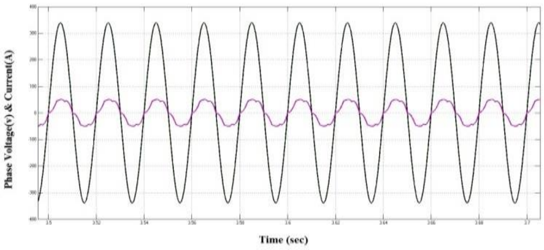

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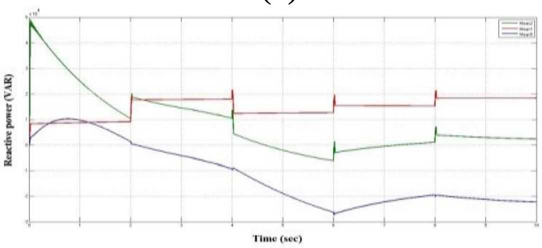

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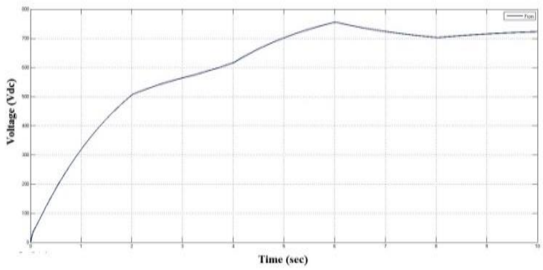

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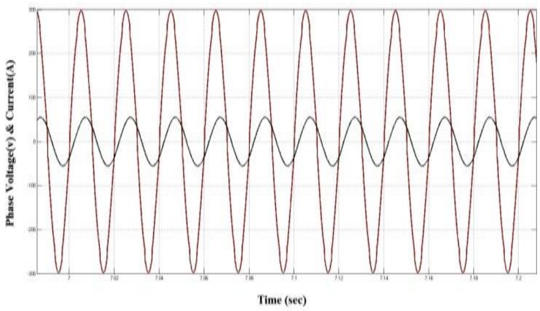

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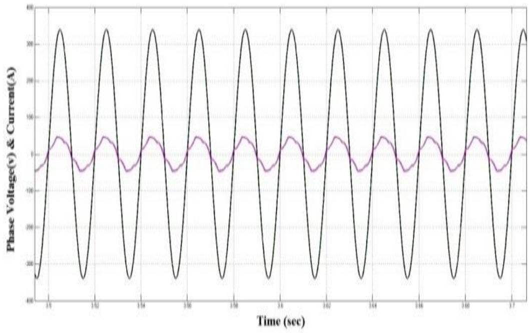

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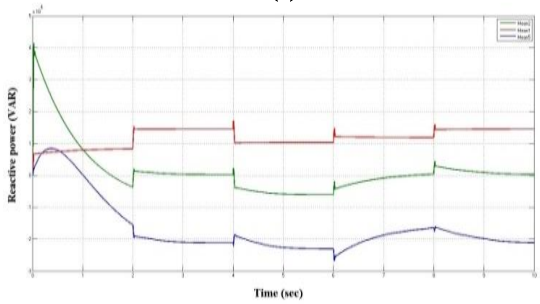

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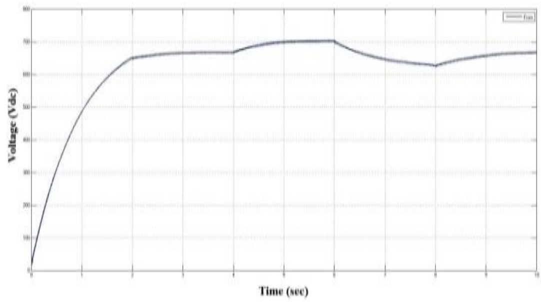

(h)

Figure 5.(a) Load Voltage and load Current waveforms with PI controller (b) Source Voltage and source Current waveforms with PI controller(c) Reactive Power delivered by The DSTATCOM with PI controller (d) DC Link Capacitor Voltage DSTATCOM with PI controller (e) Load Voltage and load Current waveforms with Fuzzy based controller (f) Source Voltage and source Current waveforms with Fuzzy based controller (g) Reactive Power delivered by The DSTATCOM with Fuzzy based controller (h) DC Link Capacitor Voltage DSTATCOM with Fuzzy based controller

TABLE 2: COMPARISON OF RESULTS USING PI AND FUZZY CONTROLLERS

Quantity	Linear load without dstatcom	Linear load with pi controller	Linear load with fuzzy controller	Variable load without dstatcom	Variable load with pi controller	Variable load with fuzzy controller
V_s in volts	239.6	239.6	239.6	239.6	239.6	239.6
I_s in amps	42.73	35.45	30.92	42.89	35.47	30.94
P_s in watts	24287	25246	22351	24323	25241	22361
Q_s in vars	18790	2112	260.2	18930	2386	307
V_L in volts	230.5	235.5	208.8	230.9	235.4	208.7
I_L in amps	42.73	43.59	38.78	42.89	43.58	38.78
P_L in watts	23730	24695	19400	23771	24679	19394
Q_L in vars	17690	18410	14540	17820	18390	14540
V_I in volts	--	327.3	300.9	--	325.7	300.6
I_I in amps	--	23.85	23.94	--	23.45	23.86
P_I in watts	--	158.02	15.10	--	168.00	28.77
Q_I in vars	--	-16740	-14910	--	-16450	-14860

From the above results, for diverse circumstances of loading one can notice the satisfactory response of the proposed Fuzzy control based single-Phase EPLL based control algorithm for controlling reactive power is working satisfactorily and its response time is somewhat faster than the conventional PI controller.

CONCLUSION

The performance of DSTATCOM with Fuzzy controlled single-Phase enhanced phase-locked loop has been implemented using Simulink block sets of MATLAB for reactive power compensation under different circumstance of loading. From results it can be concluded that the response of Fuzzy controller over PI controller in terms of compensation is found to be satisfactory, where source delivers only the required active power and the reactive power delivered by source is almost negligible and required reactive power is only supplied from the DSTATCOM . THD in the source current with fuzzy controller is found to be more satisfactorily over conventional controllers and they are within the standard. The DC bus capacitor voltage of the DSTATCOM is also controlled without creating any overshoot to get desired value during dynamic loading condition.

APPENDIX

Grid voltage (line to line) &grid frequency	415V and 50Hz respectively
Source Impendence	R_s=0.1Ω, L_s= 0.64mH
Interfacing Inductor	12.25mH
Ripple Filter	10Ω, 5.5μF
DC-Link capacitor	10000μF
K_p & K_i	30 & 40
Load	25600W,19200VAR

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