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Design of external inductor for improving performance of voltage controlled DSTATCOM using fuzzy logic controller

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Abstract

Distribution compensator (DSTATCOM) is utilized for load voltage control and its execution essentially relies on the feeder impedance and its tendency (resistive, inductive, stiff, non-stiff). Be that as it may, a review for examining voltage regulation execution of DSTATCOM relying on system parameters is not all around characterized. This paper expects to give a exhaustive investigation of design, operation, and adaptable control of a DSTATCOM working in voltage control mode. A point by point investigation of the voltage direction capacity of DSTATCOM under different feeder impedances is exhibited. At that point, a benchmark design methodology to figure the estimation of external inductor using fuzzy logic controller is exhibited. A dynamic reference regulation voltage era plot is additionally created which enables DSTATCOM to adjust load reactive power amid typical operation, notwithstanding giving voltage bolster amid unsettling influences.

Keywords: Distribution static compensator (DSTATCOM), current control, voltage control, power factor, power quality

INTRODUCTION

Faults in far reaching power system and also exchanging of vast burdens make voltage unsettling influences, for example, hang and swell in a conveyance system [1]. This power quality (PQ) issues altogether debase the execution of sensitive loads

like process-control industry, devices types of equipment, customizable drives, and so on. Traditionally, static var compensator (SVC) is utilized to manage Voltage regulation, compensation reactive current, and make strides transient solidness. Be that as it may, the SVC causes issues like harmonic current infusion in the system, harmonic enhancement, also, conceivable reverberation with the source impedance [2]. Appropriation static compensator (DSTATCOM) has been proposed to beat the constraints of SVC [3]–[9]. A DSTATCOM is a standout amongst the best answers for control the loadl voltage. It gives regulation voltage direction by providing major reactive current into source [5], [10]–[15]. In any case, the vast majority of the regular DSTATCOMs utilized for voltage direction consider exceedingly inductive and additionally altogether vast feeder impedance [11], [13]. This is generally not valid in a dispersion system where feeder impedance used to be resistive in nature. In this situation, the DSTATCOM will have little voltage direction capacity
critical issue is the era of reference load voltage. In customary DSTATCOM application for voltage direction, reference regulation voltage is set at 1.0 p.u. [13]. At this load voltage, VSI dependably trades receptive power with the source with driving force calculate. This causes constant power misfortunes in the feeder and VSI. Likewise, an ordinary DSTATCOM requires high current rating voltage source inverter (VSI) to give voltage bolster [11]. This high current prerequisite builds the power rating of the VSI and delivers more misfortunes in the switches and in addition in the feeder.

The voltage control execution of DSTATCOM basically relies on the feeder impedance and its tendency (resistive, inductive, stiff, non-stiff). For voltage control mode (VCM) operation of DSTATCOM as well as matrix associated inverters, the thought of embeddings an external inductor in line has been accounted. Be that as it may, in these plans, just the idea has been presented leaving adequate degree for further examination what's more, understanding into the plan points of interest.

II. DSTATCOM IN POWER DISTRIBUTION SYSTEM

Fig. 1 shows power circuit diagram of the DSTATCOM topology associated in distribution system. Ls and Rs are source inductance and resistance, individually. An external inductance, Lext is incorporated into arrangement amongst load and source focuses. This inductor causes DSTATCOM to accomplish regulation voltage direction capacity even in most exceedingly bad system conditions, i.e., resistive or hardened matrix. From IEEE-519 standard, point of regular coupling (PCC) ought to be the point which is available to both the utility and the client for direct estimation. Consequently, the PCC is the point where Lext is associated with the source. The DSTATCOM is associated at the point where load and Lext are associated. The DSTATCOM utilizes a three-stage four-wire VSI. An inactive LC channel is associated in each eliminate to channel high recurrence exchanging segments. Voltages crosswise over dc capacitors, Vdc1 and Vdc2, are kept up at a reference estimation of Vdcref .

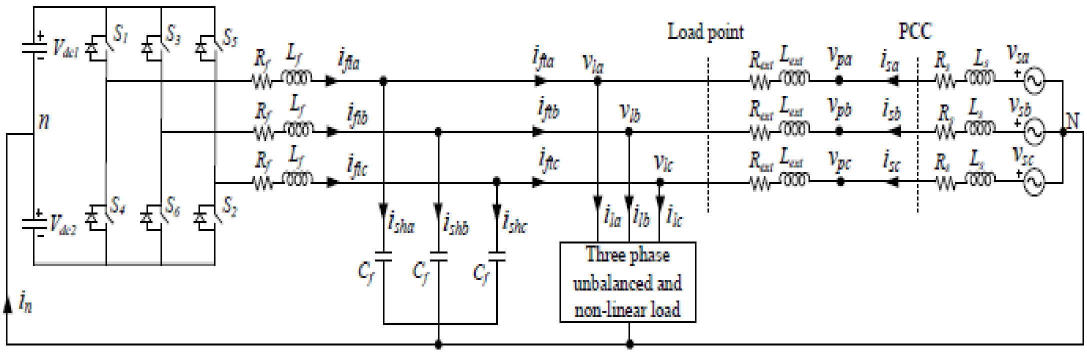


Fig. 1. Three phase equivalent circuit of DSTATCOM topology in distribution system

III. EFFECT OF FEEDER IMPEDANCE ON VOLTAGE REGULATION

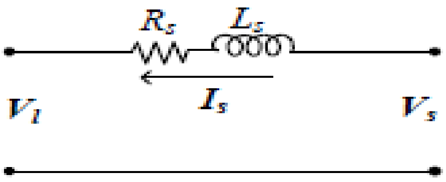


Fig.2. Equivalent source-load model without considering external inductor

To show the impact of feeder impedance on voltage control execution, a proportionate source-regulation show without considering external inductor is appeared in Fig. 2. The current in the circuit is given as

$$I_s = \frac{V_s - V_l}{Z_s} \qquad (1)$$

where $\boldsymbol{V}_s = V_s\angle\delta$, $\boldsymbol{V}_l = V_l\angle 0$, $\boldsymbol{I}_s = I_s\angle\phi$, and $\boldsymbol{Z}_s = Z_s\angle\theta_s$, with V_s, V_l, I_s, Z_s, δ, ϕ, and θ_s

are rms source voltage, rms load voltage, rms source current, feeder impedance, load angle, power factor angle, and feeder impedance angle, respectively. The three phase average load power (Pl) is expressed as

Pl = Real [3V l _ Is_] : (2)

Substituting V l and Is in (2), the load active power is

$$P_l = \frac{3\,V_l^2}{Z_s}\left[\frac{V_s}{V_l}\cos(\theta_s-\delta)-\cos\,\theta_s\right]. \qquad (3)$$

Rearranging (3), expression for δ is computed as follows:

$$\delta = \theta_s - \cos^{-1}\left[\frac{V_l}{V_s}\left(\cos\,\theta_s + \frac{P_l Z_s}{3\,V_l^2}\right)\right]. \qquad (4)$$

For power exchange from source to load with stable operation in an inductive feeder, additionally, every one of the terms of the second piece of (4), i.e., inside cos□1, are amplitude and will positive. Along these lines, estimation of the second part will be between '0' to '$\pi/2$' " for the whole operation of the loadl. Therefore, the loadl point will lie between θ_s to (θ_s - $\pi/2$) under any loadl operation, and in this manner, greatest conceivable load point is s. The vector expression for source voltage is given as takes after

$$\boldsymbol{V_s} = V_l + I_s Z_s \angle(\theta_s+\phi)\,. \qquad (5)$$

A DSTATCOM directs the loadl voltage by infusing central reactive current. To exhibit the DSTATCOM voltage direction capacity at various supply voltages for diverse Rs=Xs, vector design utilizing (5) are attracted Fig. 3. To draw graphs, voltage regulation Vl is taken as reference phasor having the ostensible esteem OA (1.0 p.u.). With point of making Vl = Vs = 1.0 p .u., locus of Vs will be a half circle of range Vl. Since, the greatest conceivable load edge is 90 in an inductive feeder, phasor Vs can be anyplace inside bend OACBO. It can be seen that the estimation of $\theta_s+\phi$ must be more prominent than 90 for zero voltage control. Furthermore, it is conceivable just when power element is driving at the loadl terminal as s can't be more than 90 Fig. 3(a) demonstrates the restricting situation when R_s/X_s = 1, i.e., θ_s = 45_. From (4), the maximum possible load angle is 45_. The maximum value of angle, $\theta_s+\phi$, , can be $135°$ when is $90°$. . Hence, the limiting source current phasor OE, which is denoted by Is limit, will lead the load voltage by $90°$. Lines OC and AB demonstrate the constraining vectors of Vs and IsZs, separately with D as the crossing point. Subsequently, range under ACDA demonstrates the working district of DSTATCOM for voltage control. The point D has a constraining estimation of Vs limit = Is Zs = 0.706 p .u. In this way, greatest conceivable voltage control is 29.4%. Nonetheless, it is difficult to accomplish these two breaking points all the while as and - can't be most extreme at a similar time. Again if Zs is low at that point source current, which will be practically inductive, will be sufficient to be acknowledged by a DSTATCOM.

Fig. 3(b) considers situation when Rs=Xs = p 3 i.e., s = 30The region under ACDA recoils, which demonstrates that with the expansion in Rs=Xs from the restricting quality, the voltage direction ability diminishes. For this situation the constraining esteems of Vs limit and Is Zs are observed to be 0.866 and 0.5 p.u., separately. Here, greatest conceivable voltage direction is 13.4%. Nonetheless, because of high current prerequisite, a reasonable DSTATCOM can give little voltage control. Voltage control execution bends for more resistive matrix, i.e., s = 15 as appeared in Fig. 3(c), can be drawn likewise. Here, range under ACDA is immaterial. For this case, barely any voltage direction is conceivable. In this manner, more the feeder is resistive in nature, lesser will be the voltage direction ability. Consequently, it is gathered that the voltage direction capacity of DSTATCOM in a circulation system for the most part relies on the feeder impedance. Because of resistive nature of feeder in a Distribution system, DSTATCOM voltage regulation ability is restricted. In addition, high current is required to alleviate little voltage unsettling influences which brings about higher rating of IGBT switches and also expanded misfortunes. One more point worth to be noted is that, in the resistive feeder, there will be some voltage drop in the line at ostensible source voltage which the DSTATCOM may not be capable compensate to look after load voltage at 1.0 p.u. indeed, even with a perfect VSI..

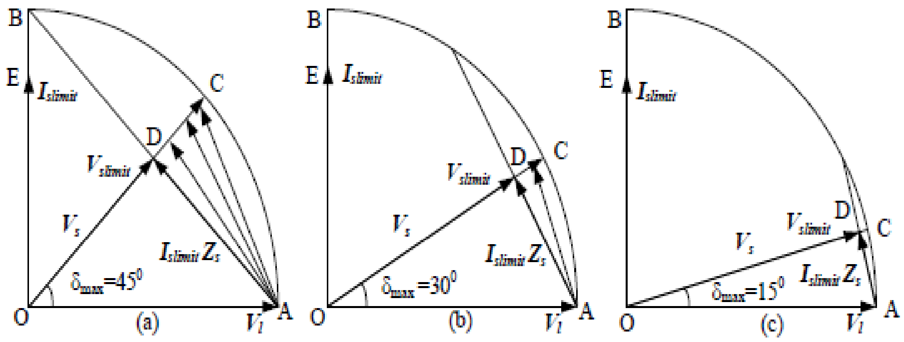


Fig. 3. Voltage regulation performance curve of DSTATCOM at different Rs=Xs. (a) For Rs=Xs = 1. (b) For Rs=Xs =p3. (c) For Rs=Xs= 3.73

IV. SELECTION OF EXTERNAL INDUCTOR FOR VOLTAGE REGULATION IMPROVEMENT AND RATING REDUCTION

This segment exhibits a summed up system to choose External inductor for development in DSTATCOM voltage control ability while lessening the present rating of VSI. Fig. 4 indicates single stage comparable DSTATCOM circuit design in distribution system. With adjusted voltages, source current will be

$$\boldsymbol{I}_s = \frac{V_s\angle\delta - V_l\angle 0}{(R_s + R_{ext}) + j\,(X_s + X_{ext})} = \frac{V_s\angle\delta - V_l\angle 0}{R_{sef} + jX_{sef}} \quad (6)$$

where $R_{sef} = R_s + R_{ext}$ and $X_{sef} = X_s + X_{ext}$ are effective

feeder resistance and reactance, respectively. Rext is equivalent series resistance (ESR) of external inductor, and will be small. With $\theta_{sef} = \tan^{-1}\frac{X_{sef}}{R_{sef}}$ and $Z_{sef} = \sqrt{R_{sef}^2 + X_{sef}^2}$ as effective impedance angle and effective feeder impedance, respectively, the imaginary component of Is is given as effective impedance angle and effective feeder impedance, respectively,

the imaginary component of Is is given as

$$I_s^{im} = \frac{V_l \sin\theta_{sef} + V_s \sin(\delta - \theta_{sef})}{Z_{sef}}. \qquad (7)$$

With the addition of external impedance, the effective feeder impedance becomes predominantly inductive. Hence, Zsef _ Xsef . Therefore, approximated Iims will be

$$I_s^{im} = \frac{V_l \sin\theta_{sef} + V_s \sin(\delta - \theta_{sef})}{X_{sef}}. \qquad (8)$$

DSTATCOM Power rating (Svsi) is given as follows [21]:

$$S_{vsi} = \sqrt{3}\,\frac{V_{dc}}{\sqrt{2}}\,I_{vsi} \qquad (9)$$

This area exhibits a summed up methodology to choose External inductor for development in DSTATCOM voltage direction ability while lessening the present rating of VSI. Fig. 4 demonstrates single stage comparable DSTATCOM circuit graph in circulation system. With adjusted voltages, source current will be

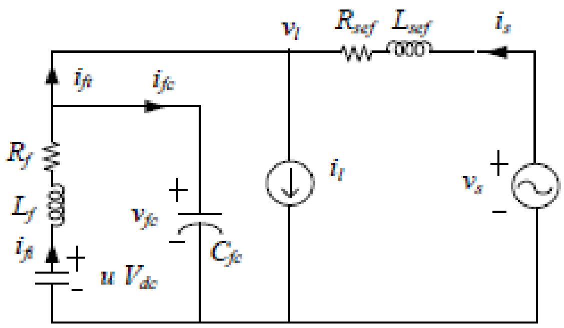


Fig.4. Single phase equivalent circuit of DSTATCOM topology with external inductor in distribution system. Compensator current used for voltage regulation (same as Iims) is obtained by subtracting Iim l from Ivsi and given as follows

$$I = I_{vsi} - I_l^{im} = \frac{\sqrt{2}S_{vsi}}{\sqrt{3}V_{dc}} - I_l^{im}. \qquad (10)$$

Comparing (8) and (10) while using value of _ from (4), following expression is obtained

$$X_{sef} = \frac{V_l \sin\theta_{sef} - V_s \sin\left[\cos^{-1}\left[\frac{V_l}{V_s}\left(\cos\,\theta_{sef} + \frac{P_l X_{sef}}{3\,V_l^2}\right)\right]\right]}{\frac{\sqrt{2}S_{vsi}}{\sqrt{3}V_{dc}} - I_l^{im}} \qquad (11)$$

The above expression is utilized to process the estimation of external inductor. Plan case of external inductor, utilized for this work, is given in next area

V. FLEXIBLE CONTROL STRATEGY

This areas shows an adaptable control technique to move forward the execution of DSTATCOM in nearness of the external inductor Lext. Right off the bat, a dynamic reference voltage regulation based on the planned control of theload basic current, PCC voltage, and voltage over the external inductor is figured. At that point, a corresponding necessary (PI) controller is utilized
to control the heap point which helps in managing the dc bus voltage at a reference esteem. At last, three stage reference voltages regulation are created. The square graph of the control procedure is appeared in Fig. 5.

A. Derivation of Dynamic Reference Voltage Magnitude (Vl^*)

In traditional VCM operation of DSTATCOM, the reference Voltage regulation is kept up at a consistent estimation of 1.0 p.u. [10]–[12]. Source currents can't be controlled in this reference era plot. Along these lines, control element will not be solidarity and source trades reactive power with the system even at ostensible supply. To beat this constraint, an adaptable control procedure is created to produce reference load voltage. This scheme allows DSTATCOM to set different reference voltages during various operating conditions. The scheme is described in the following

1). Normal Operation: It is characterized as the condition when Voltage regulation lies between 0.9 to 1.1 p.u. For this situation, the proposed adaptable control technique controls voltages regulation such that the source currents are adjusted sinusoidal and VSI does not trade any reactive power with the source. Subsequently, the source supplies just major positive succession current segment to bolster the normal load power and VSI misfortunes. Reference current source (isj where j = a; b; c are three stages), registered utilizing momentary symmetrical segment hypothesis, are given as

$$i_{sj}^{*} = \frac{v_{pj1}^{+}}{\Delta_1^{+}}(P_l + P_{loss}) \qquad (12)$$

where $\Delta_1^+ = \sum_{j=a,b,c}(v_{pj1}^+)^2$. The voltages v_{pa1}^+, v_{pb1}^+,
pc1 are fundamental positive sequence components of PCC voltages. Average load power (Pl) and VSI losses (P loss) are calculated using moving average filter (MAF) as follows:

$$P_l = \frac{1}{T}\int_{t_1-T}^{t_1}(v_{la}i_{la} + v_{lb}i_{lb} + v_{lc}i_{lc})\ dt \qquad (13)$$

$$P_{loss} = \frac{1}{T}\int_{t_1-T}^{t_1}(v_{la}i_{fta} + v_{lb}i_{ftb} + v_{lc}i_{ftc})\ dt. \qquad (14)$$

The reference source currents must be in phase with the respective phase fundamental positive sequence PCC voltages for achieving UPF at the PCC. Instantaneous PCC voltage and reference source current in phase-a can be defined as follows:

$$v_{pa1}^{+} = \sqrt{2}V_{pa1}^{+}\sin(\omega t - \varphi_{pa1}^{+}),\ i_{sa}^{*} = \sqrt{2}I_{sa}^{*}\sin(\omega t - \varphi_{pa1}^{+}) \quad (15)$$

where V + pa1 and '+ pa1 are rms voltage and angle of fundamental positive sequence voltage in phase-a, respectively. I_sa is the rms reference source current obtained from (12). With external impedance, the expected load voltage is given as follows:

$$\boldsymbol{V}_{la} = \boldsymbol{V}_{pa1}^{+} - \boldsymbol{I}_{sa}^{*} Z_{ext}. \qquad (16)$$

From (15) and (16), the load voltage magnitude will

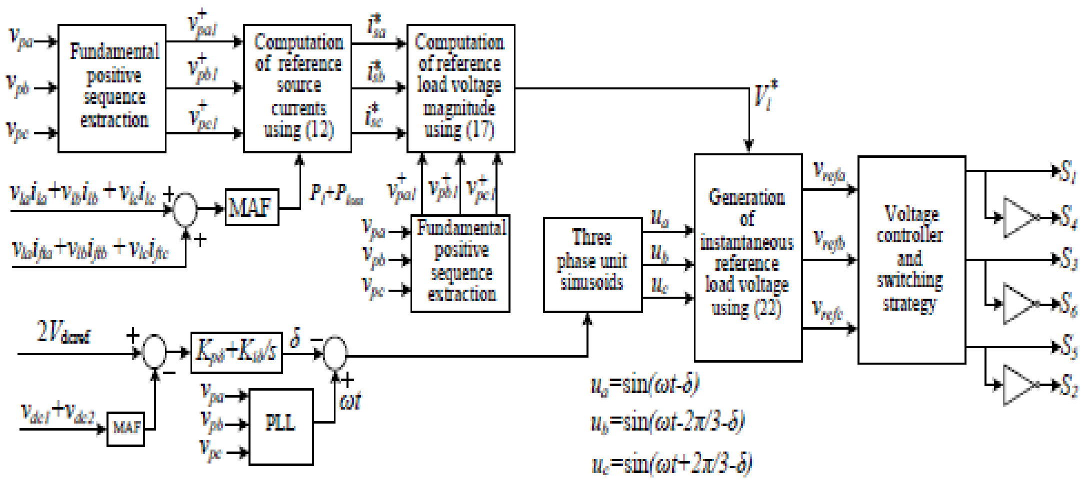


Fig.5. Block diagram of proposed flexible control strategy

$$V_{la} = \sqrt{\left[\left(V_{pa1}^{+}\cos\varphi_{pa1}^{+} - I_{sa}^{*} Z_{ext}\cos\left(\theta_{ext} - \varphi_{pa1}^{+}\right)\right)^{2} + \left(V_{pa1}^{+}\sin\varphi_{pa1}^{+} - I_{sa}^{*} Z_{ext}\sin\left(\theta_{ext} - \varphi_{pa1}^{+}\right)\right)^{2}\right]}\,. \quad (17)$$

be with UPF at the PCC, the voltage over the external inductor will lead the PCC voltage by 9. Ignoring ESR of external inductor, it can be watched that the voltage over External inductor enhances the load voltage contrasted with the PCC voltage. This highlights another favorable position of external inductor where it helps in enhancing the load voltage. As long as Vla lies between 0.9 to 1.1 p.u., same voltage is utilized as reference terminal voltage (V l), i.e.,

$$\text{if } V_{la} \in [0.9 - 1.1 \text{ p.u.}],\ \text{then } V_l^{*} = V_{la}. \qquad (18)$$

2) Operation During Sag: Voltage sag is considered when value of (17) is less than 0.9 p.u. To keep filter current minimum, the reference voltage is set to 0.9 p.u. Therefore,

$$Vl^* = 0{:}9 \text{ p.u:} \qquad (19)$$

3) Operation During Swell: A voltage swell is considered when any of the PCC phase voltage exceeds 1.1 p.u. In this
case, reference load voltage (V _l) is set to 1.1 p.u. which results in minimum current injection. Therefore,

$$V\_l = 1{:}1 \text{ p.u:} \qquad (20)$$

B. Calculation of Load Angle ((δ)) Normal real power at the PCC (Ppcc) is total of normal load power (Pl) and VSI misfortunes (Ploss). The real power Ppcc is taken from the source contingent on the point between source and load voltages, i.e., load point In the event that DSTATCOM dc bus capacitor voltage is directed to a reference esteem, at that point in consistent state condition P loss is a steady esteem and structures a small amount of P pcc. Thus, is likewise a steady esteem. The dc connect voltage is directed by producing a reasonable estimation of The normal voltage crosswise over dc capacitors (Vdc1 + Vdc2) is contrasted and a reference voltage and blunder is passed through a PI controller. Yield of PI controller, , is given as

$$\delta = K_{p\delta}\, e_{vdc} + K_{i\delta} \int e_{vdc}\, dt \qquad (21)$$

where $e_{vdc} = 2\,V_{dcref} - (V_{dc1} + V_{dc2})$ is the voltage error. Kp and Ki are relative and vital additions, individually.

C. Generation of Instantaneous Reference Voltage Choosing appropriate reference regulation voltage magnitude and processing load point from (21), the three stage adjusted sinusoidal reference load voltages are given as takes after:

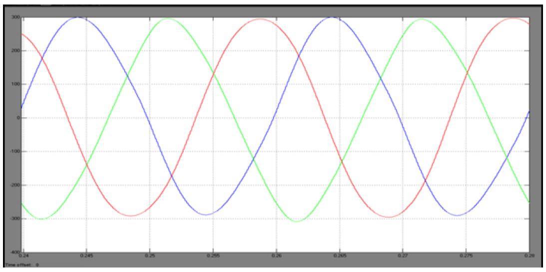
$$\begin{aligned} v_{refa} &= \sqrt{2}V_l^* \sin(\omega t - \delta) \\ v_{refb} &= \sqrt{2}V_l^* \sin(\omega t - 2\pi/3 - \delta) \\ v_{refc} &= \sqrt{2}V_l^* \sin(\omega t + 2\pi/3 - \delta). \end{aligned} \qquad (22)$$

These voltages are realized by the VSI using a predictive voltage controller.

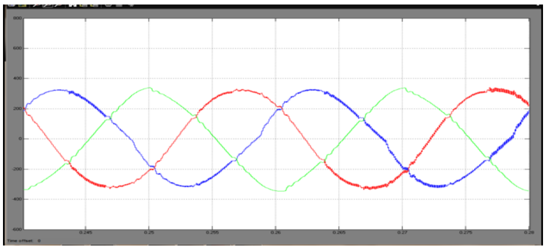
VI. SIMULATION RESULTS

1. Simulation results using conventional DSTATCOM

DSTATCOM is operated in conventional VCM, i.e., 1) without external inductor and 2) with a reference voltage of 1.0 p.u. or 230 V rms. The steady state waveforms of three phase PCC voltages, load voltages, source currents, filter currents, and load currents are shown in Figs. 6(a)-(e)



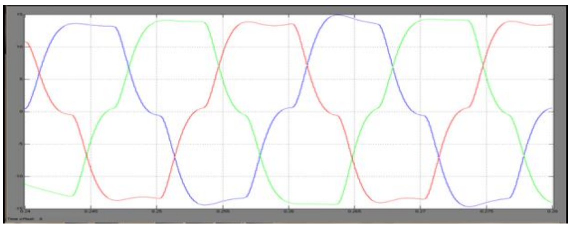
a. Load voltage



b. PCC voltage

c. Source current

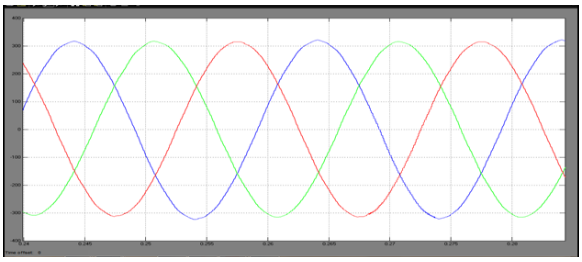
d. Filter current



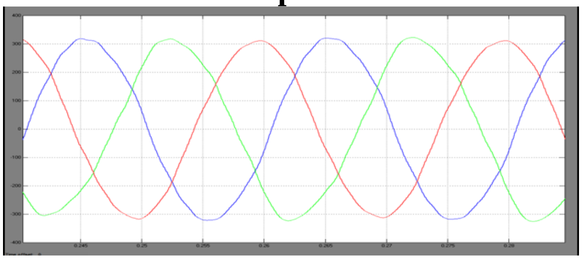
e. Load current

Fig.6. Voltage regulation performance of conventional DSTATCOM with resistive feeder.

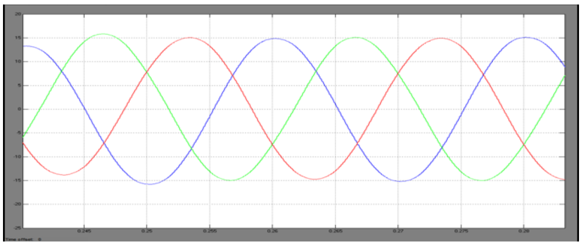
2. Simulation results using external inductor
(a) During normal operation



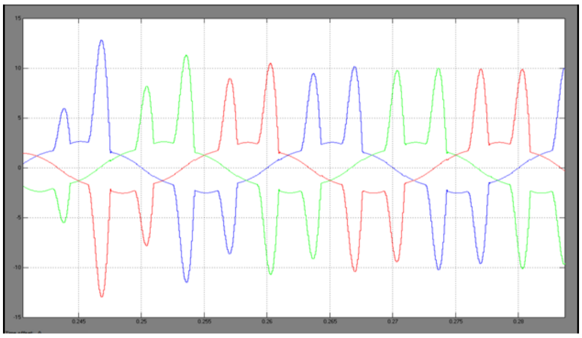
Vpcc



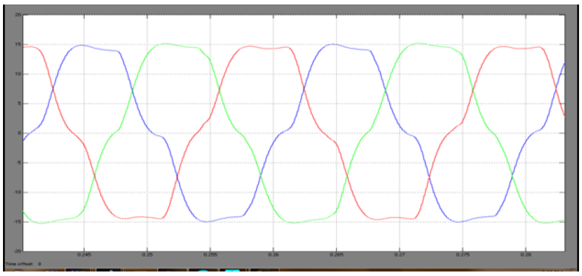
Load voltage



Source current

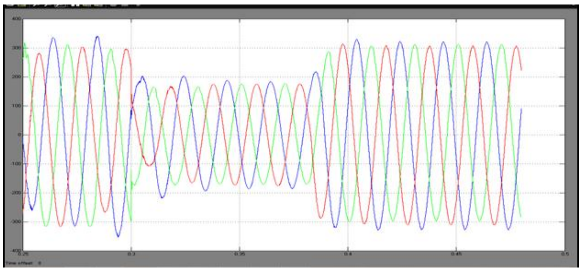


Filter current

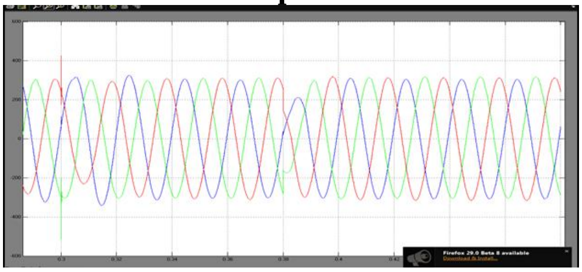


Load currents

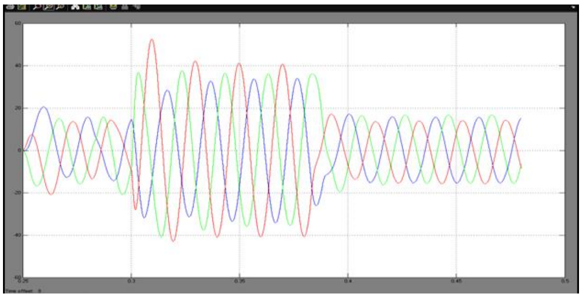
(b) During voltage sag



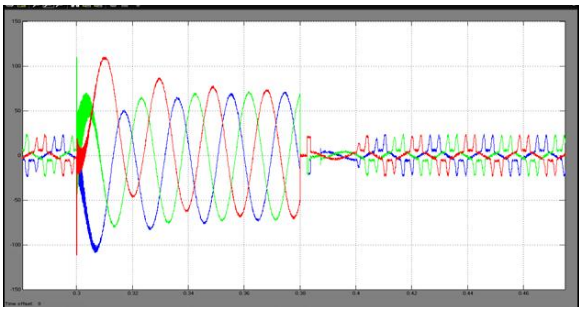
Vpcc



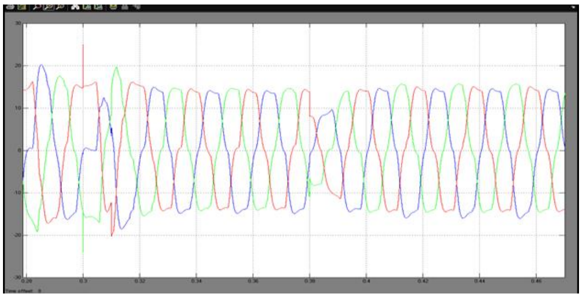
Load voltage



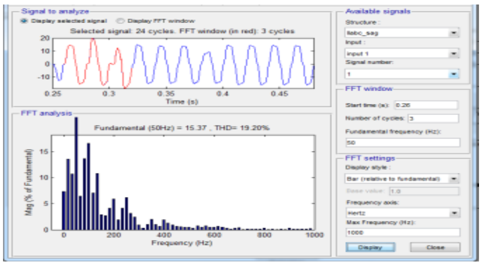
Source current



Filter current



Load currents



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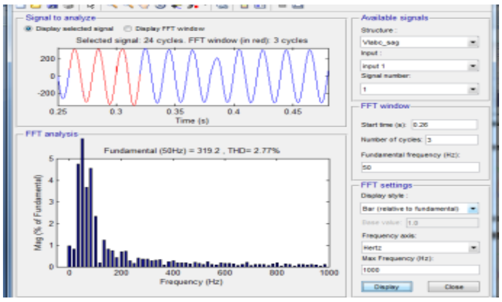
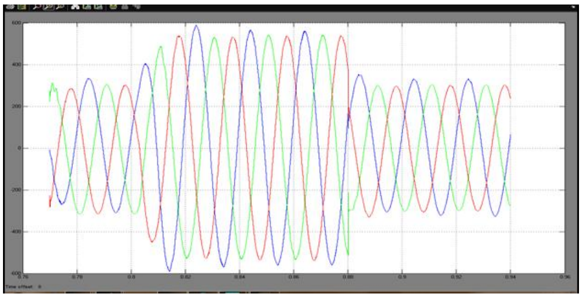
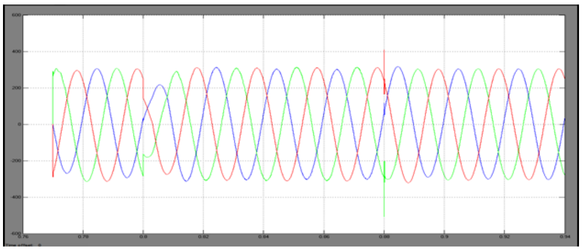


Load voltage

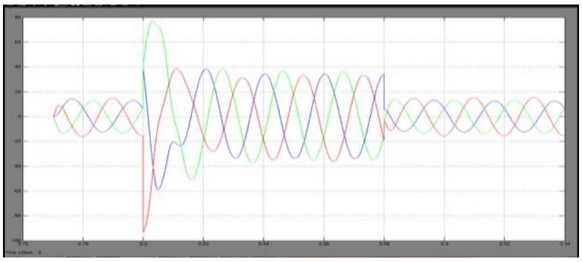
(c) During voltage swell



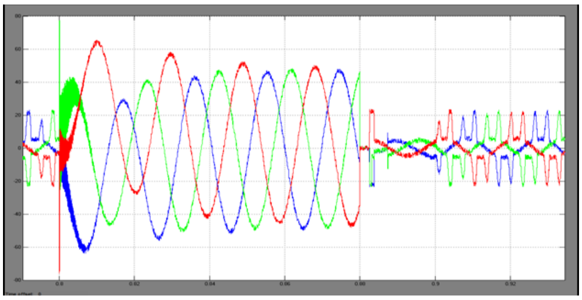
Vpcc



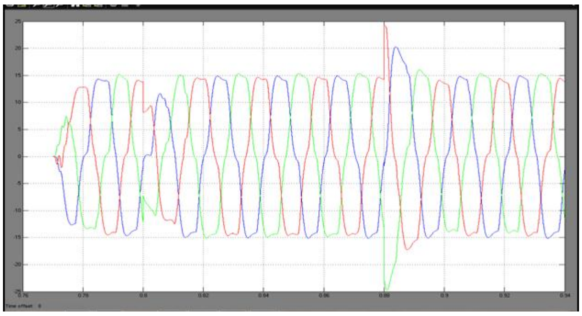
Load voltage



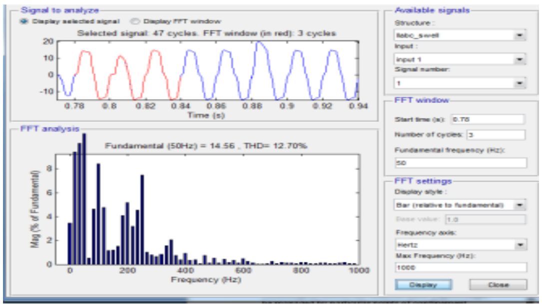
Source current



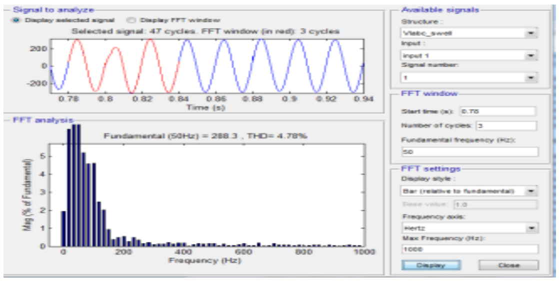
Filter current



Load currents



Load current



Load voltage

Fuzzy logic Controller

Fuzzy technique for thinking is a kind of different respected avocation in which reality estimations of factors might be any true blue number some place around 0 and 1. By partition, in Boolean strategy for thinking, reality estimations of factors may just be 0 or 1. Fuzzy technique for thinking has been reached out to handle the likelihood of halfway truth, where reality quality may extend between completely certifiable and totally false. Moreover, when etymological factors are utilized, these degrees might be managed by particular points of confinement.
Routinely Fuzzy technique for thinking control structure is delivered utilizing four immense sections showed on Figure fuzzification interface, Fuzzy insincerity motor,

cushy standard system and Defuzzification interface. Every part near to foremost Fuzzy strategy for thinking operations will be depicted in more detail below.
The Fuzzy technique for thinking examination and control approachs appeared in Figure 1 can be depicted as:

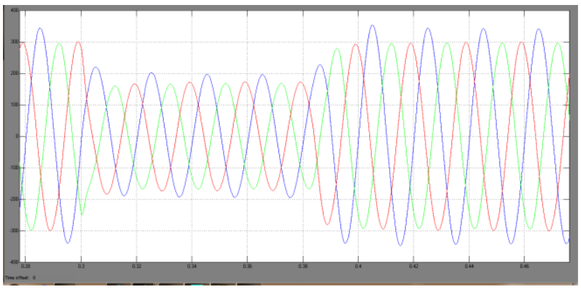
1. Receiving one or sweeping number of estimations or other assessment of conditions existing in some system that will be investigated or controlled.
2. Processing all got contributions as appeared by human based, Fuzzy "expecting then" models, which can be granted in fundamental dialect words, and joined with normal non-Fuzzy arranging.
3. Averaging and weighting the outcomes from all the individual norms into one single yield choice or sign which picks what to do or urges a controlled system what to do. The outcome yield sign is an exact defuzzified respect. Most importantly else, the unmistakable level of yield (fast, low speed et cetera.) of the stage is described by deciding the cooperation capacities with respect to the fuzzy sets.

Fuzzy Logic System

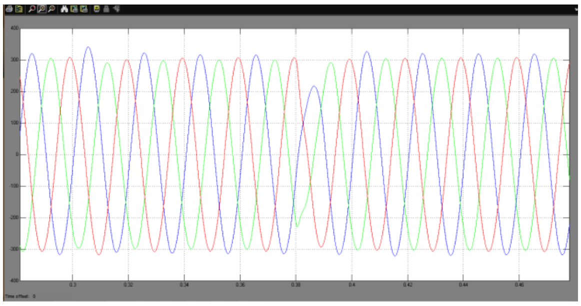
Today control systems are normally portrayed by numerical models that take after the laws of material science, stochastic models or models which have risen up out of scientific rationale. A general trouble of such built model is the manner by which to move from an offered issue to an appropriate numerical model. Without a doubt, today's propelled PC innovation makes it conceivable; however overseeing such systems is still excessively perplexing. These perplexing systems can be rearranged by utilizing a resilience edge for a sensible measure of imprecision, dubiousness and instability amid the demonstrating stage. As a result, not totally consummate system comes to presence; by and by in the greater part of the cases it is equipped for taking care of the issue in proper way. Notwithstanding missing information data has officially ended up being agreeable in learning based systems.

3. SIMULATION RESULTS USING FUZZY LOGIC CONTROLLER

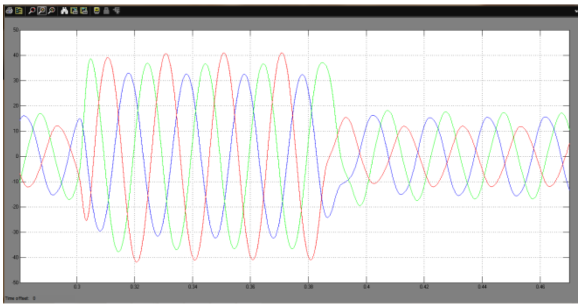
(a) During voltage sag



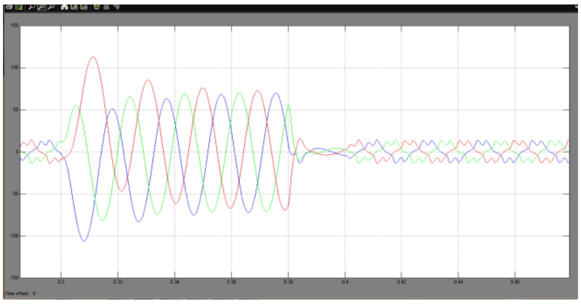
Vpcc



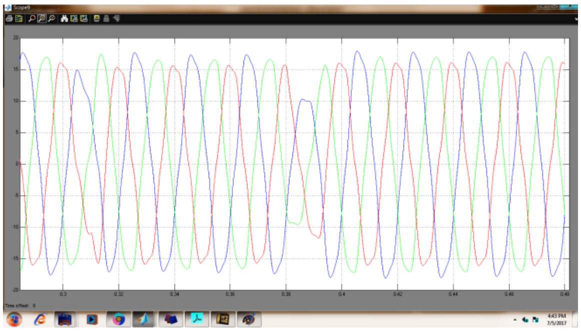
Load voltage



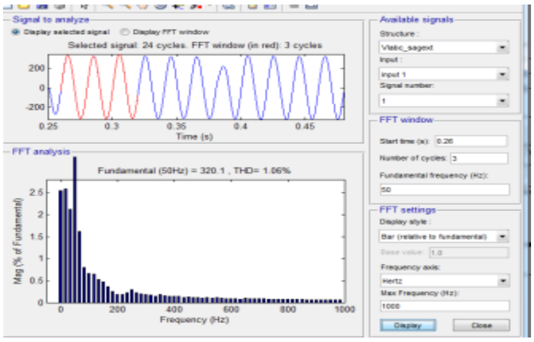
Source current



Filter current



Load currents



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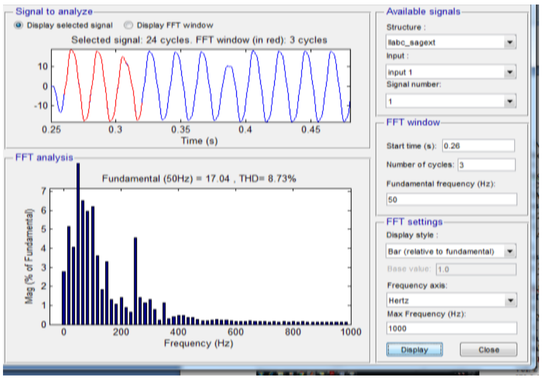
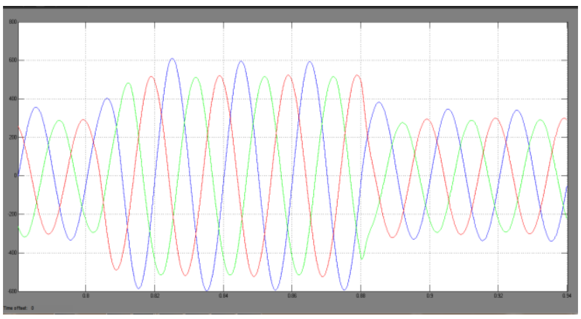
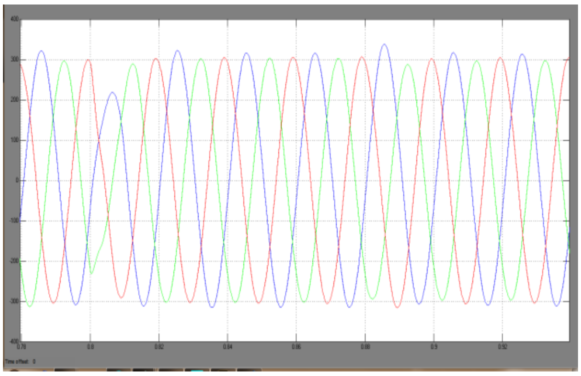


Load current

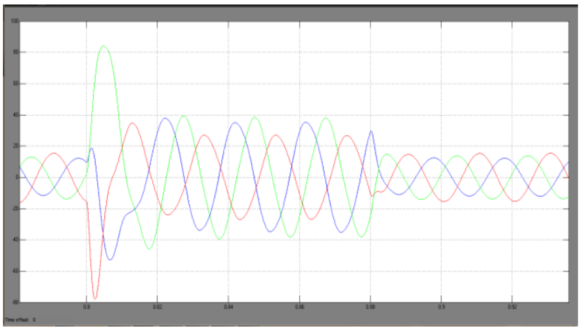
(b) During voltage swell



Vpcc



Load voltage



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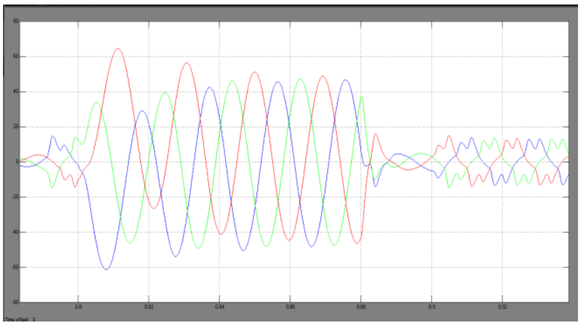
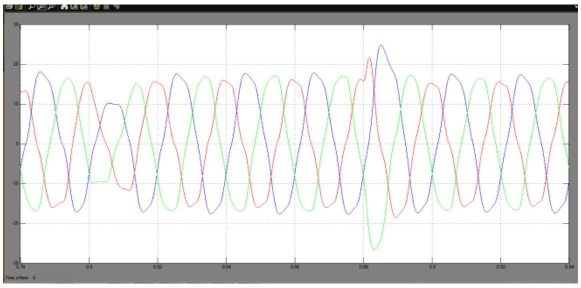


Filter current



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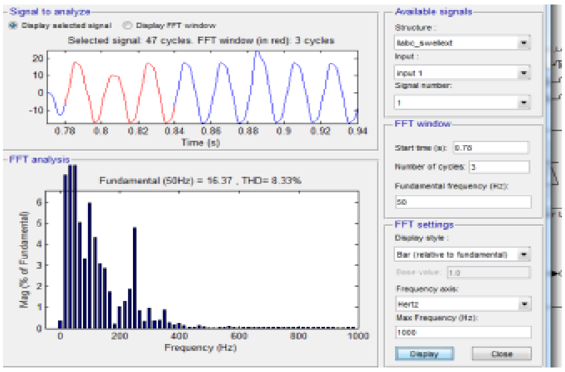

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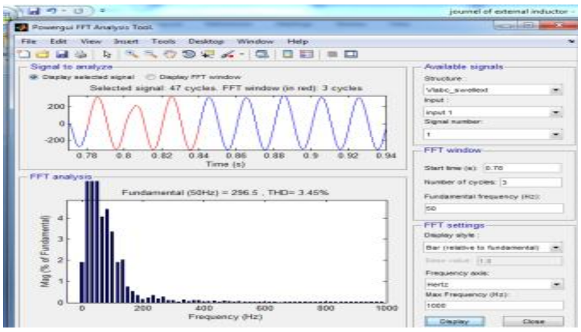
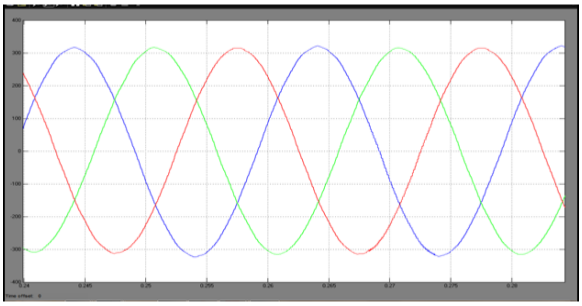
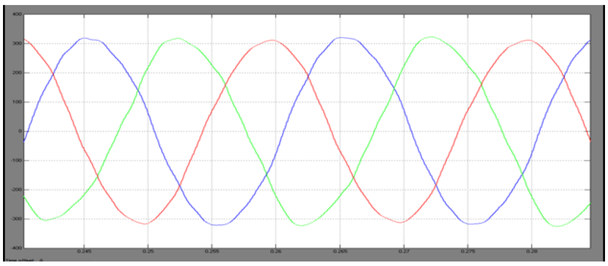


Load voltage

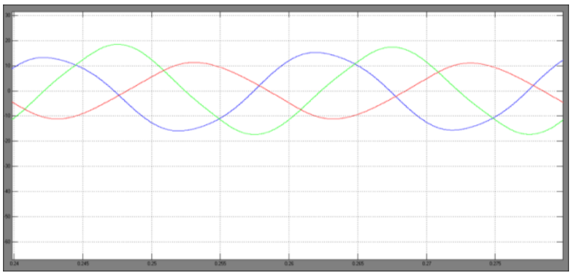
(C) During normal operation



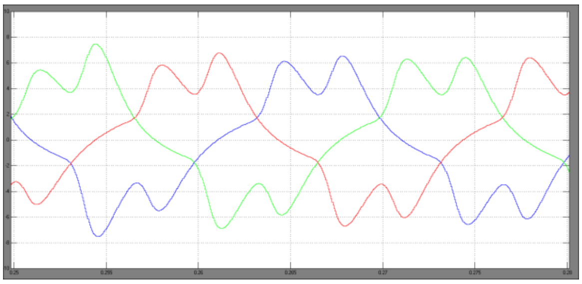
Vpcc



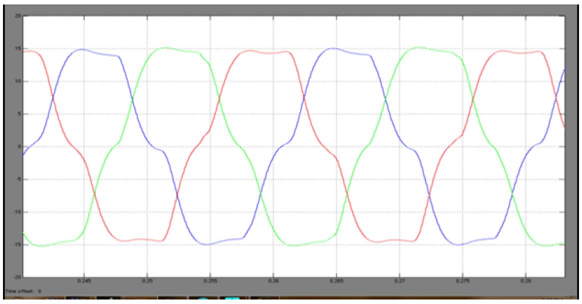
Load voltage



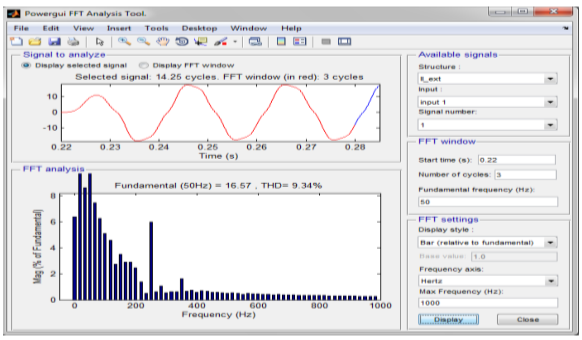
Source current



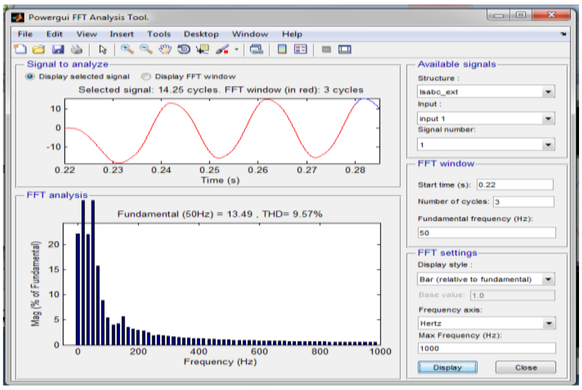
Filter current



Load currents



Load current



Source current

V11. CONCLUSIONS

This paper has introduced external, operation, and control of a DSTATCOM working in voltage control mode (VCM). Subsequent to giving a nitty gritty investigation of voltage control capacity of DSTATCOM under different feeder situations, a benchmark outline method for choosing appropriate estimation of external inductor using fuzzy logic controller is proposed. A calculation is defined for dynamic reference regulation voltage size generation. The DSTATCOM has enhanced voltage control capacity with a decreased current rating VSI, lessened misfortunes in the VSI and feeder. Additionally, dynamic reference regulation voltage era conspire enables DSTATCOM to set diverse steady reference voltage amid voltage unsettling influences. Reenactment and test comes about approve the adequacy of the proposed arrangement. The external inductor is an exceptionally basic and shabby arrangement for enhancing the voltage direction, be that as it may it remains associated all through the operation and ceaseless voltage drop crosswise over it happens. External inductor using pi controller is compared with external inductor using fuzzy logic controller. Fuzzy logic controller gives the better performance. The future work incorporates operation of this settled inductor as a controlled reactor with the goal that its impact can be limited by differing its inductance.

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