ISSN (Online) 2395-2717

International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 3, Issue 9, September 2017

Performance Improvement of Voltage Controlled D-Statcom with Design of External Inductor Using Fuzzy Logic Controller

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Abstract— **This work provides a comprehensive study of design, operation, and flexible control of a D-STATCOM operating in voltage control mode. A detailed analysis of the voltage regulation ability of D-STATCOM under different feeder impedances has been analyzed. For load voltage regulation, a D-STATCOM is used and its operation mainly depends upon nature of the feeder impedance. The procedure to design a value of external inductor has been presented in this work. A dynamic reference load voltage generation scheme is developed to compensate reactive power which not only allows D-STATCOM during normal operation, but also providing voltage profile during disturbances. The Fuzzy Logic Controller(FLC) is the most popular for the human decision-making mechanism, providing the operation of an electronic system with decisions of experts. When it is used for a nonlinear system which not only reduces uncertain effects in the system control but also improves the system efficiency by reducing THD. The results have been carried out in MATLAB/SIMULINK.**

keywords—current control, Distribution static compensator (D-STATCOM), Fuzzy Logic Controller(FLC),external inductor, power factor, power quality and voltage control.

I. INTRODUCTION

Faults in widespread power system as well as switching of large variable loads cause voltage fluctuations such as sag and swell in a distribution system. These problems significantly degrade the operation of sensitive loads like process-control industry, equipments like electronics, adjustable drives, etc.

Conventionally, load voltage regulation, reactive current compensation , and improvement of transient stability can be done by Static Var Compensator (SVC). However, the SVC is a power electronic devise which injects harmonic current in to the system, amplification of harmonics, and there is possible of resonance with the impedance of source. To overcome the limitations of SVC the D-STATCOM has been proposed. In order to regulate load voltage a D-STATCOM is very effective method to control the load voltage. The regulation

can be done by D-STATCOM by supplying reactive current to the source. The load voltage is set at 1.0 p.u. to provide voltage regulation in conventional D-STATCOM application.

At the leading power factor the VSI continuously exchanges reactive power with the source when load voltage is 1p.u.This manly results continuous power loss in the VSI and feeder.To provide a stiff voltage support an ordinary D-STATCOM must need large current rating voltage source inverter (VSI).This very high rating current requirement increases the VSI power rating and produces much power dissipasion in feeder as well as switches.The focus of this paper is to explain a complete design of External Inductor and detailed procedure to select it. Which gives meny practical constraints, which not only allows D-STATCOM to control load voltage but also stiff and resistive feeder. Which decreases the current requirement to mitigate sag, and to decrease the losses. A dynamic reference load voltage generation scheme is presented to provide coordinated control of voltage across the External Inductor, load fundamental current and terminal voltage. This scheme not only ensures constant load load voltage during disturbances but also maintains unity power factor (UPF) during normal operation.The detailed performance of the D-STATCOM is verified through simulation results.

II. DSTATCOM IN POWER DISTRIBUTION SYSTEM

Fig. 1 shows the D-STATCOM topology is connected to distribution power system. Where R_s and L_s are the source resistance and inductance respectively.The L_{ext} is included between the source and load points.The D-STATCOM voltage regulation capability can be achived by this L_{ext} even in worest grid conditions,i.e.,resistive grid. For the direct measurement of customer and utility the point of common coupling(PCC) is selected from IEEE-519standard.Therefore, the PCC is the point at which L_{ext} is conncted to the source.In between the load and L_{ext} the D-STATCOM is conncted.The Three-Phase four-wire VSI is used in the D-STATCOM. In each phase a passive LC filter is conncted to filter out switching components of

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ISSN (Online) 2395-2717

International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
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large frequency. The V_{dc1} and V_{dc2}, are voltage across dc capacitors maintained V_{dcref}.

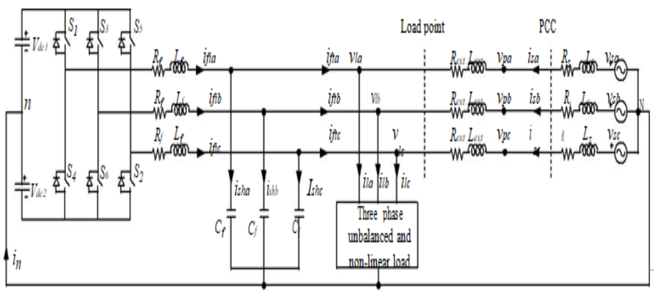

Fig. 1. Three phase equivalent circuit of D-STATCOM topology in distribution system

III. EFFECT OF FEEDER IMPEDANCE ON VOLTAGE REGULATION

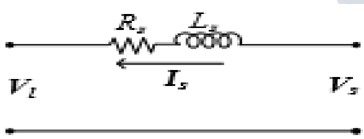

Fig.2 Equivalent circuit with absence external inductor

The above fig.2 explains the effect of line of line impedance on operation of regulation, it refers the equivalent circuit of load-source model without L_{ext} . The current in the circuit is given as

$$I_s = \frac{V_{s-}v_l}{Z_s} (1)$$

Where $V_s = V_S\angle\delta, I_s = I_s\angle\varphi, Z_s = Z_s\angle\theta,$ with $V_{s,} V_l, Z_{s,}$
$I_{s,}\ \delta, \varphi$ and θ_s are rms values of source and load voltages, rms
Source current, feeder impedance, load, power factor, and feeder impedance angles, respectively. The three phase average power P_l is expressed as

$$P_l = Real[3V_l \times I_s]. \qquad (2)$$

Substituting V $_l$ and I_s in (2), the true power of load is

$$P_l = \frac{3V_l^{\,2}}{Z_s}[cos(\theta_s - \delta) - \cos\theta_s] \quad (3)$$

Rewriting (3), expression can be as follows:

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

For power transfer from source to load with stable operation in inductive feeder, δ must be positive and less than 90^0.Also, all the terms of the second part of (4), i.e., inside $\cos^{-1}$, are aplitude and will always be positive.Therefore, value of second part will be between '0' and $\pi/2$

$$V_S = V_l + I_s Z_s\angle(\theta_s + \varphi) \qquad (5)$$

A D-STATCOM controls the voltage of the load by injecting fundamental reactive current. To demonstrate the D-STATCOM capability of voltage regulation at various supply voltages for different Rs/Xs, vector diagrams using (5) are drawn in Fig.3.To draw phaser, voltage of load V_l should be taken (1.p.u.) nominal value of OA. With aim is make $V_l = V_s = 1.0$ p.u., locus of V_s will be a semicircle of radious V_l. Since in an inductive feeder maximum passible load angle is 90^0, phasar V_s may be any where inside the OACBO curve.The regulated votage is zero can be seen at this point. Only at time of leading power factor it is passible at the load end as θ_s should not be more than than 90^0.

Fig.3(a) shows the limiting case when $R_s/X_s = 1$,i.e.,$\theta_s = 45^0$.
From (4), the maximum value of angle ,$\theta_s + \varphi$, can be 135^0 when φ is 90^0.Hence, the limiting source current phasor OE, which is denoted by I_{slimit}, will lead the load voltage by 90^0. Lines OC and AB are limiting vectors of V_s and $I_s Z_s$, correspondingly with D has a restrictive value of $V_{slimit} = I_s Z_s =$ 0.706 p.u.
The D-STATCOM voltage regulation proficiency is restricted. Owing to resistive cause of feeder in a distribution system, forther more, very huge current is essential to mitigate lesser voltage disorders which affects

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in greater rating of IGBT switches in addition to bigger losses. Onether point is must noted that is, there will be some voltage drop in the line at nominal source voltage in a resistive feeder, which the D-STATCOM may not be able recomensence to sustain load voltage at 1.0 p.u. even with an ideal VSI.

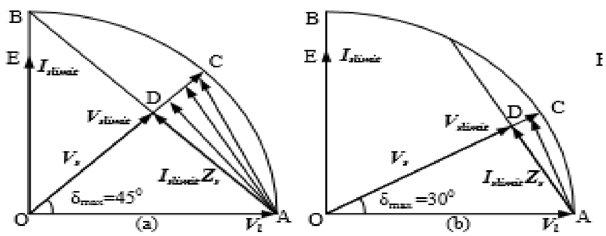

Fig.3. Voltage regulation performance curve of D-STATCOM at differentR_s/X_s (a) forR_s/X_s =1, (b) R_s/X_s =$\sqrt{3}$

IV. SELECTION OF EXTERNAL INDUCTOR FOR VOLTAGEREGULATION IMPROVEMENT AND RATING REDUCTION

This section refers external inductor selection and its general procedure to increase regulation ability of D-STATCOM while reducting current rating of VSI. Fig. 4 shows one phase D-STATCOM equivalent diagram of circuit in distribution system. With balanced voltages, source current will be

$$I_s = \frac{V_s\angle\delta - V_l\angle 0}{(R_s+R_{ext})+j(X_s+X_{ext})} = \frac{V_s\angle\delta - V_l\angle 0}{R_{self}+X_{self}} \quad \dots (6)$$

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

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

With addition of external impedance, the effective feeder impedance becomes predominantly inductive. Hence $Z_{self} = X_{self}$.

$$I_s^{im} = \frac{V_l\sin\theta_{self} + V_s\sin(\delta - \theta_{self})}{X_{self}} \quad \dots\dots (8)$$

D-STACOM power rating (S_{vsi}) is given as follows

$$S_{vsi} = \sqrt{3}\frac{V_{dc}}{\sqrt{2}}I_{vsi} \quad \dots\dots.. (9)$$

where I_{vsi} is the rms phase current rating of the VSI and V_{dc} is the voltage maintained at the dc capacitors. The D-STATCOM aims to inject harmonic and reactive current component of load currents. Suppose I_l^{im} is the maximum rms reactive and harmonic current rating of the load, then the value compensator current used for voltage regulation (same as I_s^{im}) is obtained by subtracting I_l^{im} from I_{vsi} and given as follows:

$$I = I_{vsi} - I_l^{im} = \frac{\sqrt{2}Svsi}{\sqrt{3}V_{dc}} - I_l^{im} \quad \dots\dots (10)$$

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

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

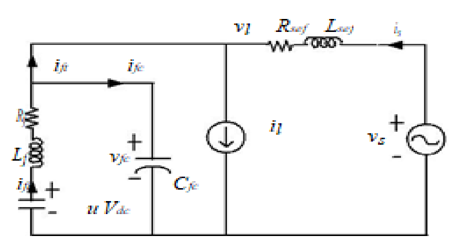

Fig.4. one-phase D-STATCOM topology with external inductor in distribution system

The above expression is used to compute the value of external inductor. Design example of external inductor, used for this work, is given in next section.

V. FLEXIBLE CONTROL STRATEGY USING

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FUZZY LOGIC CONTROLLER

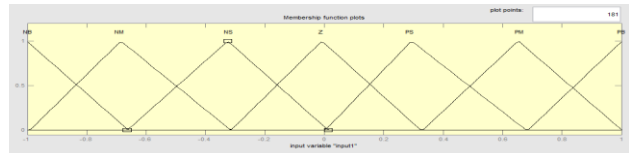
One of the ground reason for the popularity of Fuzzy Logic Controller(FLC), is its logical resemblance to operator. It operates on the grounds of a intelligence base which in turn depends upon the assorted IF-THEN rules, same to a human operator. Unlike other control strategies, this is simpler as there is no complex mathematical knowledge required. The Fuzzy logic control(FLC) needs security system with qualitative knowledge, and hence making the controller easy to design and use. Table1 denotes Fuzzy Controller(FC) rules which are used for proposed method[2, 3].

In this proposed method the inputs to the fuzzy logic controller are V_ref,I_d and the corresponding fuzzy rules are mentioned in the below Table 1.The starting step inorder to design a FLC is choosing proper inputes which are given to same.These input parameters should be such that, they represent the dynamical system completely.

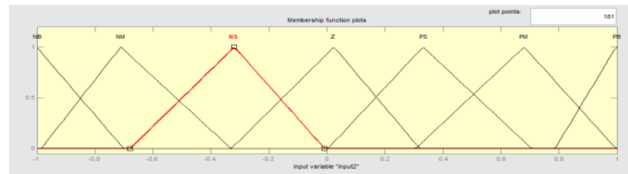
Table 1 FUZZY RULES

V_{ref} / δ	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NM	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PM	PB
PM	NS	Z	PS	PM	PM	PM	PB
PB	Z	PS	PM	PB	PB	PB	PB

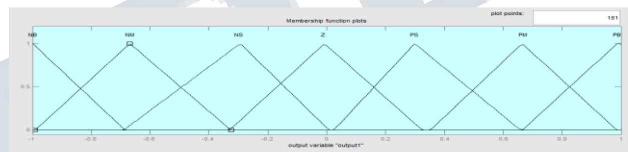
The input1, input2, of fuzzy membership functions and their output are shown below Fig. 5



5 (a)



5(b)



5(c)

This section presents a flexible control strategy to improve the performance of DSTATCOM in presence of the Lext. Firstly, a dynamic reference load voltage based on the coordinated control of the load fundamental current, PCC voltage, and dynamic reference load voltage based on the coordinated control of the load fundamental current, PCC voltage, and voltage across the external inductor is computed. Then, fuzzy logic controller (FLC) is used to control the load angle which helps in regulating the dc bus voltage at a reference value. Finally, three phase reference load voltages are generated. The block diagram of the control strategy is shown in Fig. 6.

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

In conventional VCM operation of DSTATCOM, the

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

Where $\Delta_1^+ = \sum_{j\,=\,a,b,c}\left(v_{pj1}^+\right)^2$.

The voltages v_{pa1}^+, v_{pb1}^+, and v_{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:
reference load voltage is maintained at a constant value of 1.0 p.u.. Source currents cannot be controlled in this reference generation scheme.
Therefore, power factor will not be unity and source exchanges reactive power with the system even at nominal supply.
To overcome this limitation, a flexible control strategy is developed to generate 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 defined as the condition when load voltage lies between 0.9 to 1.1 p.u. In this case, the proposed flexible control strategy controls load voltages such that the source currents are balanced sinusoidal and VSI does not exchange any reactive power with the source.
Hence, the source supplies only fundamental positive sequence current component to support the average load power and VSI losses.
Reference source currents (i_{sj} where j = a; b; c are three phases), computed using instantaneous symmetrical compo-nent theory, are given as

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

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

The reference source currents must be in phase with the respective phase fundamental positive sequence PCC voltages

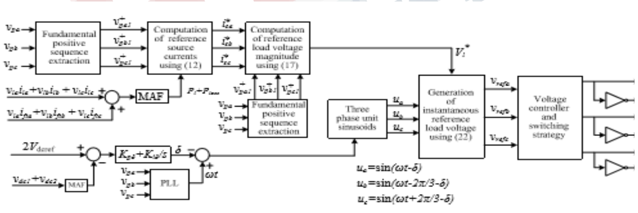


Fig.6. Block diagram of proposed flexible control strategy

for achieving UPF at the PCC. Instantaneous PCC voltage and reference source current in phase-a can be defined as follows:

$$V_{pa1}^{+} = \sqrt{2}V_{pa1}^{+}\sin(\omega t - \varphi_{p1}^{+}), \quad i_{sa}^{*} = \sqrt{2}I_{sa}^{*}\sin(\omega t - \varphi_{p1}^{+}) \quad \ldots\ldots\ldots (15)$$

$$V_{la} = V_{pa1}^{+} - i_{sa}^{*}Z_{ext} \quad \ldots\ldots(16)$$

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

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

With UPF at PCC, the voltage across the L_{ext} will lead the PCC voltage by 90^0. Neglecting ESR of external inductor, It can be detected that the voltage across external inductor improves the load voltage compared to the PCC voltage. As long as V_{la} lies between 0.9 to 1.1 p.u., same voltage used as reference terminal voltage (V_l^*), i.e.,

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

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

$V_l^* = 0.9$ p.u. ………. (19)

3) During operation of 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 1.1p.u. which effects in minimum current injection. Therefore,

$V_l^* = 1.1$ p.u. ……….. (20)

B. Computation of Load angle (δ):

The dc link voltage is controlled by generating a suitable value of δ. The average voltage across dc capacitors ($V_{dc1} + V_{dc2}$) is compared with a reference voltage and error is passed through a fuzzy controller. Output of fuzzy controller, , is given as

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

Where $e_{vdc} = 2\ V_{dcref} - (V_{dc1} - V_{dc2})$ is the voltage error. $K_{p\delta}$ and $K_{i\delta}$ are proportional and integral gains, respectively

C. Generation of Instantaneous Reference Voltage:

Selecting suitable computing load angle and reference load voltage magnitude from (21), the 3-φ balanced sinusoidal reference load voltages are:

$$V_{refa} = \sqrt{2}V_l^* \sin(\omega t - \delta)$$

$$V_{refb} = \sqrt{2}V_l^* \sin(\omega t - 2\pi/3 - \delta) \qquad \ldots\ldots\ldots(22)$$

$$V_{refb} = \sqrt{2}V_l^* \sin(\omega t + 2\pi/3 - \delta)$$

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

VII. SIMULATION RESULTS

This proposed scheme has been presented in addition PI replaced with Fuzzy Logic Controller (FLC).Figs. 8(i)-(v) provide the steady state waveforms with the designed external inductance and flexible control strategy Fuzzy logic controller (FLC). This scheme simultaneously controls load voltages and source currents. The three phase normal PCC voltages are shown in Fig. 7(a). The source currents and load voltages waveforms are shown in Figs. 7(b) and (c),respectively. These waveforms are stable and sinusoidal. Also, UPF is achieved at the PCC. Hence, compensator supplies only load harmonic and Reactive power requirement of L_ext. In the existing method THDs of reference source currents, load currents and V_pcc voltages of phases a, b, and c are 13.8%, 19.27%, and 3.01% respectively. With this proposed scheme with Fuzzy Logic Controller (FLC) THDs of source currents, load currents and V_pcc voltages have been reduced to 13.8%, 8.72% and 1.22% during sag respectively. During swell in existing method THDs of source currents, load currents and V_pcc voltages are 12.03%,0.67%, and 5.08 of phases a, b, and c respectively. In this proposed scheme with FLC they have been reduced to 8.45%,8.33% and 4.38% respectively. This paper mainly focused on proposed scheme.

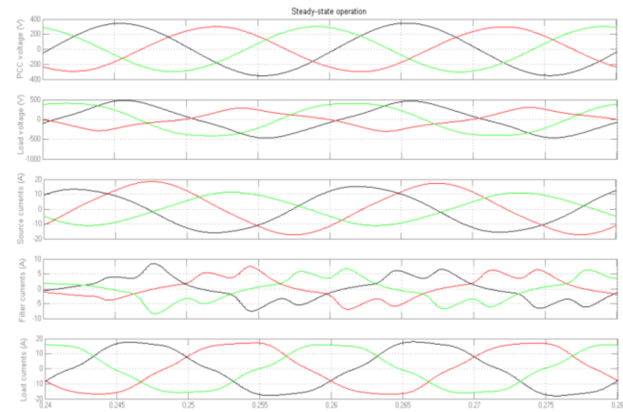


Fig.7(a) During normal operation

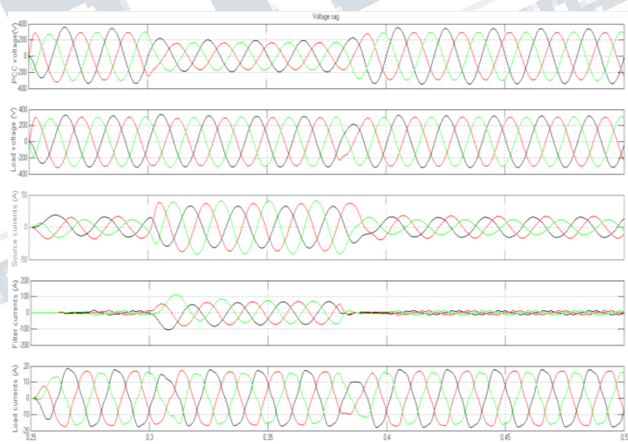


Fig.7(b) During sag

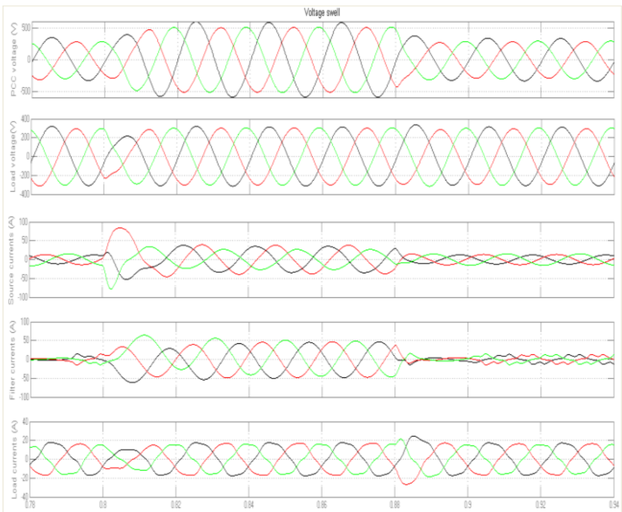


Fig.7(c) During swell

VIII. CONCLUSIONS:

This paper has been presented with design, operation, and control of a D-STATCOM operating in voltage control mode (VCM). After providing a detailed exploration of voltage regulation ability of D-STATCOM under nemorous feeder scenarios, a benchmark design procedure for selecting suitable value of L_ext with Fuzzy Logic Controller (FLC) is proposed. With this proposed method the D-STATCOM has improved voltage regulation ability with a reduced current rating VSI, reduced losses in the VSI and feeder. Also, dynamic load reference voltage generation system allows D-STATCOM to set different constant reference voltage during voltage disorders . The proposed scheme with FLC THDs of load currents, V_pcc voltages have been reduced. The future work includes operation of this fixed inductor as a controlled reactor so that its effect can be minimized by varying its inductance.

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