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Design, Operation and Flexible Control of a D-STATCOM Operating in Voltage Control Mode

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ABSTRACT: This paper presents the operating principles of a distribution static compensator (D-STATCOM) that is used to maintain the voltage of a distribution bus. A three-phase, four-wire distribution system is assumed in this study. A detailed analysis of the voltage regulation capability of D-STATCOM under various feeder impedances & design procedure to compute the value of external inductor is presented. A distribution static compensator (D-STATCOM) that can be operated flexibly in the voltage or current control mode. The objectives of this paper is To provide a detailed design procedure for selecting the external inductor regulate load voltage reduce the current, requirement reduce the system losses Switching control scheme is proposed, and its suitability is proved for this problem. The proposed scheme is verified using MATLAB Simulation results.

KEYWORDS: D-STATCOM, Voltage regulation, load voltage generation, voltage control mode

I. INTRODUCTION

Generally Static VAR Compensator is used for Load voltage regulation , reactive power compensation and for improvement of transient stability. But SVC having some limitations at the time of performance like harmonic current injection in the system, harmonic amplification and possible resonance with source impedance. This power quality problem may disturb the system that's why a new solution is introduced to overcome this limitation is A D-STATCOM[1]. A D-STATCOM is one of most effective and Cheapest solution for the Load Voltage Regulation. It regulates the Load Voltage by supplying fundamental reactive current into the source[2]. The voltage regulation performance of D-STATCOM mainly depends upon the feeder impedance and the number of sensitive loads. For voltage control mode (VCM) operation of D-STATCOM and grid connected Inverters, the idea of inserting an external inductor in line has been reported. However, in these schemes, only the concept has been introduced leaving ample scope for further investigation and insight into the design details. D-STATCOM to regulate load voltage in stiff as well as resistive feeder, reduce the current requirement for mitigation of sag, and reduce the system losses. This scheme ensures unity power factor (UPF) operation during normal operation and maintains load voltage constant during voltage disturbances [3].

'M. H. Bollen, "Understanding power quality problems." [1] focus on the power quality problems which disturb the performance of the sensitive loads, they discuss various power quality technique which resolve all the power quality problems". 'S. Ostroznik, P. Bajec, and P. Zajec, "A study of a hybrid filter," IEEE Trans. Ind. Electron.[2]" in this paper they give an ideas about voltage regulation improving electronic solution like shunt connected filters", 'C. Kumar and M. Mishra, "A voltage-controlled DSTATCOM for power quality improvement," IEEE Trans. Power Del". [3], , in this paper clearly design the D-STATCOM which operate in voltage control mode, D-STATCOM is very cheap solution for the load voltage regulation." Q. Liu, L. Peng, Y. Kang, S. Tang, D. Wu, and Y. Qi, "[4] A novel design and optimization method of an LCL filter for a shunt active power filter," IEEE Trans. Ind. Electron.[5],," they Discuss about the load voltage regulation by the LCL filter for a shunt active filter". 'T. Aziz, M. Hossain, T. Saha, and N.

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The organization of this paper is as: Section I describes introduction of D-STATCOM, its operation and necessity of it for the load voltage regulation and reactive power compensation. Section II deals with Methodology, D-STATCOM in power distribution system, Flexible control strategy , Computation of Exact value of External Inductor for Load voltage regulation, Value of fundamental current to mitigate the SAG and MATLAB simulation for Design of External inductor to improve the performance of D-STATCOM operated in voltage control mode. Section III conclude that Design of external inductor improves the performance of D-STATCOM operated in voltage control mode.

II. METHODOLOGY

2.1 DSTATCOM in Power Distribution System

Fig. shows power circuit diagram of the D-STATCOM topology connected in distribution system. L_s and R_s are source inductance and resistance, respectively. This inductor helps DSTATCOM to achieve load voltage regulation capability even in worst grid conditions[6], i.e., resistive or stiff grid. From IEEE-519 standard, point of common coupling (PCC) should be the point which is accessible to both the utility and the customer for direct measurement. The D-STATCOM is connected at the point where load and L_{ext} are connected. The D-STATCOM uses a three-phase four-wire VSI. Voltages across dc capacitors, V_{dc1} and V_{dc2} , are maintained at a reference value of V_{dcref} .

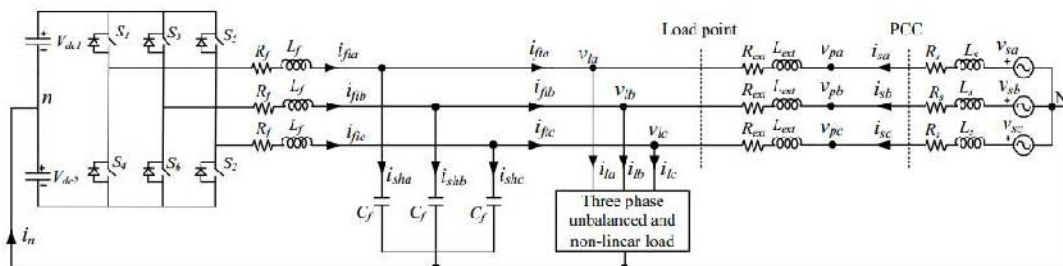


Fig.2.1 Phase equivalent circuit of D-STATCOM topology in distribution system.

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2.2 EFFECT OF FEEDER IMPEDANCE ON VOLTAGE REGULATION

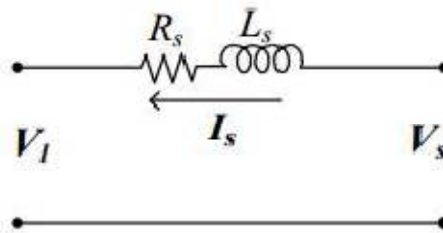


Fig.2.2 Equivalent source-load model without considering external inductor

To demonstrate the effect of feeder impedance on voltage regulation performance, an equivalent source-load model without considering external inductor is shown in Fig. 2. The current in the circuit is given as

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

where $V_s = V_s \angle \delta$, $V_l = V_l \angle 0$, $I_s = I_s \angle \phi$, and $Z_s = Z_s \angle \theta_s$, 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

$$P_l = \text{Real} (3V_l * I_s^*) \dots\dots\dots (2)$$

Substituting V_l and I_s in (2), the load active power is

$$P_l = 3 * \frac{V_l}{Z_s} \left(\frac{V_s}{V_l} \cos(\theta_s - \delta) \right) \dots\dots\dots (3)$$

Rearranging above equation, expression for δ is computed as follows:

$$\frac{V_l}{V_s} \cos(\theta_s + PlZ_s/3V^2l) \dots\dots\dots (4)$$

$$\delta = \theta_s - \cos^{-1} \dots\dots\dots$$

For power transfer from source to load with stable operation in an inductive feeder, δ must be positive and less than 90° . Also, all the terms of the second part of (4), i.e., inside \cos^{-1} , are amplitude and will always be positive. The vector expression for source voltage is given as follows:

$$V_s = V_l + I_s Z_s \angle (\theta_s + \phi) \dots\dots\dots (5)$$

A D-STATCOM regulates the load voltage by injecting fundamental reactive current. To demonstrate the D-STATCOM voltage regulation capability at different supply voltages for different R_s/X_s , vector diagrams using (5) are drawn in

Fig.3. To demonstrate the D-STATCOM voltage regulation capability at different supply voltages for different R_s/X_s , vector diagrams using (5) are drawn in Fig.3.

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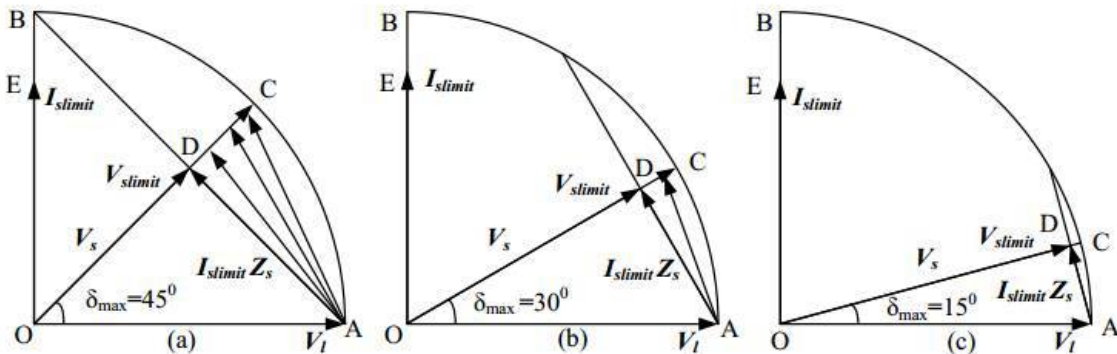


Fig.2.3 Regulation performance curve of DSTATCOM at different R_s / X_s . (a) For $R_s / X_s = 1$. (b) For $R_s / X_s = \sqrt{3}$. (c) For $R_s / X_s = 3.73$.

2.3 Regulation Improvement and Rating Reduction

This section presents a generalized procedure to select external inductor for improvement in D-STATCOM voltage regulation capability while reducing the current rating of VSI. Fig. 4 shows single phase equivalent D-STATCOM circuit diagram in distribution system. With balanced voltages, source current will be

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

Where $R_{sef} = R_s + R_{ext}$ and $X_{sef} = X_s + X_{ext}$ are effective feeder resistance and reactance, respectively. R_{ext} is equivalent series resistance (ESR) of external inductor, and will be small.

$$\theta_{sef} = \tan^{-1} X_{sef} / R_{sef} \dots\dots\dots (7)$$

$$Z_{sef} = \sqrt{X_{sef}^2 + R_{sef}^2} \dots\dots\dots (8)$$

With θ_{sef} as effective impedance angle and Z_{sef} as effective feeder impedance, respectively, the imaginary component of I_s is given as

$$I_s^{lm} = \frac{(V_l \sin \theta_{sef} + V_s \sin(\delta - \theta_{sef}))}{Z_{sef}} \dots\dots\dots (9)$$

With the addition of external impedance, the effective feeder impedance becomes predominantly inductive. Hence, $Z_{sef} \approx X_{sef}$. Therefore, approximated I_s^{lm} will be

$$I_s^{lm} = \frac{(V_l \sin \theta_{sef} + V_s \sin(\delta - \theta_{sef}))}{X_{sef}} \dots\dots\dots (10)$$

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DSTATCOM Power rating (S_{vsi}) is given as follows:

$$S_{vsi} = \sqrt{3} \left(\frac{V_{dc}}{\sqrt{2}} I_{vsi}^{si} \right) \dots \dots \dots (11)$$

Where I_v^{si} 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_{lim} is the maximum rms reactive and harmonic current rating of the load, then the value of Compensator current used for voltage regulation (same as I_s^{lm}) is obtained by subtracting I_{lim} from I_v^{si} and given as follows:

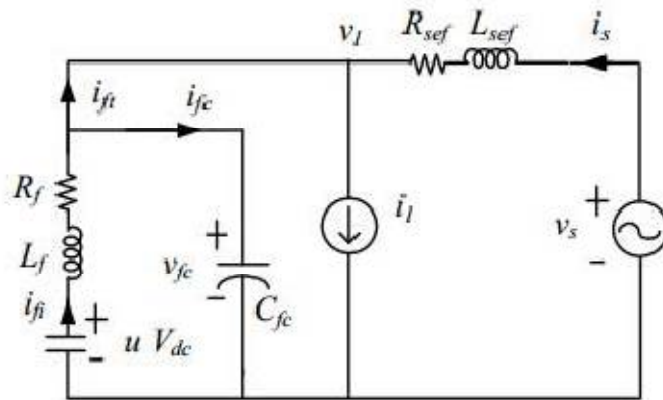


Fig. 2.4 Single phase equivalent circuit of DSTATCOM topology with external inductor in distribution system.

$$I = I_{vsi} - I_l^{lm} = \sqrt{2} V_{vsi} / \sqrt{3} V_{dc} \dots \dots \dots (12)$$

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

$$X_{sef} = \frac{\theta_{sef} + P_l X_{sef} / 3v_l^2}{\left[\frac{v_l}{v_s} \cos(\) \right] \cos^{-1} \dots \dots \dots} \dots \dots \dots (13)$$

$$V_l \sin \theta_{sef} + V_s \sin$$

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.

2.4 FLEXIBLE CONTROL STRATEGY

This section presents a flexible control strategy to improve the performance of DSTATCOM in presence of the external inductor L_{ext} . Firstly, a 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, a proportional integral



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(PI) controller 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.

2.5. Derivation of Dynamic Reference Voltage Magnitude (VI*)

In conventional VCM operation of DSTATCOM, the reference load voltage is maintained at a constant value of 1.0p.u. [10]–[12]. 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

2.6 SIMULATION PARAMETERS

System Quantities	Values
Source voltage	240 V rms L-N (1.0 P.U), 50 hz
Feeder Impedance	$R_s = 0.3\Omega, L_s = 0.3mH, \frac{R_s}{X_s} = 3.185$
External Impedance	$L_{ext} = 6.7mH, R_{ext} = 0.007\Omega$
Linear Load	$Z_{ta} = 30 + j62.8 \Omega, Z_{tb} = 40 + j78.5 \Omega, Z_{tc} = 50 + j50.5 \Omega$
Non Linear Load	Three Phase rectifier supplying R-L load of 50 Ω and 200 mH
VSI parameter	$V_{dc} = 520v, C_{dc} = 2600 \mu F, L_f = 5 mH, C_f = 20\mu F, S_{vsi} = 30kva$
Pi gain	$k_{p\delta} = 1.8e^{-8}$

2.6.1)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 loads power and VSI losses.

$$I_{sj} = V \frac{\Delta_1^+}{V_{p1}^+} (P_l + P_{loss}) \dots \dots \dots (14)$$

$$P_l = \frac{1}{T} \int_{t1-T}^{t1} (V_{1a} i_{1a} + V_{1b} i_{1b} + V_{1c} i_{1c}) dt \dots \dots \dots (15)$$

$$P_{loss} = \frac{1}{T} \int_{t1-T}^{t1} (V_{1a} i_{1a} + V_{1b} i_{1b} + V_{1c} i_{1c}) dt \dots \dots \dots (16)$$

Instantaneous PCC voltage and reference source current in phase-a can be defined as Follows

$$V_{pa1} = \sqrt{2} V_{pa1} \sin(\omega t - \phi_{pa1}) \dots \dots \dots (17)$$

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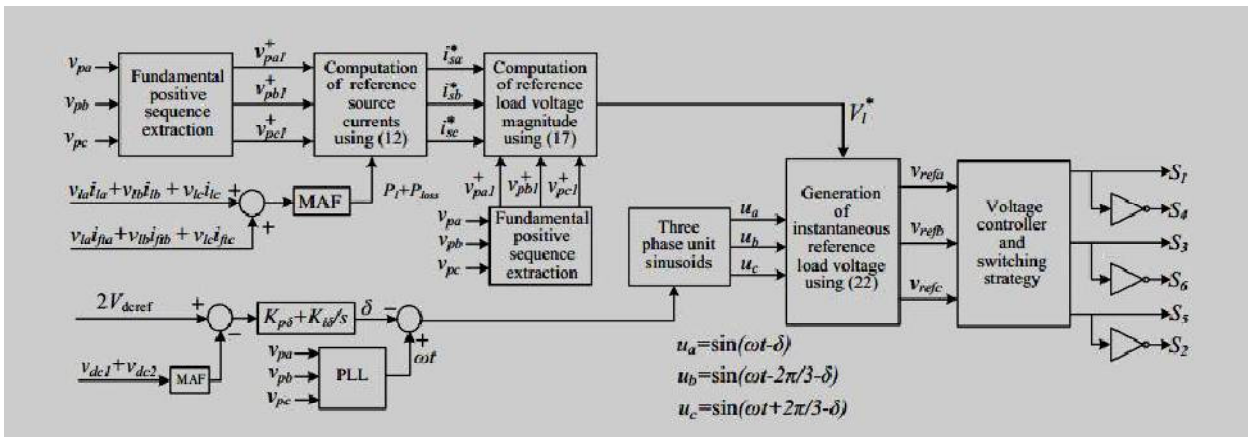


Fig.2.5 Block diagram of proposed flexible control strategy

$$I_{sa} = \sqrt{2} V_{pa1} \sin(\omega t - \phi_{pa1}) \quad (18)$$

Where V_{+pa1} and ϕ_{+pa1} are rms voltage and angle of fundamental positive sequence voltage in phase-a, respectively.

$$V_{ta} = V_{pa1} - I_{sa} Z_{sext} \quad (19)$$

The parameters of DSTATCOM compensated distribution system are given in Table I. Usual scenario in distribution system having resistive feeder impedance are considered. PSCAD software is used to simulate the system. Firstly, the D-STATCOM 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. 7(a)-(e), respectively. Here, the DSTATCOM has to compensate only for feeder drop. However, from the load voltage waveform shown in Fig. 2.5, its magnitude is found to be 227.7 V. This large reactive current is supplied by the VSI, as shown in Fig. 7(d), which increases its current rating. The load voltages and source currents waveforms are shown in Figs. 8(ii) and (iii), respectively. These waveforms are balanced and sinusoidal. Also, UPF is achieved at the PCC. Hence, compensator supplies only load harmonic and reactive [11].

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2.7 MATLAB DESIGN

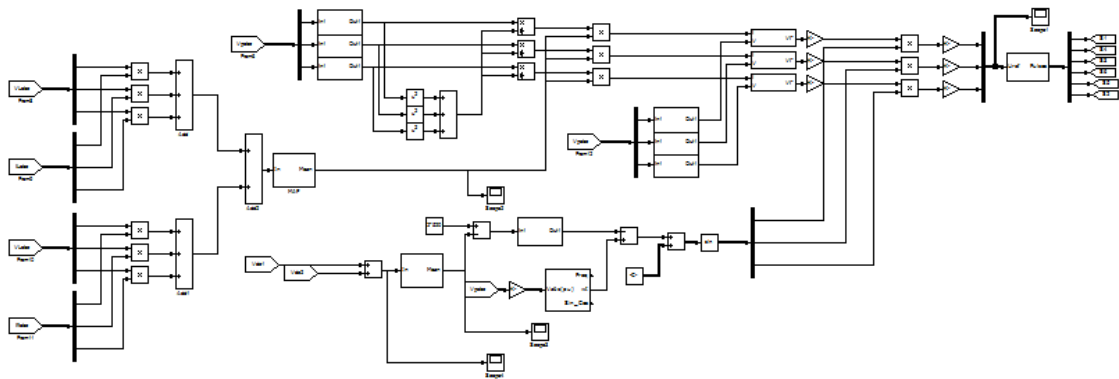


fig.2.8 MATLAB simulation design

Fig 2.9 shows detail block design of MATLAB simulation This Design divided in to two section First section generates three phase reference load voltage and second section generate D.C bus reference voltage.math function, trigonometric function, Mean value function are used while design. Universal block implement a bridge of selected power electronic device.In the first section $V_{l abc}, I_{l abc}, I_{ft abc}$ are load voltage, load current and effective feeder load current.MUX block is used to generate three phase load voltage and load current. Then product block multiply the load voltage and load current. Then SUM block add the output of MUX. After that MATH function block introduce ,The Math Function block performs numerous common mathematical functions.after that finally signal gives to PWM that is pulse with modulation block which generate three phase reference load voltage.

In the second section Vdc1 and Vdc2 are the source block, both voltage are add by the SUM block. Then the signal reaches to mean value function block this block compute the mean value of input signal over a running window of one cycle. After that signal goes to PLL block , it is a 3 phase lock loop system can be used to synchronies on a set of variable frequency. By using this MATLAB design simulation results can be validate.

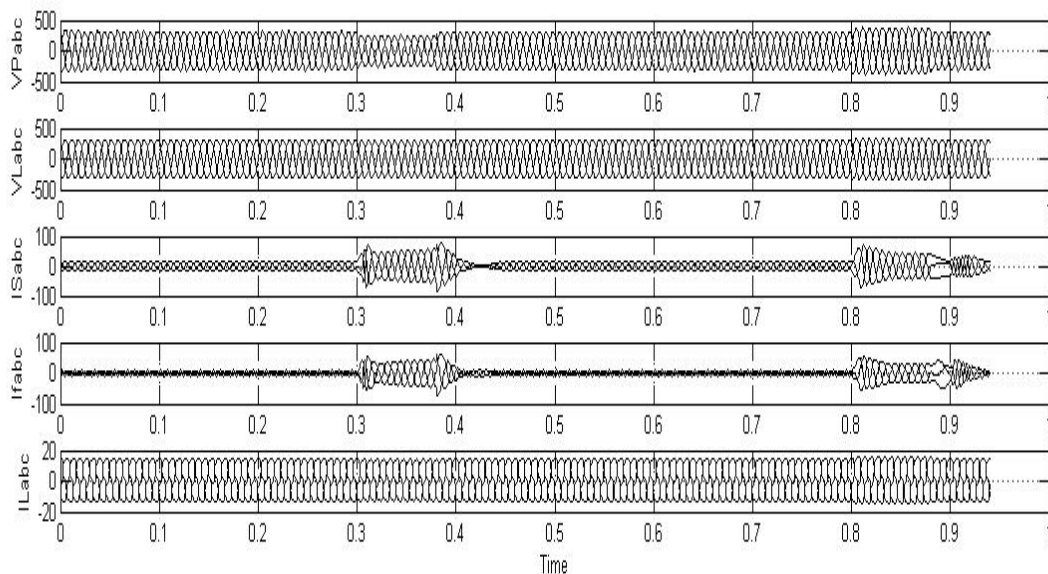


Fig 2.9 simulation Results



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The filter and load currents are shown in Figs.2.9 (iv) and (v), respectively. These waveforms validate the performance of flexible control strategy as

- 1) source does not exchange reactive power from the system,
- 2) filter does not supply additional current and reduces system losses, and
- 3) UPF is maintained at the PCC.

These features are not available in conventional DSTATCOM operating in VCM.

Approximate losses in the system are given as follows:

$$P_{loss} = 3 \left(I_{f1}^2 + (I_s^{lm})^2 R_s + (I_s^{Real})^2 R_s \right) \dots \dots \dots (20)$$

In conventional scheme, the source always exchanges reactive power. Hence, I_s^{lm} will be non-zero. Also, this current is supplied by the filter i.e., I_{f1} will be higher. However, in proposed scheme, it is seen that the source does not exchange reactive power in normal operation. Hence, $I_s^{lm} = 0$ and I_{f1} is reduced. Hence, proposed scheme reduces losses in the system and utilizes smaller VSI ratings. Small power losses will be there due to the ESR of the external inductor. However, the losses in the ESR will be much smaller than that of reduction of power losses from the conventional D-STATCOM operation. Voltage sag is created by reducing the source voltage to 0.6 P.U. at $t = 0.3$ s for 4 cycles. Fig. 2.9 (vi) shows the PCC voltages. Control of reference load voltage based on the coordinated control of fundamental load current, PCC voltage, and voltage across the external inductor allows D-STATCOM to set different constant reference voltage. The proposed scheme detects voltage sag and load voltage is changed to 0.9 P.U. The waveforms of load voltages are shown in Fig.2.9 (vii). The source currents are increased during sag period as illustrated in Fig.2.9 (viii). Fig.2.9 (ix) shows the filter currents which increase during sag period to support the load voltage. The load currents waveforms presented in Fig.2.9 (x) is nearly constant during entire operation. With the results of Figs.2.9 (vi)-(x), it can be concluded that the proposed scheme makes load operation continuous. Algorithm detects swell and maintains load voltage at 1.1 P.U. The waveforms are shown in Fig. 2.9 (xii). The waveforms of the source, filter, and load currents are shown in Figs.2.9 (xiii)- (xv), respectively. The filter currents increase during well which increases the source currents as well. Load currents are nearly constant throughout the operation. Once sag is removed, it is detected by the algorithm and system is brought to the steady state conditions. It confirms effectiveness of the proposed scheme.

III. CONCLUSION

This paper has presented design, operation, and control of a D-STATCOM operating in voltage control mode (VCM). After detailed design procedure The DSTATCOM has improved voltage regulation capability with a reduced current rating VSI, reduced losses in the VSI and feeder. Simulation and experimental results validate the effectiveness of the proposed solution. The external inductor is a very simple and cheap solution for improving the voltage regulation. The future work includes operation of this fixed inductor as a controlled reactor so that its effect can be minimized by varying its inductance.

introduction of external inductor greatly improves the D-STATCOM voltage regulation capability. Additionally, due to increased effective feeder impedance the current requirement for sag mitigation also reduces. Moreover, if ESR of the external inductors included, then the equivalent feeder impedance angle changes slightly (i.e. from 83 degree to 80.45 degree), and has negligible effect on the expression obtained as well as the voltage regulation capability of D-STATCOM.

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