Performance Comparison of Control Algorithms for Load Compensation Using D-STATCOM under Abnormal Source Voltage

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***Abstract*—Distribution Static Compensator (D-STATCOM) is a custom power device which compensates reactive power and mitigates unbalances caused by various loads in distribution system when it is operated in current control mode. When D-STATCOM is used for load comprehensive compensation, the precision in detecting the compensation current required by the system is very important for compensation effects. There are many detection methods at present. This paper evaluates and analyses three different conventional and extensively used methods of determining the compensating current for a D-STATCOM under abnormal voltage conditions i.e. asymmetric and distorted source voltages and makes comparison of the performance of each one. The algorithms compared are instantaneous reactive power theory (IPRT), synchronous reference frame theory (SRF) and I-cosɸ algorithm. All three algorithms are simulated under MATLAB environment using Simulink. The theoretical analysis and simulated results illustrate the performance and correctness of these algorithms under asymmetric and distorted source voltages. Finally, the comparison of simulated results has been done to show the accuracy in detecting the harmonics and effectiveness of compensation under abnormal voltage conditions.**

***Index Terms*—D-Statcom, harmonics, reactive current, instantaneous reactive power, detection method, synchronous reference frame, compensation current, matlab simulation.**

I. Introduction

Harmonic interference and reactive power management has become a subject of widespread concern for all the researchers around the globe [1].

The majority of power consumption has been drawn in reactive loads such as pumps, fans etc. These loads draw lagging power-factor currents hence gives rise to reactive power burden in the power distribution system. There after situation worsens in presence of unbalanced loads. The extreme reactive power drawn by load causes increased feeder losses and increased utility charges with poor DPF, reduced network capacity, reduced PF capacitor life, increased utility demand charges and reduces the active power transfer capability of power distribution system where as unbalancing of loads disturb the operation of transformers and generators[2]. D-STATCOM adopt intelligent circuits to detect harmonic and reactive power drawn by nonlinear loads and take corrective actions to make the source current purely sinusoidal. By injecting compensation current at the point of common coupling (PCC) where the nonlinear load is connected, D-STATCOM make the source current sinusoidal. Therefore, both harmonic and reactive power compensation for the nonlinear load are achieved. Compensation current detection technology is one of the most important core technologies of D-STATCOM and key factor of effectively solving power quality problems by D-STATCOM in distribution network and mainly under the grid voltage unbalanced condition and the accuracy of compensation current seems particularly very important. Therefore, study of current detection technology has great significance because with improper current detection Compensator system will become the source of Disturbance for the system itself. Hence the task of compensation current detection is according to the compensation purpose of D-STATCOM, and compensation current is separated from load current. According to the difference between compensation purposes of load compensation in distribution network, the objects detected are also different to some extent. This paper mainly studies the algorithms used for D-STATCOM in order to achieve compensation current detection, harmonic elimination and reactive power compensation during unbalance loading conditions in distribution system [3].

The performance of D-STATCOM as a compensator depends on the control algorithm i.e. the precise extraction of the current components. For this purpose there are so many control schemes which have been proposed and are reported in the literature and three of these are the Instantaneous Reactive Power Theory (IRPT), Synchronous Reference Frame Theory (SRF) and I-cosɸ algorithm which are most widely used. In this paper, controlling of D-STATCOM by IRPT [4]-[10], SRF [11]-[12] and I-cosɸ [13]-[14] algorithm for compensation of reactive power and harmonics component has been compared with each other. MATLAB based simulation study of these control techniques of D-STATCOM is presented. Simulation results demonstrate and compare the effectiveness of

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these control algorithms under asymmetric and distorted source voltage condition.

II. SYSTEM CONFIGURATION

Fig. 1 shows the basic circuit diagram of the D-STATCOM system with lagging power factor and nonlinear load connected to 3-phase and 3-wire distribution system. The lagging power-factor load is realized by delta connected Impedance, each consisting of R and L in series. Unbalancing of load is realized by eliminating load from any of the phase using circuit breaker. The 3-phase voltage source converter (VSC) working as a D-STATCOM is realized with six IGBT switches with diodes in parallel. At ac side the interfacing inductors are used so as to filter out the high frequency components of the compensating currents. The compensator must inject current such that source current becomes fundamental and positive sequence.

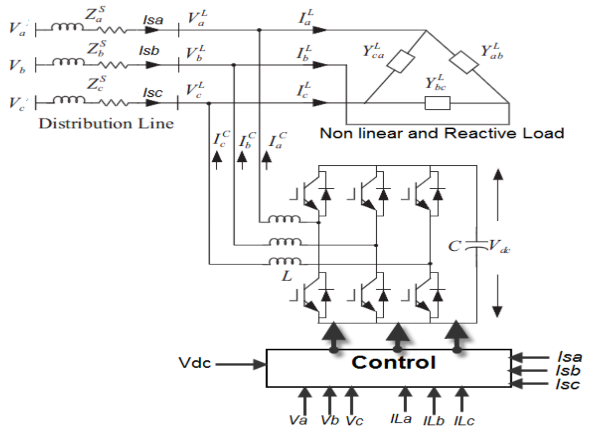


Figure 1. Basic circuit diagram of the D-STATCOM system

III. CONTROL ALGORITHM OF D-STATCOM

For Harmonics and reactive power component compensation D-STATCOM provides total power component as needed by the load and therefore the source current remains at unit power factor (UPF) from source point of view. Since only real power is being supplied by the source so the load balancing is obtained by making the source reference current balanced. The reference source current that is used to decide the switching of the controller circuit of D-STATCOM has real fundamental frequency element of the current drawn by the load which is being extracted by control algorithms.

A. *Instantaneous Reactive Power Theory (Irpt)*

The instantaneous power theory is based on a definition of instantaneous real and reactive powers in the time domain and very useful not only in the steady-state but also for the transient analysis for both three phase systems with or without a neutral conductor. In case when the source supplies a nonlinear load, the instantaneous power delivered to the load includes both real and reactive components [5]-[10]. Reference [4] proposed this well-known p-q theory which transforms the electric quantities (both v and i) from a-b-c reference frame to the α–β reference frame. This transformation is so called as the Clark transformation. The basic block diagram of the theory is shown in Fig. 2 and in this approach; current and voltage of the system are converted into α–β the system using the following equations:

$$\begin{bmatrix} i\alpha \\ i\beta \\ io \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -{}^{1}/_{2} & -{}^{1}/_{2} \\ 0 & -{}^{\sqrt{3}}/_{2} & -{}^{\sqrt{3}}/_{2} \\ {}^{1}/_{\sqrt{2}} & {}^{1}/_{\sqrt{2}} & {}^{1}/_{\sqrt{2}} \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} \tag{1}$$

Based on the IRPT theory, we have:

$$p = voio + v\alpha i\alpha + v\beta i\beta \tag{2}$$

$$q = v\alpha i\beta - v\beta i\alpha$$

If the system is a symmetric three-phase or there is no neutral point in the system, so:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v\alpha & v\beta \\ -v\beta & v\alpha \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \tag{3}$$

The active and reactive power in above Equation can be decomposed into two DC and AC parts. The DC part obtained from the fundamental current and voltage and the AC part obtained from the harmonics.

$$p = \bar{p} + \tilde{p}\ , q = \bar{q} + \tilde{q} \tag{4}$$

If just harmonic cancellation is considered then reference currents should be determined from the DC values of p and q. If reactive current compensation is also considered then the reference current should be determined based on the DC value active power. Thus in the second case, we have:

$$\begin{bmatrix} i\alpha^* \\ i\beta^* \end{bmatrix} = \frac{1}{v\alpha^2 + v\beta^2} \begin{bmatrix} v\alpha & -v\beta \\ v\beta & v\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} \tag{5}$$

where *denotes the reference value and these are reference values for the source currents. So, the reference value for the compensator is as follows:

$$i\alpha^*\mathrm{AF} = i\alpha^* + iL\alpha,\ i\beta^*\mathrm{AF} = i\beta^* + iL\beta \tag{6}$$

and the abc reference values for the compensator is,

$$\begin{bmatrix} ia^*\mathrm{AF} \\ ib^*\mathrm{AF} \\ ic^*\mathrm{AF} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{\sqrt{2}} & \frac{\sqrt{3}}{2} \\ -\frac{1}{\sqrt{2}} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i\alpha^*\mathrm{AF} \\ i\beta^*\mathrm{AF} \end{bmatrix} \tag{7}$$

Fig. 2 shows block diagram according of this algorithm that has been simulated with MATLAB/Simulink also:

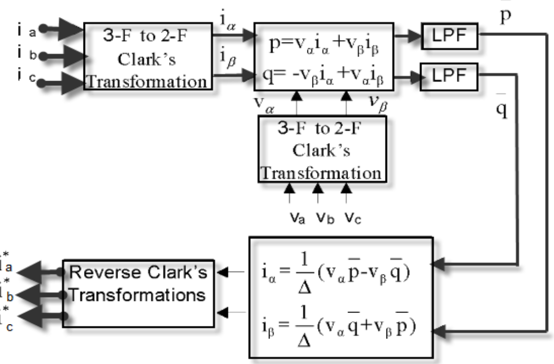


Figure 2. Block diagram of the reference current extraction through IRPT algorithm.

B. Synchronous Reference Frame Algorithm

The synchronous reference frame theory is based on the transforming the load current into synchronously rotating d-q frame [11]-[12].It is two-step procedure for determining compensator reference compensation current. In the proposed approach, the load current in the a-b reference frame is transformed to the α-β reference frame according to (1).If Θ is the transformation angle, then the transformation of currents from α-β to d-q frame is defined as:

$$\begin{bmatrix} id \\ iq \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \quad (8)$$

Here DC component is extracted by low pass filters (LPF) for each id and iq. The extracted DC components iddc and iqdc can be transformed back into α-β frame as shown below,

$$\begin{bmatrix} i\alpha dc \\ i\beta dc \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} iddc \\ iqdc \end{bmatrix} \quad (9)$$

From here the transformation can be done to find three phase reference currents in a-b-c coordinates according to equation (1).Fig. 3shows block diagram of SRF algorithm that has been simulated with MATLAB/Simulink also.

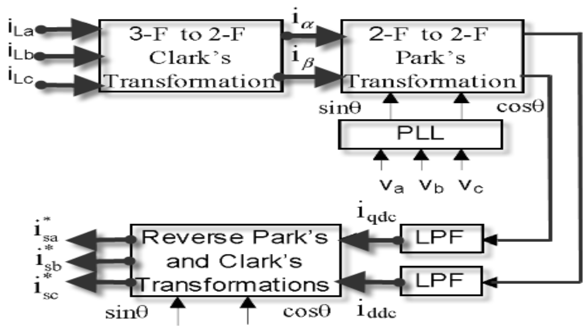


Figure 3. Block diagram of the reference current extraction through SRF theory.

C. I-cosɸ Algorithm

In the I.cosφ algorithm [13] - [14], the desired mains current is assumed to be the product of the magnitude I.cosφ and a unit amplitude sinusoidal wave in phase with the mains voltage.

The mains is required to supply only the active portion of the load current as compensator is expected to provide compensation for the harmonic and reactive portion of the three-phase load current, and also for any imbalance in the three-phase load currents. Hence, only balanced current will be drawn from the mains which will be purely sinusoidal and in phase with the mains voltages.

The reference compensation currents for the D-STATCOM are thereby deduced as the difference between the actual load current and the desired source current in each phase.

$$ia(comp) = iLa - isa(ref);$$

$$ib(comp) = iLb - isb(ref);$$

and,

$$ic(comp) = iLc - isc(ref);$$

where, the desired (reference) source currents in the three phases are given as,

$$isa(ref) = |Is(ref)| \times Ua = |Is(ref)| * sin\omega t$$

$$isb(ref) = |Is(ref)| \times Ub = |Is(ref)| * \sin(\omega t - 120°)$$

$$isc(ref) = |Is(ref)| \times Uc = |Is(ref)| * \sin(\omega t + 120°)$$

Ua, *Ub* and *Uc* are the unit amplitude templates of the phase to ground source voltages in the three phases respectively.

D. Controller for Maintaining Constant DC Bus Voltage of D-STATCOM

The operation of the D-STATCOM system requires ac main source to supply active power needed to the load and some losses (switching losses occurred in devices, losses in reactor and dielectric losses of dc capacitor) in the D-STATCOM. Since otherwise these losses will force the DC capacitor to discharge, resulting in a loss of tracking. Therefore, the reference source current used to decide the switching of the D-STATCOM, which use to have two components one is real fundamental frequency component of the load current being extracted using IRPT algorithm, SRF algorithm or I.cosφ algorithm and another component, that corresponds to the losses in the D-STATCOM, is estimated by the PI controller over dc voltage of D-STATCOM. To compute the second component of reference active current, a reference dc bus voltage (Vdc*) is compared with sensed dc bus voltage (Vdc) of D-STATCOM. The comparison of sensed dc bus voltage to the reference dc bus voltage of VSC outcomes in a voltage error, which in the nth sampling instant is expressed as:

$$Vdcl\ (n) = Vdc^*(n) - Vdc\ (n) \quad (10)$$

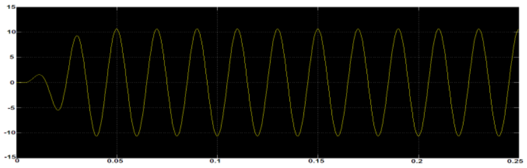
This error signal, Vdcl (n), is processed in a PI controller and the output of PI controller accounts for the losses in D-STATCOM and it is considered as loss component of the current. This component of current can be added with the average active power component for controlling D-STATCOM by IRPT algorithm. If the control is made by SRF theory the output of PI controller can be added with d-axis part of the current signal.

IV. Result and Discussion

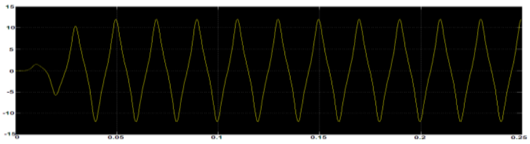
The performance of D-STATCOM is studied for all three algorithms of controlling. The following observations are made based on the results obtained. Under unbalanced source voltage conditions, a 45% amplitude unbalance is introduced in the b and c phases with respect to phase a, so that the phase voltages are 230 V in phase a, 334 V in phase b, and 127 V in phase c, respectively. The unbalance is reflected on the load currents in the three phases too.

A. Control of D-STATCOM by IRPT Algorithm

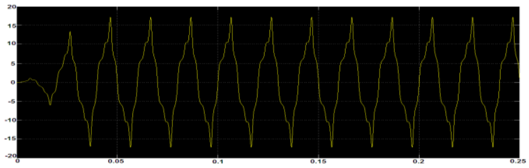
Fig. 4(a)-(c) shows the dynamic performance of D-STATCOM using the IRPT algorithm based current extractor under pure sinusoidal, asymmetric and distorted source voltage. Waveforms of extracted compensation current clearly shows that IRPT algorithm fails under asymmetric and distorted source voltage as extracted three phase compensation current of D-STATCOM is non-sinusoidal thereby will make the D-STATCOM source of disturbance itself.



(a)



(b)



(c)

Figure 4. Dynamic performance of D-STATCOM using the IRPT algorithm based current extractor

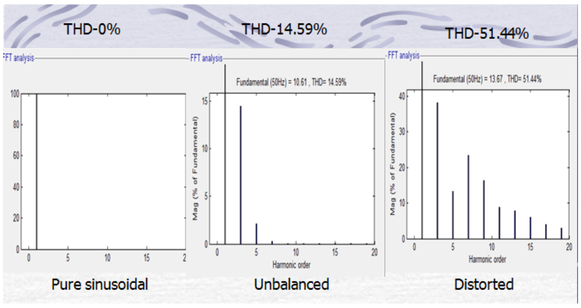


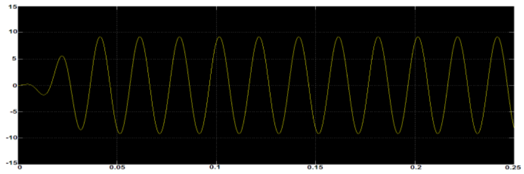
Figure 5. THD of current extracted with IRPT algorithm

Since, IRPT algorithm uses voltage signals to compute instantaneous active and reactive powers, hence any distortion and unbalance in source voltage will lead to inaccurate calculation of reference source currents which should contain only real fundamental frequency component of load current.

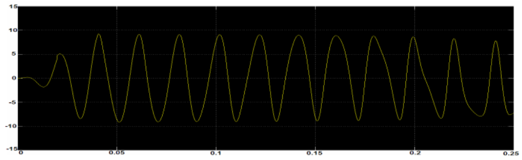
B. Control of D-STATCOM by SRF Algorithm

Fig. 6 (a)-(c) shows the dynamic performance of D-STATCOM using the SRF algorithm based current extractor under pure sinusoidal, asymmetric and distorted source voltage. Waveforms of extracted compensation current clearly shows that this algorithm also fails under asymmetric and distorted source voltage as extracted three phase compensation current of D-STATCOM is non-sinusoidal thereby will make the D-STATCOM source of disturbance itself.

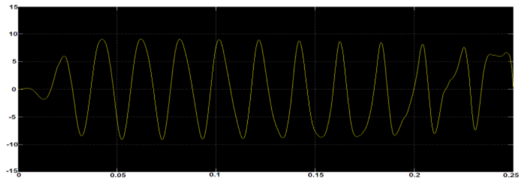
Since, SRF algorithm uses voltage signals to calculate instantaneous active and reactive powers, hence any distortion of harmonics and unbalance in source voltage will lead to imprecise calculation of reference source currents which should contain only real fundamental frequency component of load current.



(a)



(b)



(c)

Figure 6. Dynamic performance of D-STATCOM using the SRF algorithm based current extractor

LPF used for filtering the active power signal will cause delay in compensation. Further the generation of voltage templates (sine and cosine) using PLL plays a significant role in calculation of reference source currents, therefore the tuning of PLL is crucial. The operation of phase lock loop (PLL) slows as well as it imposes some amount of delay in calculation hence in compensation also.

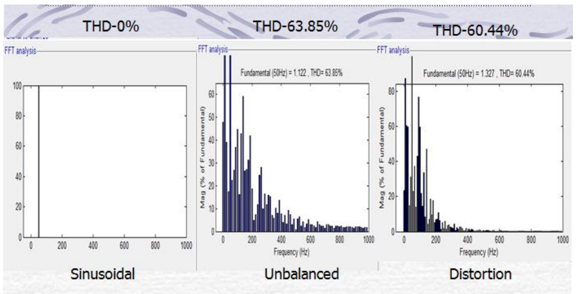


Figure 7. THD of current extracted with SRF algorithm

C. Control of D-STATCOM by I-cosϕ Algorithm

Fig. 8 shows the dynamic performance of D-STATCOM using I-cosϕ algorithm based current extractor under pure sinusoidal, asymmetric and distorted source voltage.

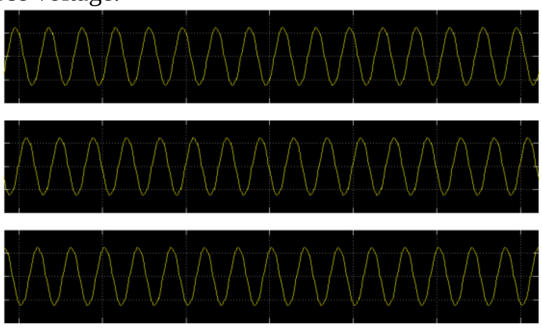


Figure 8. Dynamic performance of D-STATCOM using I-cosϕ algorithm based current extractor

Waveforms of extracted compensation current clearly shows that this algorithm also fails under asymmetric and distorted source voltage as extracted three phase compensation current of D-STATCOM is non-sinusoidal but its performance is somewhat better than IRPT and SRF algorithms.

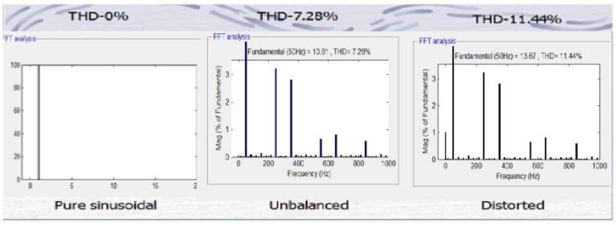


Figure 9. THD of current extracted with I-cosф algorithm

V. Conclusions

The paper presents a comparative study on effectiveness of three approaches for determining D-STATCOM reference compensation currents. The mathematical derivation of the IRPT, SRF and I-cosф algorithm has been employed to demonstrate the behavior of D-STATCOM. Simulation results show that D-STATCOM compensation strategies based on I-cosф algorithm is most effective in comparison with IRPT and SRF. This study can be extended to include more critical source voltage conditions for further evaluation of the effectiveness of these three compared compensation approaches.

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