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A New Approach for Resolving Power Quality Issues in a Distribution System with an Unbalanced Non-linear Load using Two DSTATCOMs

Deepthi Janyavula[1], Dr Satyendra Nath Saxena[2]

[1]Department of Electrical Engineering, Government Polytechnic, Sangareddy, Telangana 5002001, India
[2]ACE Engineering Academy, Hyderabad, Telangana 500090, India

Abstract
There is requirement of fast acting devices for power quality improvement due to rapidly changing nature of electric distribution. In this paper, a comparative analysis of power quality improvement in a three-phase three-wire distribution system has been observed when one distribution static compensator (DSTATCOM) is connected at the point of common coupling by a three-phase, two-winding transformer and two DSTATCOMs are connected by a three-phase, three-winding transformer. The two-winding and three-winding transformers are in star-delta and star-delta-delta configurations, respectively. The performance of the system is examined when the DSTATCOMs are operated in power factor correction and voltage regulation modes. Their performance is evaluated when various pulse-width-modulation techniques are used along with an unbalanced variable non-linear load. It has been shown that the usage of two DSTATCOMs yields power factor improvement, harmonic reduction and voltage regulation simultaneously.
Keywords: *Harmonic reduction, power factor improvement, voltage regulation, power quality improvement, distribution static compensator, synchronous reference frame theory.*

1. Introduction

Power systems are getting more complex due to the rapidly changing nature of loads and increasing demand of power supply. Power utilities are facing serious challenges to maintain continuity of supply and provide quality power to the consumer. Harmonic distortion, temporary and permanent interruption of supply, sag and swell in voltage, flicker and transients are some of the most commonly encountered power quality issues. Some of the power quality issues, solutions and standards are given in [1].

Several flexible AC transmission systems (FACTS) devices were introduced in the power system at various locations in order to tame the power quality issues pertaining to voltage and current. DSTATCOM is a shunt connected FACTS device. It is widely used to subdue power quality issues, such as, power factor improvement, mitigation of voltage sag, swell and flicker, and as an active power filter (in order to cut down the current harmonics). The next section explains how DSTATCOM can be used for power factor improvement, voltage regulation and harmonic reduction.

2. Configuration of DSTATCO M

Detailed survey of applications for DSTATCOM in power systems is given in [2] - [7]. DSTATCOM usage for power quality improvement has been demonstrated in [8] - [11]. Figure 1 shows a DSTATCOM, which is a shunt connected FACTS device, injecting or absorbing reactive current at the point of common coupling (PCC) dynamically.

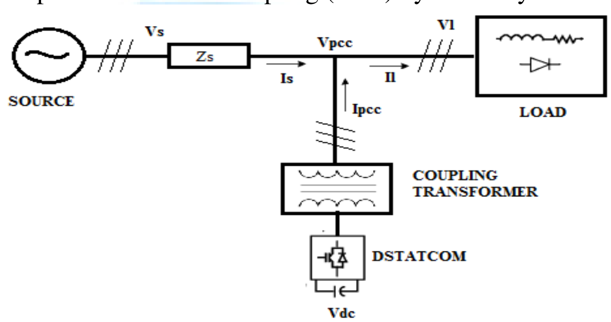

Fig. 1 Basic layout of DSTATCOM.

2.1 Power Factor Improvement

Most of the industrial loads, such as, induction motors, furnaces and discharge lamps, are inductive in nature. These loads will reduce the power factor, which requires increased current to meet the same load. This increased current has several detrimental effects, such as, increased copper losses, low efficiency, requirement of larger conductor size, increase in cost and poor voltage regulation. Power factor improvement can be done using static compensator, synchronous condenser and phase advancer. Compensation of displacement power factor using PI and feed forward controllers is given in [12]. Power factor correction by DSTATCOM using the instantaneous power control is explained in [13], [14]. Power factor control algorithm is presented in Figure 2. The load current is divided into d-q components. The filtered d-axis component is added to the error signal of DC bus voltage. The resultant is split into a-b-c components to obtain the reference signal of the source current.

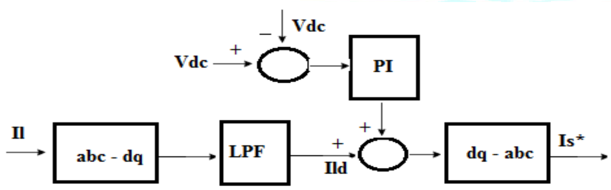

Fig. 2 Power factor control block diagram.

2.2 Voltage Regulation

Sudden changes in current or load and faults are the primary cause of sags and swells in power systems. A comprehensive survey of voltage sags/swells is provided by Sedaghati et al in [15]. A new method of voltage sags and swell detection and its comparison with existing methods is shown in [16]. Performance evaluation of a STATCOM used for overcoming voltage fluctuations is given in [17]. Mitigation of voltage sag, swell and power quality issues using DSTATCOM are explained in [18].
The voltage regulation loop is as depicted in Figure 3. The load current is split into d-q components using "a-b-c to d-q transformation". The q-axis component is added to the error signal of the source voltage. This signal is fed to "d-q to a-b-c transformation block" in order to generate reference source current.

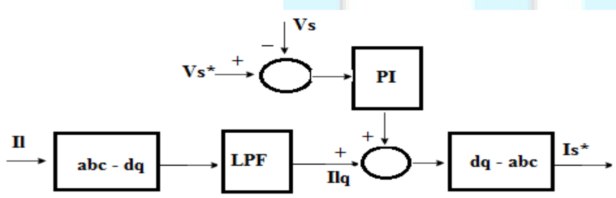

Fig. 3 Voltage regulation block diagram.

2.3 Harmonic Reduction

The role of power electronics is inevitable in modern day applications. This has contributed to the introduction of harmonic components, which bring on heat and torsional oscillations in motors. Reduction of harmonics using DSTATCOM has been explained in [19], [20]. Harmonic reduction can be obtained by timing the pulses of the insulated gate bipolar transistors (IGBTs) in the voltage source converter (VSC) of DSTATCOM in such a manner so as to cancel out the harmonics. The next section explains the proposed system configuration.

3. Mathematical Modeling

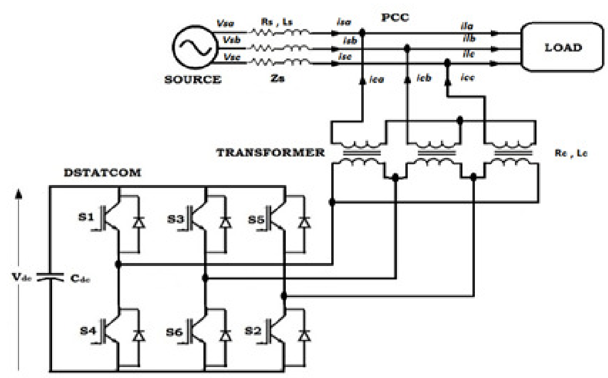

Fig. 4 Layout of DSTATCOM in a three-phase three-wire distribution system

Figure 4 shows the layout of DSTATCOM in a three-phase three-wire distribution system.
First order differential equation in a-b-c frame can be written as

$$\begin{aligned} R_c i_{ca} + L_c \frac{di_{ca}}{dt} &= v_{sa} - v_{ca} \\ R_c i_{cb} + L_c \frac{di_{cb}}{dt} &= v_{sb} - v_{cb} \\ R_c i_{cc} + L_c \frac{di_{cc}}{dt} &= v_{sc} - v_{cc} \end{aligned} \qquad (1)$$

The above equations can be rewritten as

$$\frac{d}{dt}\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \begin{bmatrix} -\frac{R_c}{L_c} & 0 & 0 \\ 0 & -\frac{R_c}{L_c} & 0 \\ 0 & 0 & -\frac{R_c}{L_c} \end{bmatrix} \begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} + \frac{1}{L_c}\begin{bmatrix} v_{sa} - v_{ca} \\ v_{sb} - v_{cb} \\ v_{sc} - v_{cc} \end{bmatrix} \qquad (2)$$

Using synchronous reference frame theory, these equations can be converted into d-q frame using Park's transformation as

$$R_c i_d + L_c \frac{di_d}{dt} = v_{sd} - mv_{dc}\cos\alpha + L_c \omega i_q$$
$$R_c i_q + L_c \frac{di_q}{dt} = v_{sq} + mv_{dc}\sin\alpha - L_c \omega i_d \quad (3)$$

Where w → angular frequency of the system
m → modulation index

Rewriting the above equations in matrix form, we get

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \end{bmatrix} = \begin{bmatrix} -\frac{R_c}{L_c} & \omega \\ \omega & -\frac{R_c}{L_c} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L_c} \begin{bmatrix} v_{sd} - v_{pd} \\ v_{sq} + v_{pq} \end{bmatrix} \quad (4)$$

Where

$$v_{pd} = mv_{dc}\cos\alpha$$
$$v_{pq} = mv_{dc}\sin\alpha$$

4. Proposed System

The proposed system is a three-phase three-wire system. Its parameters are presented in Table 1. A sag and swell of 25% of the rated value is introduced in the source voltage during the interval (0.2-0.3)s and (0.6-0.8)s, respectively. The load consists of a combination of unbalanced and a variable non-linear load. Three different values of resistive and inductive components in the three phases form the unbalanced component. A three-phase SCR bridge with resistive load forms the non-linear part of the load. Results are also observed when the load is made purely non-linear i.e., a three-phase diode bridge rectifier is used.

Table 1. System parameters

Parameter	Value
Source RMS Voltage	415V
System Frequency	50Hz
Line impedance	(0.01+j0.626) Ω
Ripple Filter	Rf=5 Ω, Cf=5μF
Unbalanced Load	R Phase : 25 Ω, 1 mH Y Phase : 5 Ω B Phase : 10 Ω, 5 mH
Nonlinear Load	Three-phase SCR converter with R= 25Ω
DC Bus Voltage	700V
DC Bus Capacitance	3mF

Several control algorithms for DSTATCOM, such as, instantaneous reactive power theory, synchronous reference frame theory, and Adaline based algorithms have been described in literature [21]. In the proposed work, synchronous reference frame theory has been applied. Applying this algorithm, the source reference current required to obtain the desired performance can be obtained from the power factor improvement and voltage regulation loops. The reference and the actual values of source current are given to the pulse-width-modulation block to generate the pulses for switching devices of DSTATCOM.

An inductive interface is essential in order to connect the DSTATCOM to the PCC. Several transformer configurations, such as, star-hexagon, star-delta and t-connection can be used to connect the DSTATCOM at the PCC. In the proposed work, a star-delta transformer has been used.

A single DSTATCOM can be made to operate either in the power factor improvement (PFI) mode or voltage regulation (VR) mode. So, the drawback of a single DSTATCOM is that either PFI or VR can be obtained, but not both. Hence, in order to overcome this drawback, two DSTATCOMs have been used in the proposed work as shown in Figure 5; where, one DSTATCOM will take care of the power factor and the other will look into the voltage regulation. In order to connect the two DSTATCOMs to the PCC of the proposed system, a star-delta-delta transformer is used.

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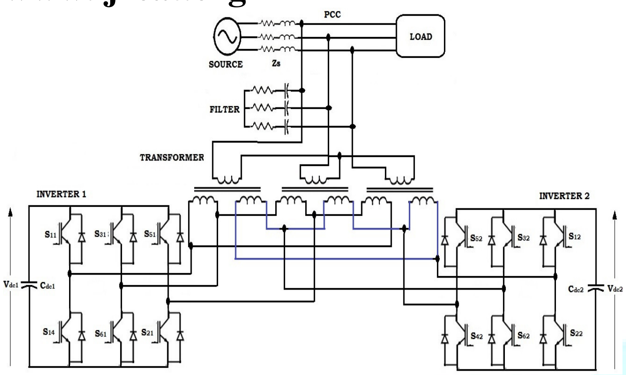

Fig. 5 Two DSTATCOMs connected to a three-phase three-wire distribution system

For generating the pulses for switching devices of DSTATCOM, sinusoidal pulse-width-modulation (SWPM), space vector modulation (SVM) and hysteresis pulse-width-modulation (HPWM) have been used. The results obtained when one/two DSTATCOMs are used in PFI/VR mode of operation and pulse generation done by SPWM/SVM/HPWM are given in the next section.

5. Results

All the waveforms shown below correspond to the results when the three-phase SCR converter connected to the load is fired at an angle of 30°. For the system under consideration without DSTATCOM, the source voltage, source current, load voltage and load current are given in Figure 6. It can clearly be understood that the source voltage experiences sag and swell during the interval (0.2-0.3)s and (0.6-0.8)s, respectively.

Figure 7 and Figure 8 depict waveforms when one DSTATCOM is used for compensation and is controlled by SPWM in PFI mode of functioning. Inspite of inductive and non-linear components in load, it can be observed from Figure 7 that the PCC voltage and source current are in phase with respect to each other. Figure 8 shows the source, PCC and load voltages in PFI mode of operation. Therefore, it is clear that the load voltage is not regulated in this mode of operation.

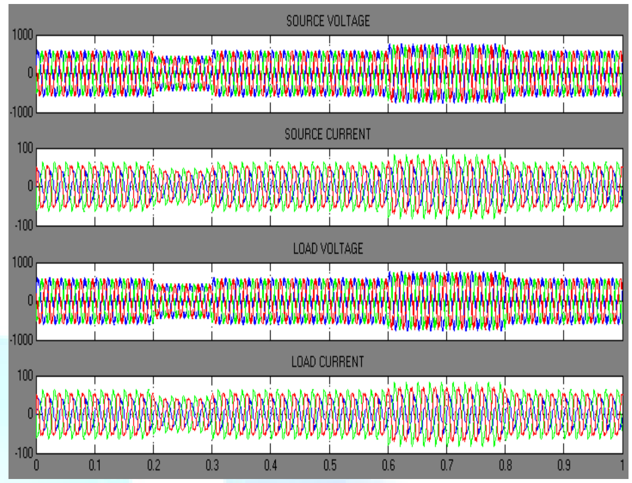

Fig 6. Waveforms without DSTATCOM

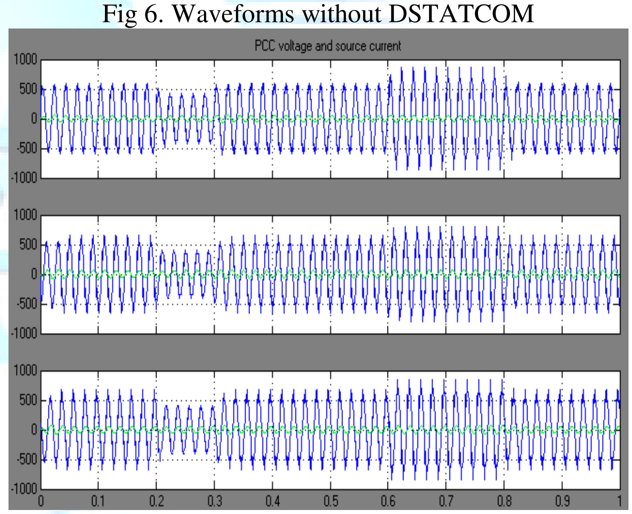

Fig 7. PCC voltage versus source current in PFI mode with one DSTATCOM

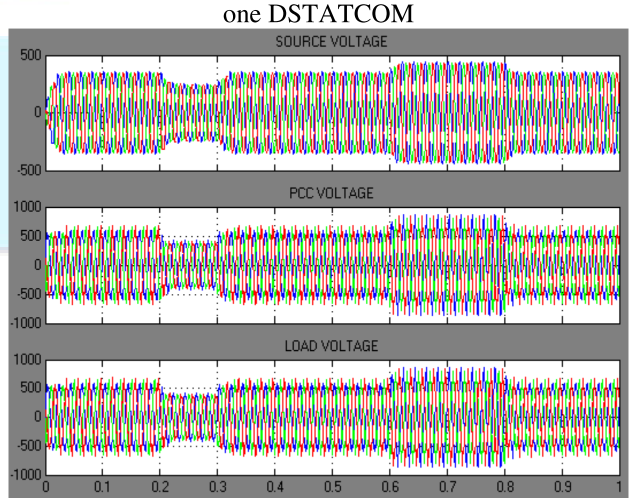

Fig 8. Source, PCC and load voltages in PFI mode with one DSTATCOM

Figure 9 and Figure 10 depict waveforms when one DSTATCOM is used for compensation and is controlled by SPWM in VR mode of operation. Figure 9 shows the PCC voltage and source current, which are observed to be out of phase with respect to each other. Figure 10 shows source, PCC and load voltages. It can clearly be observed that the load voltage is regulated even during the presence of sag and swell in the source voltage.

It is clearly evident from waveforms of Figure 7 – Figure 10 that PFI and VR modes of operation cannot be achieved simultaneously by using one DSTATCOM. Hence, two DSTATCOMs are connected to the proposed scheme. Among the two DSTATCOMs, one operates in PFI mode and the other in VR mode.

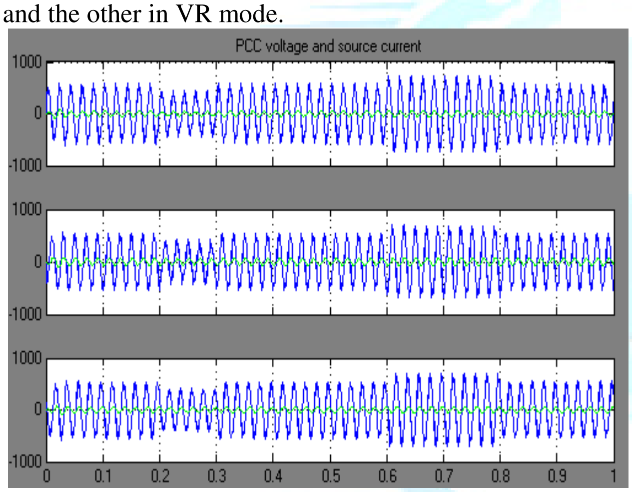

Fig 9. PCC voltage versus source current in VR mode with one DSTATCOM

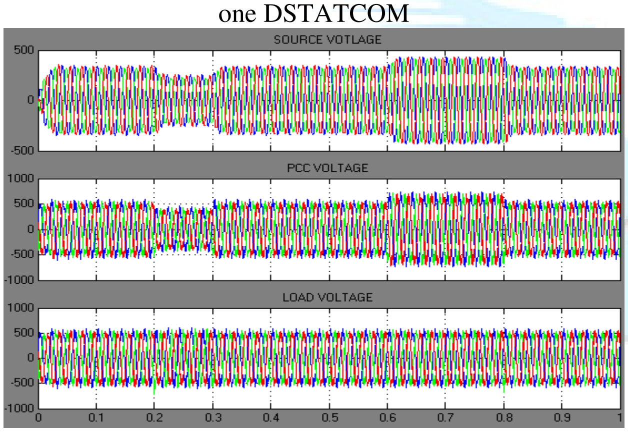

Fig 10. Source, PCC and load voltages in VR mode with one DSTATCOM

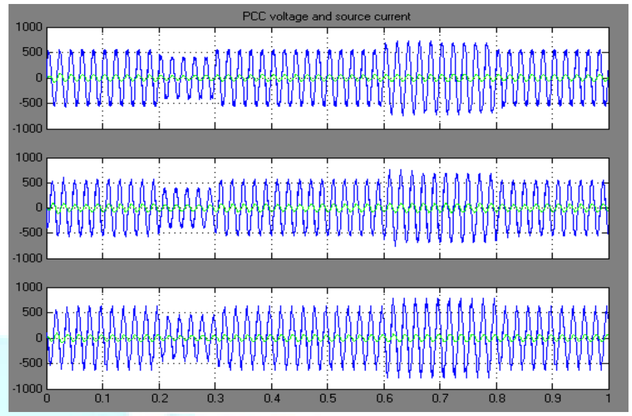

Fig 11. PCC voltage versus source current with two DSTATCOMs

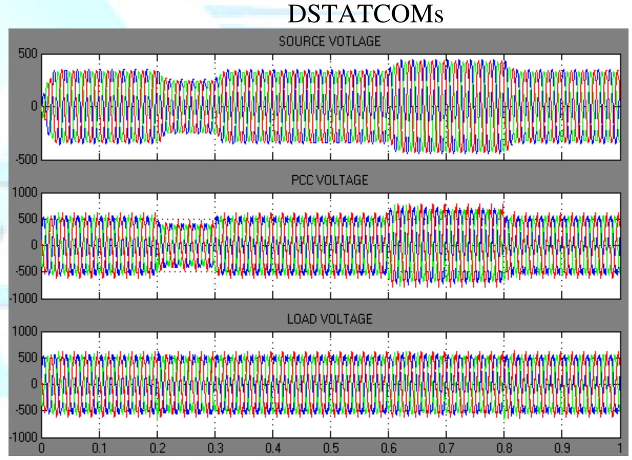

Fig 12. Source, PCC and load voltages with two DSTATCOMs

Figure 11 and Figure 12 depict waveforms when two DSTATCOMs are used for compensation, and both are controlled by SPWM. Figure 11 shows the PCC voltage and source current, which are observed to be in phase with respect to each other eventhough the load consists of non-linear elements. Figure 12 shows the source, PCC and load voltages. The load voltage is regulated to a constant value even in the presence of sag and swell in the source voltage. Therefore, it can be observed that both PFI and VR modes of operation can be attained simultaneously by using two DSTATCOMs

Table 2. THD values for various control strategies with a single DSTATCOM

Control Strategy	THD for firing angle	
	30°	60°
Without DSTATCOM	18.03%	5.14%
PFI – SPWM	2.15%	4.48%
VR – SPWM	2.94%	1.61%
PFI – SVM	0.67%	0.12%
VR – SVM	0.99%	0.17%

PFI – HPWM	2.18%	4.38%
VR – HPWM	0.61%	1.22%

Table 3. THD values for various control strategies with two DSTATCOMs

Control Strategy	THD for firing angle	
	30°	60°
PFI & VR – SPWM	2.05%	3.51%
PFI & VR – SVM	0.49%	0.55%
PFI & VR – HPWM	2.8%	4.62%
PFI– SPWM & VR – SVM	1%	1.15%
PFI– SVM & VR – SPWM	0.57%	0.58%
PFI– HPWM & VR – SVM	1.8%	2.43%
PFI– SVM & VR – HPWM	0.24%	0.28%
PFI – HPWM & VR – SPWM	2.8%	4.63%
PFI – SPWM & VR – HPWM	2.83%	4.62%

Performance of DSTATCOM is also observed by using SVM and HPWM in place SPWM for the proposed system for all the above cases. The THD values of phase-A source current for various firing angles and control strategies of the proposed system using one and two DSTATCOMs are given in Table 2 and Table 3, respectively. It can be inferred from the tabulated values that with DSTATCOM, the THD of phase-A source current decreased significantly, which complies with IEEE – 519 standard. As per IEEE 519 standard, the acceptable level of THD is less than 5%.

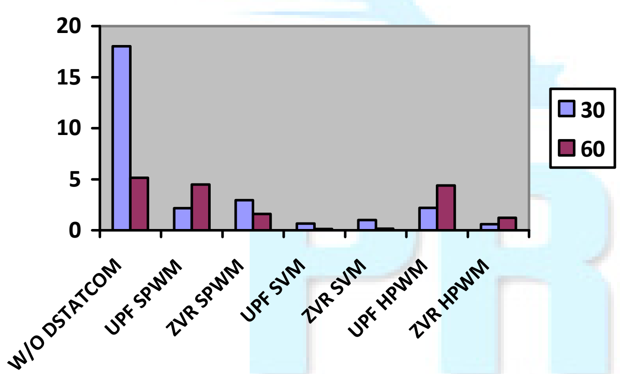

Fig 13. THD value of phase-A source current with one DSTATCOM

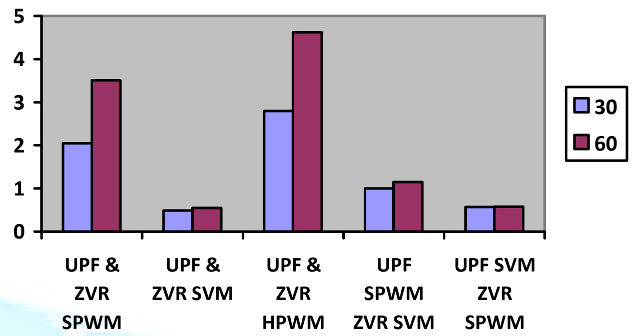

Fig 14. THD value of phase-A source current with two DSTATCOMs

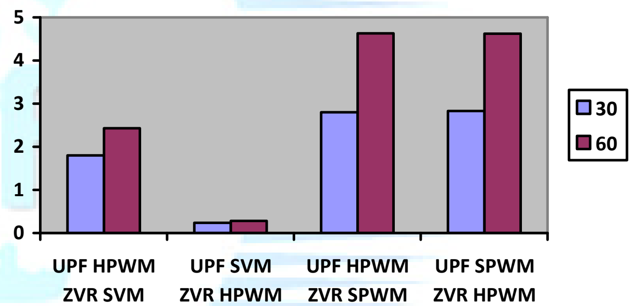

Fig 15. THD value of phase-A source current with two DSTATCOMs

When firing angles of load side three-phase SCR converter are 30 and 60 degrees without DSTATCOM, the THD of phase-A source current is 18.03% and 5.14%, respectively. But, when two DSTATCOMs are used, with one DSTATCOM operated in PFI mode controlled by SVM and the other DSTATCOM operated in VR mode controlled by HPWM, the lowest value of THD, i.e., 0.24%, 0.28%, have been obtained for firing angles of 30 and 60 degrees, respectively. The same information is also depicted in Figure 13 – Figure 15.

6. Conclusion

This paper gives the results of voltage and current waveforms at the source and load sides for a period of one second for a three-phase three-wire system. During this one second, there was a sag for 0.1 s and later a swell for 0.2 s in the supply voltage. The operation of the arrangement is observed when load is variable non-linear load. In the above cases, the THD values have been compared for different control schemes using one and two DSTATCOMs connected at the PCC. It has been observed that PFI, VR modes of operation and harmonic reduction can be achieved simultaneously by using two DSTATCOMs. It has likewise been shown that, with two DSTATCOMS, the minimum value of THD is obtained when one DSTATCOM operates in PFI mode controlled by SVM and the other DSTATCOM operates in VR mode controlled by HPWM for an unbalanced and variable non-linear load.

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