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Performance Evaluation of a Three-Phase Improved Power Quality Converter under Unbalanced Mains Conditions

Deepak Sharma[1], Abdul Hamid Bhat[2], Aijaz Ahmad[3]
[1, 2, 3]Department of Electrical Engineering, National Institute of Technology, Srinagar, Jammu and Kashmir,
Email address: [1]deepaksmail99@yahoo.com, [2]bhatdee@nitsri.net, [3]aijazahmad45@gmail.com

***Abstract*—**Space vector modulation (SVM) algorithm has been used for the control of the Converter. The trajectory of reference vector is very important for SVM technique to obtain exact switching times under balanced/unbalanced voltage disturbance. Due to unbalanced voltage disturbance in a three-phase system, the trajectory of reference vector gets affected which results in low input power factor, high input current THD and high ripple factor of the DC output voltage. This paper presents an improved control approach for better performance of Three-phase Improved Power Quality Converters (IPQC) with unbalanced AC Mains. This improvement is achieved using technique based on retransformation of Clarke Transformation for unbalanced AC Mains. Three-Phase, IPQC system along with proposed control scheme is modeled in MATLAB/Simulink environment. The simulation results are presented to demonstrate the effectiveness of the new proposed control technique. Three-Phase IPQC with proposed control scheme displays better performance with nearly unity input power factor, low input current THD and reduced ripple factor of the regulated DC output voltage under unbalanced AC mains.

Keywords— Power quality; improved power quality converters; multilevel converters; harmonics compensation; unbalanced AC mains.

I. INTRODUCTION

AC-DC power converters are extensively used in various applications like power supplies, HVDC transmission, UPSs, SMPSs, front-end converters in adjustable-speed ac drives and utility interface with non-conventional energy sources and power supplies for telecommunications systems. Traditionally, AC-DC power conversion was done by diode rectifiers or phase-controlled converters but they suffered from serious drawbacks like poor input power factor and distorted line currents which results in poor performance of sensitive equipments and other associated power quality problems in power system.

Power quality is defined in the IEEE 100 Authoritative Dictionary of IEEE Standard Terms as "The concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment Utilities may want to define power quality as reliability" [1]. Voltage sag (dip) is the power quality problem that is defined by IEEE-1159 (1995) as a decrease in rms voltage to between 0.1 to 0.9 of nominal voltage at power frequency for duration of 0.5 cycle to 1 minute [2], [3]. Voltage swell is also a power quality problem that is defined by IEEE-1159 (1995) as an increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min. Typical magnitudes are between 1.1 and 1.8 pu [4].

Use of passive filters, active power filters and hybrid filters has been made along with conventional rectifiers to meet these standards and improve the power quality, especially in high power rating and already existing installations. The fixed compensation, bulkiness of the components, series and parallel resonance phenomena in passive filters and large rating and complexity of active power filters are the greatest drawbacks with these compensation techniques.

Recently IPQCs are included as an inherent part of the AC-DC conversion system for higher efficiency, reduced size, and well regulated DC output. They act as linear loads on power systems. The output voltage in these converters is regulated even under the fluctuations of the input voltage but up to some limited range.

In the literature, limited work has been reported on the effects of the unbalanced voltage disturbances on converters. Most related work is based on detection and classification of the unbalanced supply in power system [5-15].There are some schemes reported in the literature to overcome the problem of unbalance supply by providing insensitivity towards supply disturbances within certain limited ranges [13-15]. The [14] schemes is based on providing insensitivity towards supply disturbances using inverse Clarke Transformation. But no compensation technique is reported for optimising the performance of the converter using SVPWM under unbalanced main condition.

In conventional SVPWM scheme, reference vector of particular magnitude moves with uniform angular velocity resulting in a circular trajectory in α-β plane. The angular velocity depends upon the supply frequency and magnitude depends upon load conditions. This revolving vector is responsible for generating switching pulses for various phase lags of IPQC. The switching pulses are based upon nearest three vector scheme (decided by angle ø) and their timings depend upon the magnitude of the space vector or the modulation index. The duty cycle for each leg is same but displaced 120^0. Under unbalanced AC mains, the trajectory vector is disturbed resulting in deviations of source and load side parameters beyond acceptable limits. These non- ideal

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supply conditions are regularly encountered in practical operating conditions resulting in the deteriorating performance of converter in real time applications. The stable operation of the IPQC under disturbed mains condition is a burning issue and has been a topic of intensive international research.
In this paper an attempt has been made to minimize the effect of unbalanced ac supply and to maintain source and load parameters within acceptable limits i.e. nearly unity input power factor, low input current THD and reduced ripple factor of the regulated DC output voltage.

II. PROPOSED TECHNIQUE

To overcome power quality issue, new compensated technique is proposed. The proposed algorithm is used to form a required reference space vector trajectory for particular unbalanced magnitude in respective phase(s) by modifying current vector of Under ideal conditions, the duty cycle of all the phase legs of the 2 level IPQC is same but displaced by 120^0 . Under unbalanced conditions, the duty cycle for each phase leg of IPQC needs to be modified for maintaining load and source parameters within acceptable limits. This modification of duty cycle is achieved by implementing the proposed algorithm in the control scheme. The important requirement for the proposed control algorithm is that it very simple, easy to implement, works satisfactorily under large supply disturbances and gives excellent performance of the converter in terms of unity power factor, low input current THD and less ripple factor of the regulated DC output voltage with unbalanced AC mains. The three-phase IPQC, as shown in Fig.1.

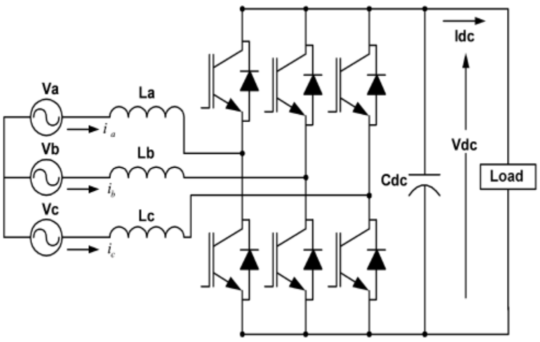

Fig. 1. Bi-directional three-phase boost converter topology.

provides smooth powering and regeneration capability with 6 semiconductor power switches. Its current regulators can control the power factor close to unity and the boost inductance L limits the magnitude of the input current ripple, thus reducing harmonics and it also serves as an energy-storage device to allow the overall converter circuit to act as a boost rectifier. Fig.2 shows the overall control scheme of the converter. The outer-loop PI voltage controller controls the magnitude of the reference space vector. Voltage control loop of the converter and the inner-loop PI current controllers controls the d and q components of the source current, resulting in the unity power factor operation of the converter. Space vector PWM is used as the modulation algorithm for the control of converter.

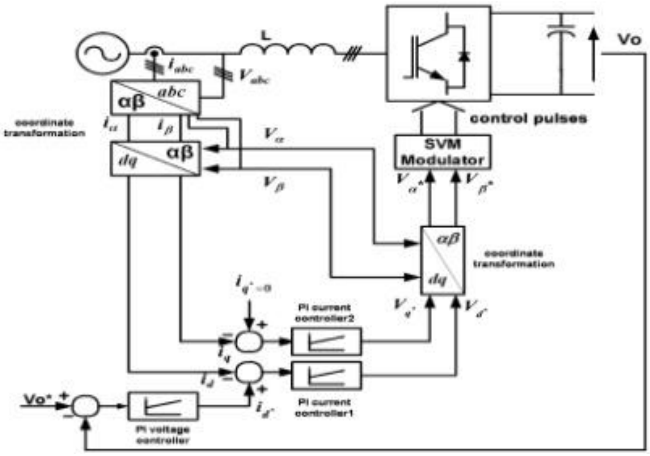

Fig. 2. Block diagram of voltage-oriented control scheme.

The proposed algorithm is used to form a required reference space vector trajectory for particular unbalanced magnitude in respective phase(s) by modifying current vector of Clarke Transformation in order to minimize the effect of unbalanced voltage disturbances. Modified reference space vector will modify modulation index, so as to vary duty cycle ratio of each leg of the IPQC. Under balanced conditions, three-phase IPQC has same input current in all phases, with high input power factor, low input current THD and less ripple factor of the regulated DC output voltage. The needed space vector trajectory is circular. But in case of unbalanced condition, the trajectory of space vector should be an ellipse in shape as shown in figs 3.

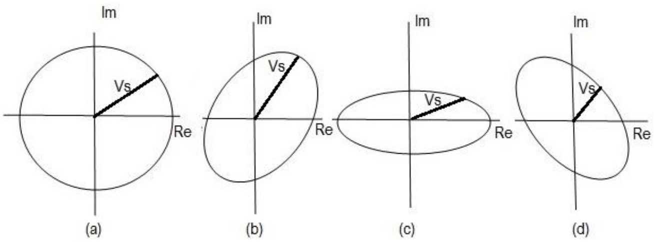

Fig. 3. Desired shape of the space vector trajectory: (a) under balanced condition, (b) single phase dip on phase A, (c) single phase dip on phase B, (d) single phase dip on C.

In other words to minimize the effects of unbalanced voltage disturbances for different faults, the original model of the Clarke Transformation is again transformed for current vector, in order to take care of increase in THD, unequal supply current to the rectifier, low power factor, non sinusoidal current wave forms and unregulated DC output voltage. The space vector trajectory is made up of positive angular frequency, and follows a circle in the complex plane with equal radius at every point in the space vector trajectory. When there is a balanced dips in all phases, the radius become smaller with same circular shape of the space vector trajectory. Under unbalanced dip condition, the space vector trajectory becomes irregular circle due to presence of positive and negative angular frequency, this forms an ellipse if

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magnitudes are high for both positive and negative angular frequency. Under balanced condition, main objective of Space Vector PWM technique is to form reference voltage vector 'Vs' to obtain exact switching times. The reference voltage vector 'Vs' is obtained by mapping three phase output voltages (line to neutral) in the (d-q) frame through the Clarke transform given by,

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \frac{1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{AN} \\ v_{BN} \\ v_{CN} \end{bmatrix} \quad (1)$$

Under balanced three phase sinusoidal voltages, Vs is a vector rotating, forming a circular trajectory in shape in the complex (α - β) plane at a constant amplitude with fundamental angular speed. This circular trajectory is sampled instantly in each 60^0 in order to have 6 active vectors sector for two level three-phase rectifiers as shown in fig.4.There are two more non active sectors. So there are eight basic space vectors defined for the combination of the switches.

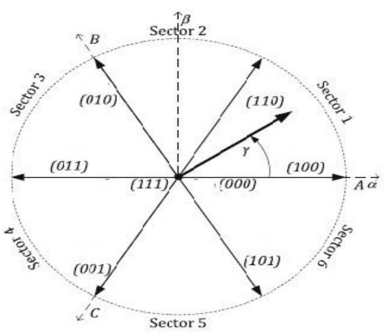

Fig. 4. Rotating reference vector.

In order to have modified modulation in each sector, it is required to generate the reference vector Vs for that particular sector. Time average of the associated basic space vectors is required for each sector, which is synthesized as a linear combination of the two adjacent space vectors, Ux and Uy which form any sector.

Vs = TaUx + TbUy + ToUz (2)

The sum of duty ratios for a PWM period is always constant i.e.

Ta + Tb + To = constant value (3)

and the magnitude of the Vs depends on the duty ratio of active vectors only as zero vectors makes no effect on the IPQC voltage but are used for balancing the voltage. From equations (2) and (3), Vs magnitude in respective sector affects the duty ratios Ta, Tb, To will change accordingly but the total sum of the duty ratios in the each sector will remain same (i.e. Ta + Tb + To = Constant value). Therefore switching time for a switching state can be increased or decreased according to requirement. It is noticed that under unbalanced conditions, the supply currents became unbalanced because of the non-circular trajectory of the space vector as shown in Fig.3.In order to have same supply currents in all the phases, the duty time for rectifier legs on which sag occurs must be increased and the duty time for the rectifier legs on which current increases after sag must be reduced. Therefore, for a particular sector, if Ta changes (increases/decreases) for any switching state, then Tb and To will change (increase/decrease) for associated switching state and vice versa.

$Vs=MV_{max}=TaUx+TbUy+ToUz$ (4)

where M is the modulation index and V_{max} is the maximum value of the desired dc voltage

Now, projecting Vs along the two adjacent space vectors Ux and Uy, we have,

$MV_{max}\cos\alpha=Ta|Ux|+Tb|Uy|\cos60^0$ (5)

$MV_{max}\sin\alpha=|Uy|\sin60^0$ (6)

Since the voltages are normalized by the maximum phase voltage V_{max}=Constant value. Then by knowing |Ux| = |Uy| = $\frac{2}{\sqrt{3}}$ (when normalized by maximum phase voltage).

The duty ratios can be derived as,

Ta=M sin(60-α) (7)

Tb=M sin(α) (8)

Substituting equations 7, 8 in equation

Vs=(Msin(60-α))(Ux)+(Msin(α))(Uy)+(Msin(60-α)+(Msin(α)-1ordesired)(Uz) (9)

III. Proposed Technique

In the case of any symmetric three-phase system, the space vector trajectory is circular in shape, but in case of asymmetric three-phase system, the space vector trajectory is elliptical in shape. If there is no zero component (in case of symmetric three-phase system), the current vector is created from the positive-sequence phasor rotating in the positive direction at electrical angular speed and complex conjugate current of the negative sequence phasor rotating in the negative direction at angular speed. Both positive-sequence and the negative-sequence components are constant which results in a circular trajectory of the space vector. A three phase system can be represented using a local phase shift of 120 electrical degrees between the different phases.

An asymmetric system can be represented by introducing the suitable temporal components to the current vector, which will automatically result in required space vector elliptical orbit. The basic theory of the proposed controller is based on the GWLS (*Generalised weighted Least Square*) algorithm. The proposed controllers retransform the Clark Transformation for improving the power quality of IPQC under unbalanced supply by making use of adjustable suitable weight at the input power side of converter. Weights at input supply sides for current vector are adjusted linearly in proportional to variation till same current flows in all the phases. The weights are variable and the change as per magnitude of the sag .The estimation of weight at any given of time is given by,

Estimation of weight (I_{x1} I_{x2} I_{x3}) = Initial weight (at balanced condition) ± Error between the line currents.

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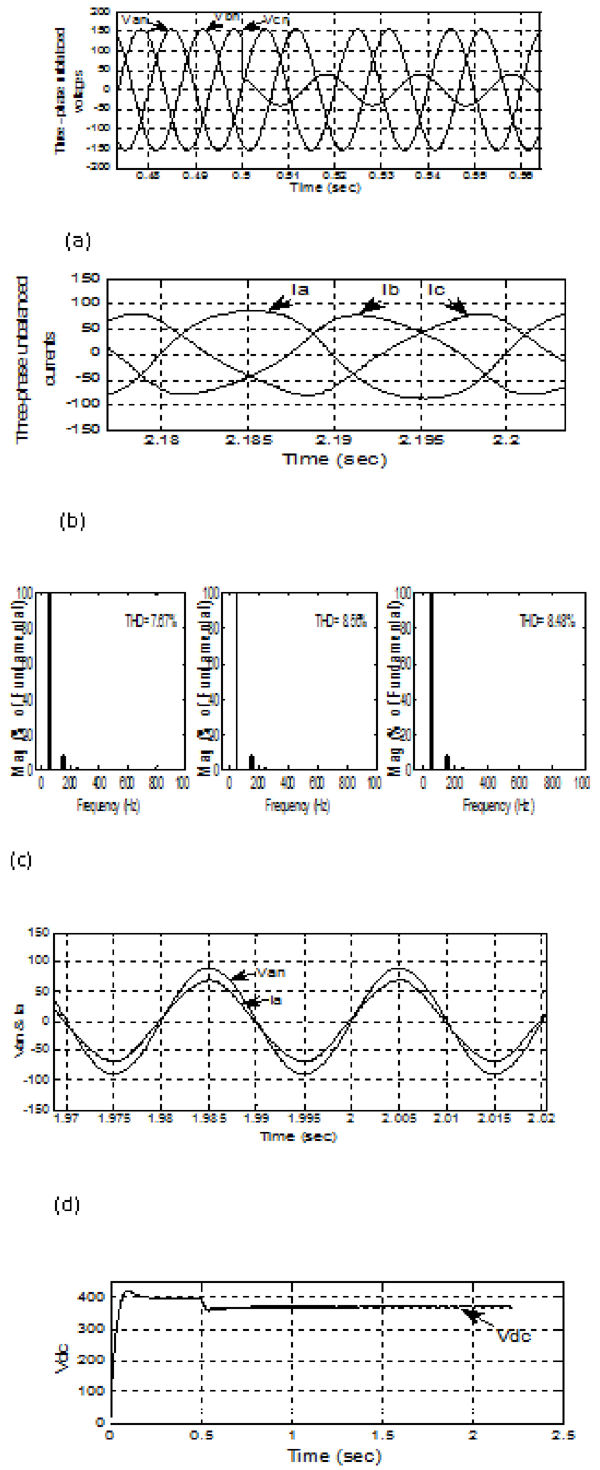

Fig: 6 i) For unbalanced phase voltage in phase 'a, without proposed controller.
a) Three-phase unbalanced supply voltages.
b) Three-phase unbalanced currents drawn by rectifier.
c) High THD of source currents
d) Source voltage & current for phase 'a', with low input supply power factor.
e) High ripples and dips in V_{dc}.

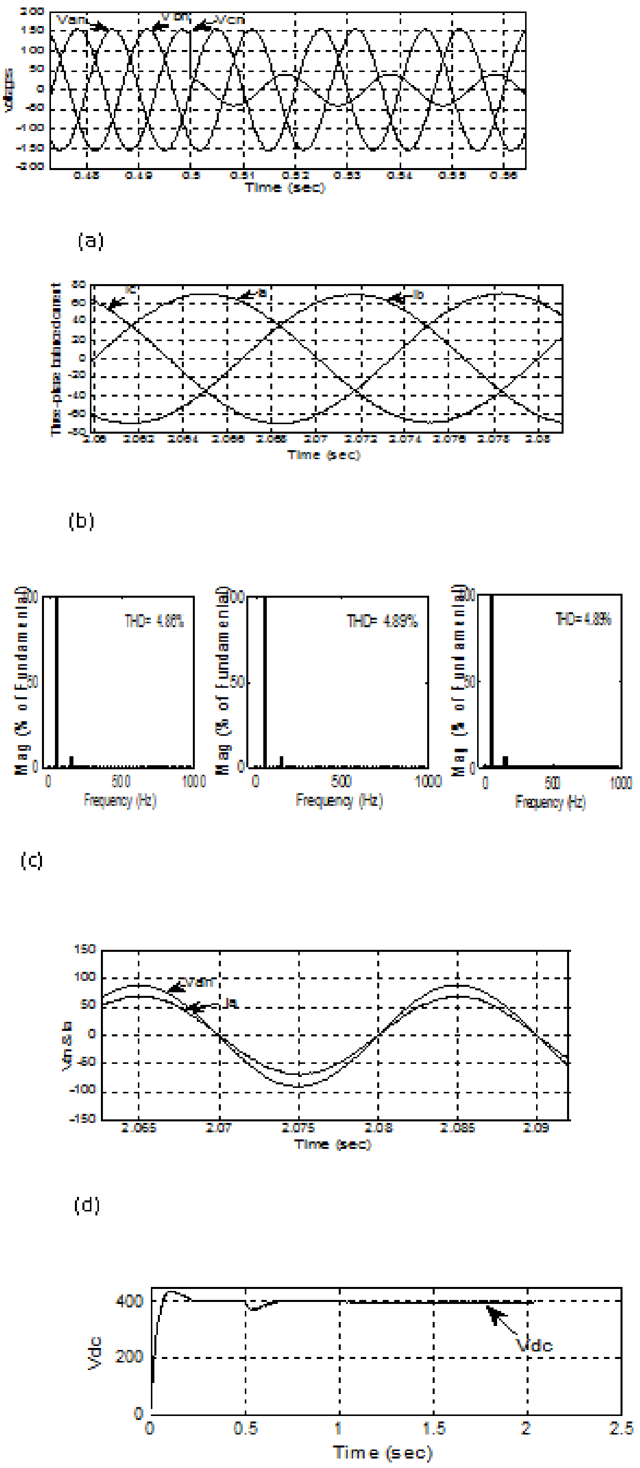

Fig: 6 ii) For unbalanced phase voltage in phase 'a' with proposed controller.
a) Three-phase unbalanced supply voltages.
b) Three-phase balanced currents drawn by rectifier.
c) THD of source currents
d). Source voltage & current for phase 'a', with near unity supply power factor.
e) Less ripples with regulated V_{dc}

The scaling used for V_α,V_β is compensated in proportion to change in the original magnitude of V_α,V_β as given by, Compensated value can be formulated as n = Constant value (under balance condition) X multiplying factor ± difference in the sag. Power quality can be maintained after implementing both the steps describe above for any type of sag. The

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following transformed equations (10) & (11) were framed out keeping in view any type of voltage sag.

$$\begin{bmatrix} v_{\alpha} \\ v\beta \end{bmatrix} = n_{(\alpha,\ \beta)} \begin{bmatrix} 1 & \frac{1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} I_{\alpha} \\ I_{\beta} \end{bmatrix} = N \begin{bmatrix} 1/Ix1 & \frac{1}{2}/Ix2 & \frac{-1}{2}\ /Ix3 \\ 0 & \frac{\sqrt{3}}{2}/Ix2 & -\frac{\sqrt{3}}{2}/Ix3 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (11)$$

where $n_{(\alpha,\beta)}$ is the new coefficient value for V_{α}, V_{β}.
N is the new coefficient value for I_{α}, I_{β}.
x1, Ix2, Ix3= new transformed values.

The main inconvenience in already proposed algorithms is reported in the literature that they need consistent details of exact measurements of error at each step till iteration process stops. This is not practical in real time applications where system cannot wait even for the completion of one cycle for the generation of error. So there is desperately a need of an algorithm for deriving estimates only from whatever available data. This is achieved by retransformation of Clarks Transformation. It has the advantages such as, it is straight forward in nature, it does not require any data in vector form or matrix inversion, and it does not require any other correlation measurements.

IV. Performance Evaluation

The performance of traditionally controlled IPQC and proposed Control of IPQC under unbalanced condition converter is evaluated using MATLAB/Simulink and Sim Power System environment. For Three-Phase, bidirectional rectifier, the system parameters are: Peak Input Phase Voltage =155.6 V, 50Hz.Boost inductance = 1mH, operating frequency is 5 KHz. The desired DC-link voltage of the proposed rectifier is set at 400 V. Traditionally Control IPQC and Modified Control IPQC under unbalanced condition
At t=0.5 sec, the controller is tested by introducing voltage magnitude unbalance of peak input phase voltage 40 V in phase C and peak input phase voltage 155.6 V in phase A and B. Comparative results from fig: 8 reveal that under unbalanced mains condition, there is low input power factor, high input current THD without controller. With proposed controller the maximum THD of the source currents Ia, Ib, Ic reduced to just 4.86%, 4.89%, 4.89% from 7.67%, 8.56%, 8.48% respectively, which is well within acceptable limits. Further with the proposed algorithm, there is no reduction in DC bus voltage and ripple content is negligible.

V. Conclusion

In this paper, a new technique based on Clarke transformation is proposed for unbalanced conditions and analysis is also done to mininise the effects on the balanced/ unbalanced voltage disturbances in the conventional SVPWM. Simulation results are explored using Matlab/Simulink software. Relevant figures and graphs have been shown to understand the conclusive results for the simulation model. The source current harmonics are compensated very effectively by using the new proposed technique and also at the same time maintaining unity input power factor, low input current THD and regulated DC output voltage. The proposed control algorithm proves to be very effective in addressing the voltage sags (balanced and unbalanced) which are practically encountered in real power system.

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