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Unified Power Quality Conditioner with minimum VA rating for harmonic compensation

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Abstract : The project deals with Minimum VA rating handled by a Unified Power Quality Conditioner, which consists of Series and Shunt Active Power Filter. The Series Active Filter is Dynamic Voltage Restorer (DVR), which regulates the voltage at the point of common coupling with minimum VA loading. The Shunt Active Filter is Distribution Static Compensator (DSTATCOM) which compensates the reactive power and eliminates the load current harmonics from the source current. In this proposed method the total power handled by UPQC is minimum than the other conventional methods and it has been investigated by simulation using MATLAB/SIMULINK.

Keywords: Unified Power Quality Conditioner (UPQC), Dynamic Voltage Restorer (DVR), Static Compensator (STATCOM), Minimum VA, Optimum angle, injection voltage and voltage sag.

I. INTRODUCTION

Power quality problems are arising due to increased use of the non-linear (power electronic) loads, the faults in distribution network, the starting and stopping of heavy loads. In that, load harmonic currents, voltage sag, swell, and reactive power are considered as major power quality problems. These causes the tripping of contactors and relays, damage of sensitive equipments, over heating of the cables and the equipments, electromagnetic interference with the communication systems and loss of efficiency in electrical machines.

UPQC is a modern CUSTOM power device, which is used to solve almost all types of power quality problems. The UPQC consists of series and shunt active filter as shown in fig.1. Series active filter is used to mitigate the voltage sag and swell problems and shunt active filter is used to improve the power factor and eliminate the load harmonics. In series active filter the voltage will be injected at an optimum angle. In that optimum angle total VA requirement of UPQC will be less than the UPQC-P (series injected voltage is in phase with the source current) and the UPQC-Q (series injected voltage is in 90^0 with the source current) method. Therefore, the active power requirement will be less than the UPQC-P and an injected voltage magnitude is less than the UPQC-Q. The minimum VA method is one of the effective methods among others.

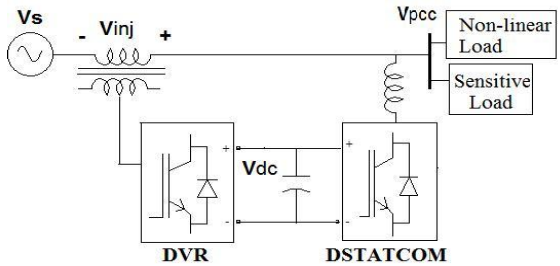


Fig.1. Schematic diagram of UPQC

Regarding to this project,

- The schematic block diagram of UPQC is explained section I. The phase diagram of various sag compensation methods have shown separately in section II. The control block diagram for both DVR and STATCOM is explained in section III.
- The minimum VA calculation and the step by step procedure of minimum VA algorithm have been developed in section IV.
- The simulation results of minimum VA method are presented and also the power handled by the UPQC in other methods are graphically represented and tabulated in section V.

In this method the injected voltage (V_{inj}) from the series active filter is in-phase with the voltage sag source(V_{s2}) and the voltage source current (I_{s2}) as shown in figure 2. The assumption here is the shunt active filter is always maintaining the unity power factor. So the angle between the injected voltage and the voltage source current will be zero. So that the active power requirement will be more in this case. But the reactive power requirement will be zero. In this method, the magnitude of injected voltage will be less when compare to other methods. Even though it takes less injected voltage, the additional active power requirement drawn from the source. It adds the further burden to the source. This is the main drawback of the UPQC-P method.

II. QUADRATURE COMPENSATION METHOD (UPQC-Q)

In this method the injected voltage (V_{inj}) from the Series active filter is in quadrature with the sag source voltage (V_{s2}). So the angle between the injected voltage and the sag source current (I_{s2}) will be 90^0. From this it can identify that the active power requirement will be zero in this method. But the reactive power requirement will be more. Though it takes zero active power, the magnitude of injected voltage will be more. That is the main drawback of this method. Hence, the minimum VA method is used to overcome the drawbacks of both the UPQC-P and the UPQC-Q method.

III. PROPOSED -UPQC MINIMUM VA METHOD

In this minimum VA method the voltage injection will be based on an optimum angle α. α is an angle between the sag source voltage and the load voltage shown in figure.4.Optimum angle is an angle in which the VA requirement of the UPQC will be minimum. Based on this optimum angle, the magnitude of injected voltage and the injection angle will be derived. In that particular magnitude of injected voltage and an injection angle, the active power requirement of the UPQC will be less than the UPQC-P method and the reactive power requirement of the UPQC will be less than the UPQC-Q method. So the total VA requirement of the UPQC will be less compare to the other two methods. And also the magnitude of injected voltage will be less than the UPQC-Q method. So the minimum VA method is one of the very efficient methods.

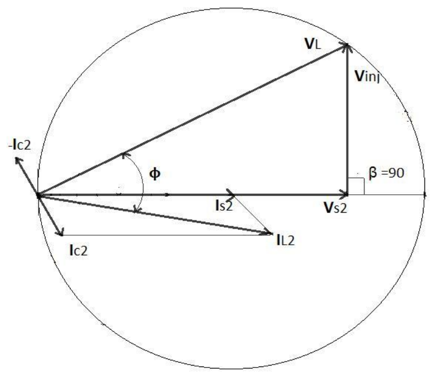


Fig.3. Phase diagram of Quadrature compensation method

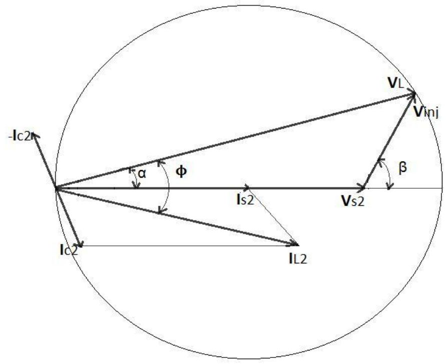


Fig.4. Phase diagram of Minimum VA method

The injected voltage and the power limitation in the minimum VA method (V, P, Q and S indicates injected voltage, real, reactive and apparent power and subscripts such as In, Quad, Min indicates UPQC-P, UPQC-Q, Minimum VA method) will be,

$$\mathbf{V_{In} < V_{Min} < V_{Quad}}$$

$$\mathbf{P_{Quad} < P_{Min} < P_{In}}$$

$$\mathbf{Q_{In} < Q_{Min} < Q_{Quad}}$$

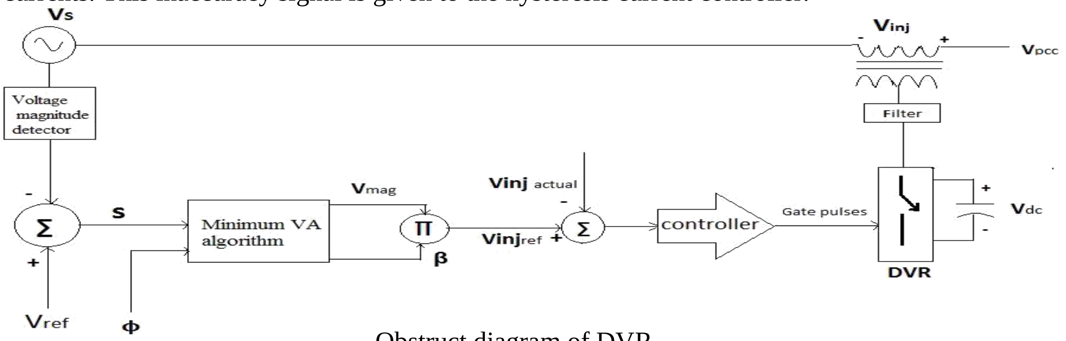
$$\mathbf{S_{Min} < S_{In} < S_{Quad}}$$

III. BLOCK DIAGRAM EXPLANATION OF DVR

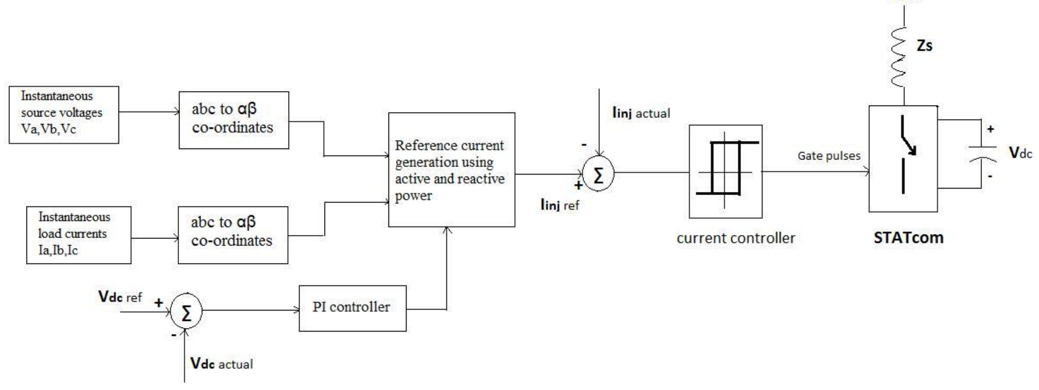
The total VA requirement of the DVR is based on the injected voltage and the sag source current. An injected voltage and the sag source current are depending on the sag, the load displacement power factor and an optimum angle. For calculating the sag, the instantaneous source voltage is compared with the reference voltage. That difference is taken as sag (in p.u.). The load active and reactive power is used to calculate the load displacement power factor. With these two parameters, the optimum angle is varying till power factor angle for finding an optimum VA. At the minimum VA angle the magnitude of injection voltage and the injection angle is determined. The injection voltage is considered as a reference voltage. This reference voltage is compared with the actual injection voltage. That error signal is going to the PWM generator or hysteresis comparator for producing the gate signals. Finally the gate pulses are given to the gate terminal of the converter IGBTs. By tuning the value of LC filter, we can reduce the switching noises in the actual injected voltage.

IV. BLOCK DIAGRAM EXPLANATION OF STATCOM

Instantaneous Reactive Power Theory (IRPT) is used to calculate the reference shunt compensated currents. As per IRPT, the instantaneous source voltage and load current is used to find the instantaneous active and reactive power. And also the voltage across dc capacitor (V_{dc}) needs to be maintaining as constant. In order to maintain V_{dc} constant, the actual dc voltage is compared with the dc reference voltage. The difference is given to the PI controller for regulating the dc link voltage. Based on the values, the instantaneous active and the reactive power reference currents will be generated. Further these reference currents compared with the actual injected currents. This inaccuracy signal is given to the hysteresis current controller.



Obstruct diagram of DVR

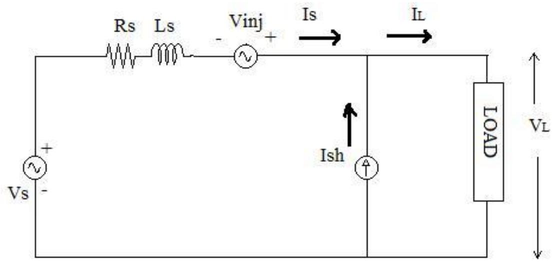


Obstruct diagram of STATCOM

The hysteresis current controller will generate the required gate signals. The gate signals are given to the converter circuit of the STATCOM.

V. MINIMUM VA CALCULATION

The total VA requirement of the UPQC (SUpqc) is depending on the VA requirement of both the series (S_{Sr}) and shunt active filter(S_{Sh}) [5]. By considering the sag source voltage and the sag load voltage (VL) are 1 p.u, we can write the total VA requirement is in terms of the load displacement power factor ($\cos\varphi$), the sag in p.u, and an optimum angle. Here, R_S, L_S is series resistance and inductance respectively.



Equivalent circuit of UPQC

$$S_{Upqc} = S_{Sr} + S_{Sh}$$

In this case we are taking the load current as constant in both the normal and the sag condition. So the load current is considered as 1 p.u.

VI. THE APPARENT POWER CALCULATION OF THE SERIES ACTIVE FILTER

Total VA requirement of Series active filter depends on the injected voltage and the sag source current. Similarly the sag source current in terms of sag and power factor can be found.
The sag source voltage is (1-*s)* V_{S1} p.u and the sag

Source voltage is V_{S1}. So we can write the sag voltage as follows,
We are maintaining the active power as constant in both the normal and during the sag condition i.e.

To clarify this study a general case was studied theoretically for three phase three wire systems and then special cases which can be occur in industrial loads were derived, such as current harmonics, unbalance and/or distorted currents. Practically each case has its calculation to achieve exactly the compensation needed to improve the power quality from the source power system. Moreover, lots of studies have been pursued on SAPF. But in most studies, the supply voltage is considered as a sinusoidal variable with constant amplitude. In the present study, as the supply-voltage unbalance is very serious problem for the load, especially due to the appearance of the negative sequence, the unbalance of line voltage must be taken into account as a design factor in the shunt APF. Therefore, the power system voltage is expressed by:

$$V_i = V_m \sin\left(\omega t + \varepsilon_i \frac{2\pi}{3}\right)$$

where, I = a, b, c presenting the three phases, $\varepsilon_a = 0$, $\varepsilon_b = -1$, $\varepsilon_c = 1$.
The h component of the load currents are defined as follow:

$$i_{ih} = k_i \cdot I_{mh} \cdot \sin\left(\omega t + \varepsilon_i \frac{2\pi}{3} + \gamma_{ih}\right)$$

where, k_a, k_b, k_c are the magnitude currents unbalance factors, γ_{ah}, γ_{bh}, γ_{ch} are the phase shift unbalance for the phases a b and c load currents. h presents the harmonics order h = 1, 2, 3......, I_{mh}, the current magnitude of the harmonics order h.

The necessary apparent power which responds to the load requirement following to the effective apparent definition is expressed

$$S_e = 3V_e I_e$$

where, V_e and I_e are the corresponding effective voltage and effective current of the power supplied applied to the load which are calculated as follow:

$$I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2}{3}} = \sqrt{I_{e1}^2 + I_{eh}^2}$$

Where:

$$I_{e1} = \sqrt{\frac{I_{a1}^2 + I_{b1}^2 + I_{c1}^2}{3}}, \quad I_{eh} = \sqrt{\frac{I_{ah}^2 + I_{bh}^2 + I_{ch}^2}{3}}$$

where, I_{e1} is the fundamental component effective current, from Eq. 4 and 7 it can be expressed as:

$$I_{e1} = \frac{I_M}{\sqrt{3}} \sqrt{k_a^2 + k_b^2 + k_c^2}$$

The effective voltage of the three-wire power system is expressed as Eq. 37-39:

$$V_e = \sqrt{\frac{V_{ab}^2 + V_{bc}^2 + V_{ca}^2}{3}}$$

From Eq. 3 and 9 the effective voltage of the power supply can be presented as follow:

$$V_e = V$$

From Eq. 5 and 6 the effective apparent power can be presented by:

$$S_e^2 = 9V_e^2 I_e^2 = 9V^2 \cdot I_{e1}^2 + 9V^2 \cdot I_{eh}^2$$

$$S_e^2 = S_{e1}^2 + S_{eh}^2$$

where, S_{eh} is the apparent power responsible of different harmonics contained in the load current. On the other side the effective apparent power due to the fundamental component of the current is calculated as follow:

$$S_{e1}^2 = 9V^2 \cdot I_{e1}^2$$

This power contains two parts: A component due to the fundamental positive component of current, it is the one generated by the power system to the load. This power is given by:

$$S_{umb}^2 = S_{e1}^2 - S_{e1}^{+\,2}$$

A component due to the negative and zero components of the current, it is the one responsible of the unbalance in the load side. The shunt APF must produce and inject this power to eliminate the unbalance of the current absorbed from the source of the power system. This power is given by:

$$I_{e1}^{+} = \frac{I_M}{3} \sqrt{k_a^2 + k_b^2 + k_c^2 + \Delta I}$$

The effective fundamental positive component of the effective current is given by:

$$I_{e1}^{+} = \frac{I_M}{3}\sqrt{k_a^2 + k_b^2 + k_c^2 + \Delta I}$$

Where:

$$\Delta I = \sum_{\substack{i,j=a,b,c \\ i\neq j}}^{a,b,c} k_i k_j \cdot \cos\left(\gamma_i - \gamma_j\right)$$

The effective apparent power responsible of the unbalance in the load currents is expressed by:

$$S_{unb} = 3V \cdot \sqrt{I_{e1}^2 - {I_{e1}^{+}}^2}$$

It can be written as:

$$S_{unb} = V \cdot I_M \cdot \sqrt{2 \cdot \Delta k - \Delta I}$$

Where:

$$\Delta k = k_a^2 + k_b^2 + k_c^2$$

The power responsible of different harmonics contained in the load current is given by:

$$S_{eh} = 3V \cdot I_{eh}$$

Where the effective harmonic current is:

$$I_{eh} = I_h\sqrt{\frac{k_a^2 + k_b^2 + k_c^2}{3}}$$

$$I_{eh} = I_h\sqrt{\frac{\Delta k}{3}}$$

From Eq. 8, 21 and 24 can be written as:

$$I_{eh} = I_h \cdot \frac{I_{e1}}{I_M} = THD_e^I \cdot I_{e1}$$

where, THD^I_e is the total harmonic distortion of the load current, it is presented by σ so:

$$S_{eh} = \sqrt{3}V_e I_M \cdot \sigma \cdot \sqrt{\Delta k}$$

$$S_{eh} = \sqrt{3}V_e I_M \cdot \sigma \cdot \sqrt{\Delta k}$$

Finally in order to achieve a unite power factor in the source, the reactive power needed by the load have to be canceled from the fundamental components of voltage and current. Thus, the shunt APF has to generate the apparent power needed so that the voltages in the three phases have the same shift phase angles as the currents absorbed from the source by the load in the corresponding three phases. In Fig. 5, phase a is presented to show clearly the principle of the reactive power compensation. Hence, the required phase shift between the power system voltage and the source current is obtained.
The magnitude of the positive sequence of the current is the same as the magnitude of the effective positive sequence:

$$\begin{bmatrix} I_{a1}^{+} \\ I_{b1}^{+} \\ I_{c1}^{+} \end{bmatrix} = \begin{bmatrix} I_{e1}^{+} \\ I_{e1}^{+} \\ I_{e1}^{+} \end{bmatrix}$$

The currents needed to achieve the elimination of the reactive power to be absorbed from the power system are I^{+}_{a1q}, I^{+}_{b1q} and I^{+}_{c1q}. To obtain the minimum magnitude of these components they must be perpendicular on the source currents of the corresponding phases as it is shown in Fig. 5, the magnitude of these currents are then:

$$\begin{bmatrix} I_{a1q}^{+} \\ I_{b1q}^{+} \\ I_{c1q}^{+} \end{bmatrix} = \begin{bmatrix} I_{a1q\gamma}^{+} \\ I_{b1q\gamma}^{+} \\ I_{c1q\gamma}^{+} \end{bmatrix} = I_{e1}^{+} \cdot \begin{bmatrix} \sqrt{1-\cos^2(\gamma_1^{+})} \\ \sqrt{1-\cos^2(\gamma_1^{+})} \\ \sqrt{1-\cos^2(\gamma_1^{+})} \end{bmatrix}$$

Where, the phase shift of the positive components is give by:

$$\gamma_1^{+} = a\tan\left[\frac{\sum_{i}^{a,b,c} k_i.\sin(\gamma_i)}{\sum_{i}^{a,b,c} k_i.\cos(\gamma_i)}\right]$$

The effective current of these components can be evaluated as:

$$I_{e1q}^{+} = I_{e1}^{+} \cdot \sqrt{1-\cos^2(\gamma_1^{+})}$$

Or:

$$I_{e1q}^{+} = I_{e1}^{+} \cdot \Delta q$$

Where:

$$\Delta q = \sqrt{1-\cos^2(\gamma_1^{+})}$$

The corresponding effective apparent power responsible of the phase shift between the power system voltage and the load current is expressed as:

$$S_{e1q}^{+} = 3 \cdot V.I_{e1q}^{+}$$

This leads to the following expression:

$$S_{e1q}^{+} = S_{e1}^{+} \cdot \sqrt{1-\cos^2(\gamma_1^{+})}$$

Finally it can be written as:

$$S_{e1q}^{+} = V \cdot I_M \cdot \sqrt{\Delta k + \Delta I} \cdot \Delta q$$

The total apparent power necessary to achieve a good compensation for the unbalances, harmonics and reactive power is deduced from Eq. 20, 27 and 35. It is presented by the following expression:

$$S_{comp} = \sqrt{S_{unb}^2 + S_{eh}^2 + {S_{e1q}^{+}}^2}$$

So:

$$S_{comp} = V \cdot I_M \sqrt{S_{comp1} + S_{comp2}}$$

Where:

$$S_{comp1} = \Delta k \cdot \left(2 + 3 \cdot THD_e^{I2} + \Delta q^2\right)$$

$$S_{comp2} = \left(\Delta q^2 - 1\right) \cdot \Delta I$$

The positive apparent power ratio is supposed as:

$$R_p = \frac{S_{e1}^{+}}{S_{e1}}$$

This can be written as:

$$R_p = \frac{I_{e1}^{+}}{I_{e1}}$$

It leads to:

$$R_p = \frac{1}{\sqrt{3}} \cdot \sqrt{1 + \frac{\Delta I}{\Delta k}}$$

Where:

$$0 \prec R_p \leq 1$$

But practically values of R^+ are not far from 1.
The main objective described in this study is to obtain the apparent power ratio of the shunt active power filter which characterizes its capability for achieving the main aim of compensation. This ratio is presented as follow:

$$R = \frac{S_{comp}}{S_s}$$

Where:

$$S_s = 3 \cdot V \cdot I_{se}$$

Presents the apparent power delivered by the power system (source) to the load with an optimized cost. I_{se} is the effective current circulating from the source to the PCC, it can be calculated by:

$$I_{se} = \sqrt{\frac{I_{sa}^2 + I_{sb}^2 + I_{sc}^2}{3}}$$

Where:

$$\begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} = I_{e1}^{+} \cdot \begin{bmatrix} \cos\left(\gamma_1^{+}\right) \\ \cos\left(\gamma_1^{+}\right) \\ \cos\left(\gamma_1^{+}\right) \end{bmatrix}$$

The resulting effective source current is:

$$I_{se} = I_{e1}^{+} \cdot \cos\left(\gamma_1^{+}\right)$$

And the apparent power becomes as follow:

$$S_s = 3 \cdot V \cdot I_{e1}^{+} \cdot \cos\left(\gamma_1^{+}\right) = S_{e1}^{+} \cdot \cos\left(\gamma_1^{+}\right)$$

The compensation apparent power produces by the active power filter is presented as:

$$S_{comp} = \frac{S_{e1}^{+}}{R_p} \sqrt{1 + \sigma^2 + R_p{}^2 \cdot \left(\Delta q^2 - 1\right)}$$

The apparent power ratio of the shunt APF can then be written by the following expression:

$$R = \frac{1}{R_p \cdot \cos\left(\gamma_1^{+}\right)} \cdot R_0$$

Where:

$$R_0 = \sqrt{1 + \sigma^2 + R_p{}^2 \cdot \left(\Delta q^2 - 1\right)}$$

where, R gives a clear idea about the shunt active power filter dimension to fulfill the desired compensations, it can also be used in the process design of the devices used in this compensators. In this study the loses due to the devices operations such as the switching lose of static switches were not taken into account, as it is neglected beyond the apparent power needed for the compensation.

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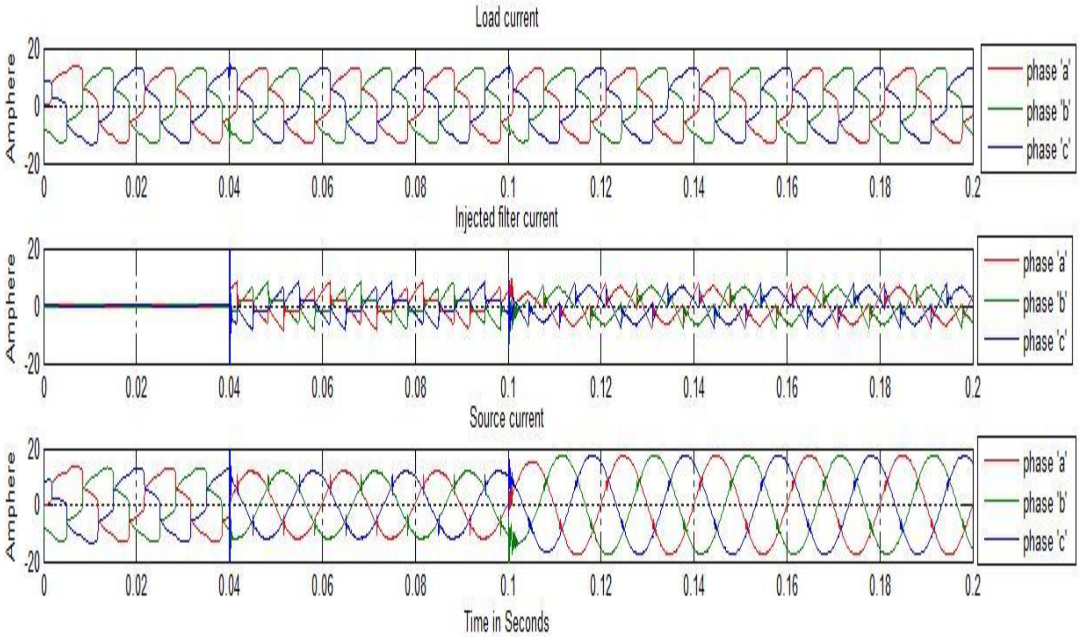
VII. SIMULATION RESULTS



Load, shunt active filter and source currents with minimum VA method

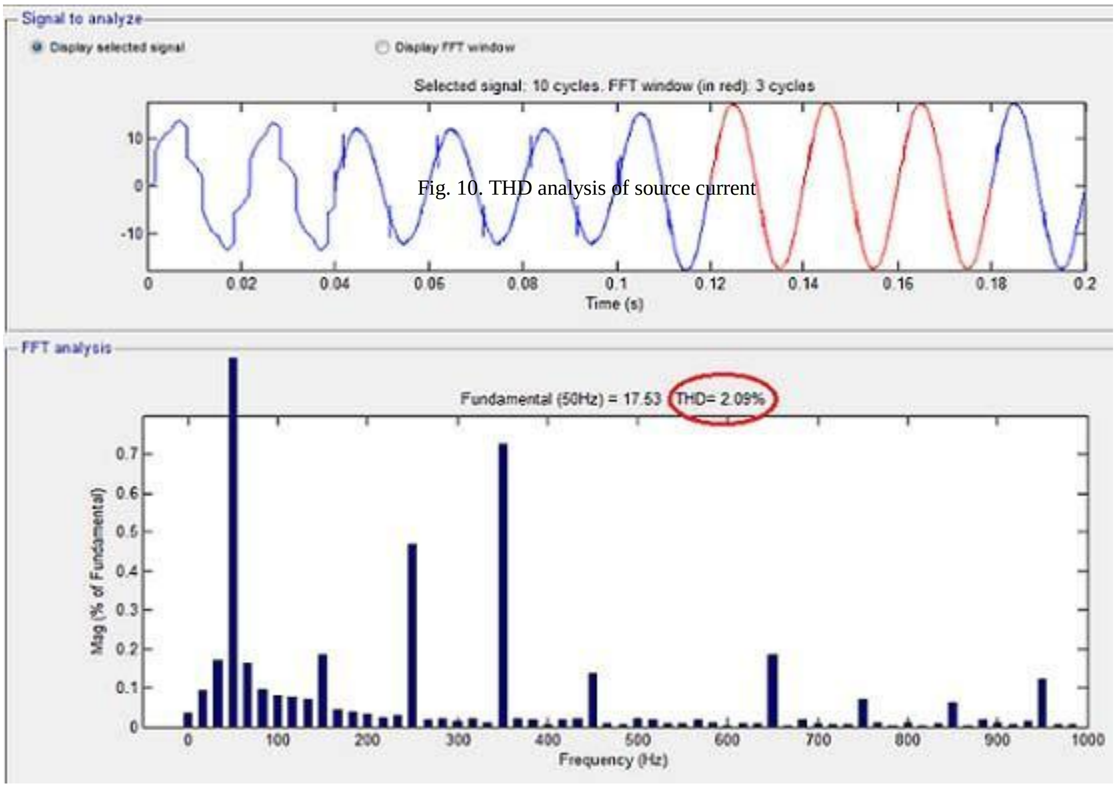
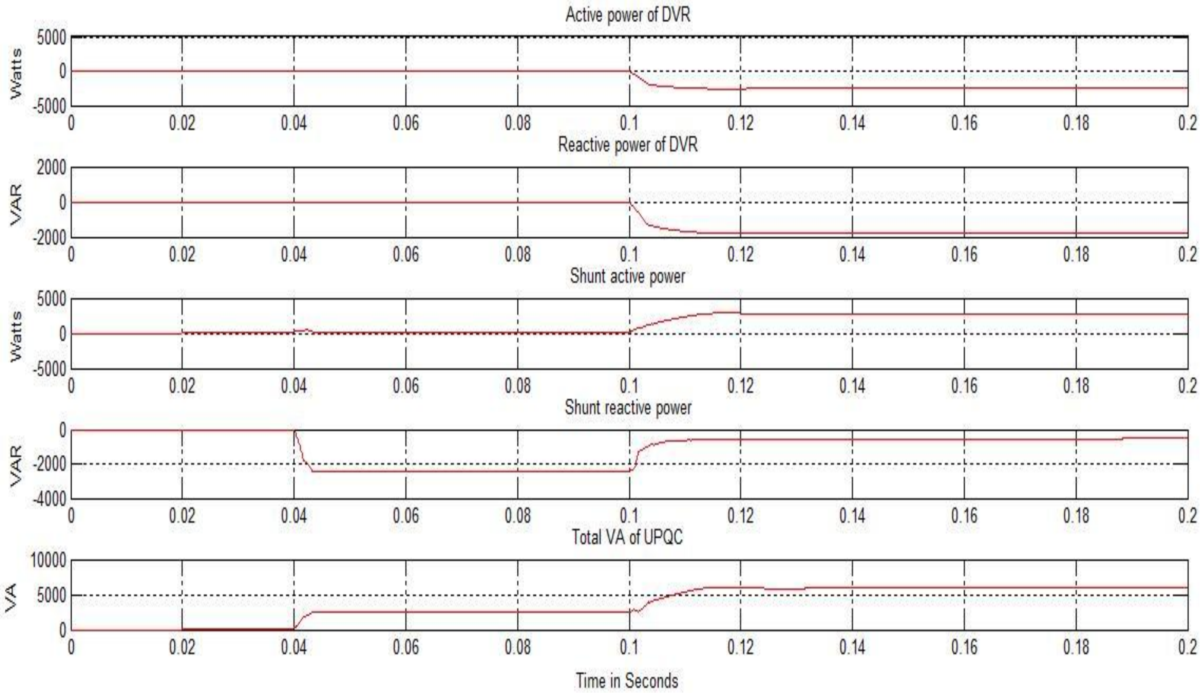


Fig. 10. THD analysis of source current



Method	P_{Sr} (kW)	Q_{Sr} (kVAR)	S_{Sr} (kVA)	P_{Sh} (kW)	Q_{Sh} (kVAR)	S_{Sh} (kVA)	S_{Upqc} (kVA)
UPQC-P (In-phase method)	-2.67	0.087	2.671	2.88	-2.348	3.722	6.394
UPQC-Q (Quadrature method)	-0.222	-6.58	6.583	0.497	4.259	4.288	10.870
Minimum VA method (at an optimum angle)	-2.544	-1.765	3.096	2.729	-0.524	2.779	5.875
When p.f angle is equal to optimum angle	-2.254	-2.98	3.738	2.44	0.675	2.531	6.269

Positive sign indicates the absorbed power and Negative sign indicates the delivered power

System parameters

Source Voltage	415 V
Series Injection Transformer rating	7.5 kVA 350V/350V
DVR LC Filter	L=3.5mH,C=15 uF
Frequency	50Hz
DC Link Voltage	760 V
DC Link Capacitance	5000uF
DVR Switching Frequency	10kHz
Linear Load	2 kW,2.2 kVAR
Non Linear load : Full Bridge Rectifier with RL load on DC side	4 kW
Synchronous Link Inductance	2.5 mH
Sag (s)	0.3 p.u
p.f. Angle	20.13^0
Optimum Phase Angle α	12^0
Angle of Voltage Injection β	36.78^0

VIII. CONCLUSION

In this paper the sag of the load voltage has been compensated by using the UPQC with minimum VA loading. And the total harmonic distortion of the source current has been reduced with the improved power factor. The results of various sag compensation methods are obtained separately and that results are compared with this method. The total VA obtained by this method is less than the other conventional methods. And also the active power handled by the UPQC is less than the UPQC-P and the injected voltage through the series active filter is less than the UPQC-Q.

IX. APPENDIX

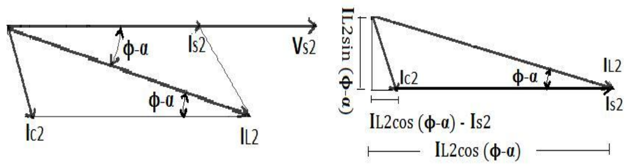
a) Calculation of injected filter current :

Consider the parallelogram for finding the injected filter current. By applying the cosine law of triangle we can get the shunt compensated current,

$$I_{C2} = \sqrt{\left(I_{L2}^2 + I_{S2}^2 - 2I_{L2}I_{S2}\cos(\varphi - \alpha)\right)}$$

Load active current $I_{L2}\cos(\varphi - \alpha)$ and Load reactive current $I_{L2}\sin(\varphi - \alpha)$. Apply Pythagoras theorem to this right triangle and Substitute $I_{S2} = I_{L2}\cos\varphi/(1-s)$ and I_{L2} =1 p.u

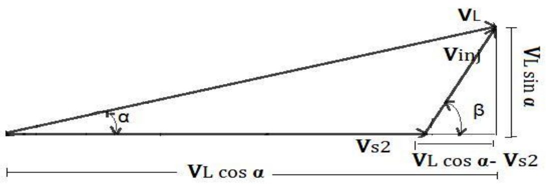
$$I_{c2} = \frac{\sqrt{\left((1-s)^2 + \cos^2\varphi + 2(1-s)\cos\varphi\cos(\varphi - \alpha)\right)}}{(1-s)}$$



b) Calculation of injected voltage and angle :

From the below fig, the load voltage is dividing as two parts $V_L\cos\alpha$ and $V_L\sin\alpha$. Using these we can calculate the value of injected voltage V_{inj} and the injected angle β. Here

$V_L = V_{S1} = 1p.u$



$$V_{inj} = \sqrt{\left((\cos\alpha - (1-s))^2 + (\sin\alpha)^2\right)}$$

Injected angle β is, $\beta = \tan^{-1}\frac{V_L\sin\alpha}{(V_L\cos\alpha - V_{S1}(1-s))}$

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