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Closed Loop Non Linear Control of Shunt Hybrid Power Filter for Harmonics Mitigation in Industrial Distribution System

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ABSTRACT

In recent years, the amount of non-linear loads has increased considerably since there were improvements in power electronic equipment (such as adjustable speed drives or converter ac-dc, ac-ac, dc-ac and dc-dc) in industrial sectors which cause deterioration of the quality of the electric power supply through distortion of supply voltage and supply current. This has led to improvement of many stringent needs regarding generation of harmonic current, which are found in IEEE519 and IEC61000 standards. This paper proposes a non-linear function based closed loop control strategy (without load current extraction) for three-phase Shunt Active Power Line Conditioner and LC passive filter to compensate harmonics, power factor improvement and enhance the dynamic performance of Shunt Hybrid Power Filter (SHPF). By using a PI controller the DC bus voltage of the Shunt Active Power Filter is maintained constant. Results obtained from simulation shows the performance of expected hybrid filter in transient and steady state operation . This indicates that the controller is able to compensate even under severe load current imbalances.

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1. INTRODUCTION

The increased level of nonlinear loads due to usage of more electronic equipment leads to deterioration of power quality in the power system. Whenever the nonlinear load draws harmonic current from a supply there occurs a distortion in the supply voltage waveform at the common coupling (PCC) point because of the source impedance. The distorted voltage and current may cause end-user equipment to malfunction and overheating of conductors. Due to this, the component connected at the PCC gets affected by reduction in efficiency and life period.

Usually, to reduce and avoid current harmonics, a passive LC power filter is used when connected parallel to the load. These types of passive power filter have some drawbacks, due to which it cannot provide a complete solution. These have the disadvantages of large size, resonance, and fixed compensation. In recent days, based on power electronic methods the harmonic suppression facilities have been improved. These facilities are known as active power filter which can suppress various order harmonic components simultaneously for loads which are nonlinear in nature. Depending on the compensation types, the active power filter is categorized into reactive power, harmonic, balancing of three-phase systems and multiple compensations.

This study of active power filter and its operating principle were introduced by H.Sasaki and T.machida in 1970 [1]. The current source converter type based active power filters were implemented with GTO thyristors for first time in the world in 1982 [2], Nowadays the IGBTs are been used for the real improvement in active power filter technology. Among the subjects related to the active filter’s design techniques and applications, the technique used for extracting the harmonic load currents and determining the filter reference current has a major role. The accuracy and response speed of the SAPF are taken into consideration [3], [4]. The techniques of reference current generation are categorized as below: 1) time-domain and 2) frequency domain methods [5], [6]. Time-domain methods such as *p–q* transformation and*d–q* transformation etc. depend on the measurements and conversion of three-phase quantities. Fast response is the major advantage of the time-domain control techniques in comparison with the frequency-domain techniques depending on the fast Fourier transformation. On the other hand, frequency-domain control techniques detect the individual and multiple harmonic load current with more accuracy. The loop for control of operation of the controller can be categorized as open loop control and closed loop control. The control algorithm for closed loop control system is less complicated then in open loop method and requires minimal number of current sensors.

Many control techniques have been shown in the literature, such as instantaneous active & reactive power theory [7], synchronous reference frame [8], Fuzzy control [9], PI control [10], Sliding mode control [11],Neural Network approach [12], and Open loop Nonlinear control [13].

In this paper, a three-phase shunt hybrid power filter is modeled in the three-phase “abc” coordinates, and then, to avoid time dependence, the model is transformed to the rotating "dq" reference frame. On the other hand, A proportional–integral (PI) controller is used to control the SAPF dc bus voltage. The dynamic performances of the SAPF using the Non-linear function based closed loop control approach with shunt LC passive filter are obtained by simulation using Simulink.

2. RESEARCH METHOD

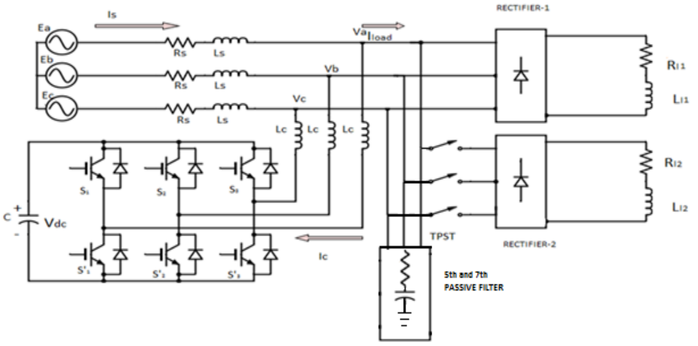

Figure 1. Configuration of Shunt Hybrid Power Filter

2.1. Estimation of Harmonics

Power quality measurements are done using a power quality analyzer. The power quality analyzer used in this work is YOKOGAWA CW240. It is capable of detecting the presence of voltage and current harmonics and measuring their characteristics (order, amplitude and phase).

Loads under study include nonlinear loads in the E & D building of Delphi-TVS, Mannur. Loads include power electronics equipment such as adjustable speed drives and DC drives. The readings are taken at the input distribution panel. The current THD is found to be 18.3% and voltage THD to be 2.251%.With onlypassive filter being implemented in the building, the current THD is found to be 8.2% and voltage THD to be 1.71%.

2.2. Hybrid Power Filter Configuration

The hybrid filter configuration is twofold, with a non-linear control of active filter and RC passive filter. An active power filter, APF, comprises a three phase pulse width modulation (PWM) voltage source inverter. The inverter has one 500µF capacitor in the DC side and is shunt connected with the electrical grid. Series passive element which consist of three 3mH inductors and 0.01Ω resistor. The passive filters are an important part of the Active Filter design. It must be dimensioned appropriately so that the switching frequency does not affect the source currents THDafter the compensation. During designing care must be taken to prevent the interference of the passive filters with the control of the Active Filter. In this paper an Active Filter is presented where inductor and resistor has been used as series passive filter, but the passive filter configuration can be a LCor RLC, or even more complex topologies. Each one of these topologies hasdrawbacks and advantages, which must be weighted according with the type of loads that will be compensated, the IGBT switching frequency, the control of the Active Filter and the final costThe shunt passive filter parameters are selected in such a manner that it is capable of eliminating 5th harmonics and 7th harmonics which are more prominent.

2.3. Modeling of Shunt Active Power Filter

2.3.1. Modeling in Three Phase 'abc' Frame

The model of active filter is first developed in three-phase 'abc' frame. Kirchhoff's voltage and current laws are applied at the supply terminal, and it yields the following three differential equations in the stationary 'abc' frame [13].

$$\begin{aligned} E_1 &= L_s \frac{di_{s1}}{dt} + R_s I_{s1} + V_1 \\ E_2 &= L_s \frac{di_{s2}}{dt} + R_s I_{s2} + V_2 \\ E_3 &= L_s \frac{di_{s3}}{dt} + R_s I_{s3} + V_3 \end{aligned} \tag{1}$$

Where V_1, V_2, and V_3 indicate the line-to-ground voltages at the point of common coupling (PCC), E_1, $E_2$and E_3 indicate the line-to-ground voltage at the supply terminal.

Also,

$$\begin{aligned} V_1 &= L_f \frac{di_{f1}}{dt} + V_{FM} + V_{1M} \\ V_2 &= L_f \frac{di_{f2}}{dt} + V_{FM} + V_{2M} \\ V_3 &= L_f \frac{di_{f3}}{dt} + V_{FM} + V_{3M} \end{aligned}$$

The voltage drop across the inductor is small as compared to the Shunt Active Filter voltage, which gives us the relation,

$$\begin{aligned} L_f \frac{di_{f1}}{dt} &\ll V_{FM} + V_{1M} \\ L_f \frac{di_{f2}}{dt} &\ll V_{FM} + V_{2M} \\ L_f \frac{di_{f3}}{dt} &\ll V_{FM} + V_{3M} \end{aligned}$$

$$\begin{aligned} V_1 &\approx V_{FM} + V_{1M} \\ V_2 &\approx V_{FM} + V_{2M} \\ V_3 &\approx V_{FM} + V_{3M} \end{aligned}$$

By summing the three equations in (1), and with an assumption that the voltages of AC supply are balanced, and by neglecting the zero-sequence currents in the three wire systems, (i.e.,) using the following assumptions:

$$\begin{aligned} &E_1 + E_2 + E_3 = 0 \; ; V_1 + V_2 + V_3 = 0 \\ &I_{s1} + I_{s2} + I_{s3} = 0 \; ; I_{f1} + I_{f2} + I_{f3} = 0 \end{aligned}$$

One can obtain:

$$V_{FM} = -\frac{1}{3}\sum_{f=1}^{3} V_{fM} \tag{2}$$

The switching function sw_k of the k^{th} leg (for k = 1, 2, 3) of the converter can be defined as:

$$sw_k = \begin{cases} 1, if\ S_k\ is\ On\ and\ S'_k\ is\ Off \\ 0, if\ S_k\ is\ Off\ and\ S'_k\ is\ On \end{cases} \tag{3}$$

Therefore, $V_{kM} = sw_k V_{dc}$.The dynamic equation of phase-*k* filter's model is denoted by the equation given below:

$$E_k = L_s \frac{di_{sk}}{dt} + R_s I_{sk} + (sw_k - \frac{1}{3}\sum_{f=1}^{3} sw_f)V_{dc} \tag{4}$$

In addition, we may define a function ss_{nk} switching state function which is denoted as follows:

$$ss_{nk} = (sw_k - \frac{1}{3}\sum_{f=1}^{3} sw_f)_n \tag{5}$$

Equation (5) denotes that the value of ss_{nk} is dependent on the switching function sw_k of all three legs of the shunt active power filter. This shows that the three phases interacts with each other. Further, depending on (5) and from the eight allowable switching states of the active filter (n=1… 7), the conversion of [sw_{nk}] to [ss_{nk}] is given by the following:

$$\begin{pmatrix} ss_{n1} \\ ss_{n2} \\ ss_{n3} \end{pmatrix} = \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \begin{pmatrix} sw_1 \\ sw_2 \\ sw_3 \end{pmatrix} \tag{6}$$

Note that [ss_{nk}]has no zero-sequence component $(ie., ss_{n1} + ss_{n2} + ss_{n3} = 0)$

On the other hand, Analysis of the dc component of the system gives:

$$\frac{dV_{dc}}{dt} = \frac{1}{C} i_{dc} = \frac{1}{C}\sum_{m=1}^{3} sw_k i_{sk} \tag{7}$$

It can be shown that,

$$\sum_{k=1}^{3} sw_k i_{sk} = \sum_{m=1}^{3} ss_{nk} i_{sk} \tag{8}$$

And it can be verified that:

$$\frac{dV_{dc}}{dt} = \frac{1}{C}\sum_{m=1}^{3} ss_{nk} i_{sk} \tag{9}$$

And, using $i_{s1} + i_{s2} + i_{s3} = 0$ and [ss_{nk}] in the functions leads to the differential equation on the dc side as shown below:

$$\frac{dV_{dc}}{dt} = \frac{1}{C}(2ss_{n1} + ss_{n2})i_{s1} + \frac{1}{C}(ss_{n1} + 2ss_{n2})i_{s1} \tag{10}$$

From this result, active filter in the 'abc' referential obtains it complete model by using (4) for phases '1' and '2', and (10):

$$
\begin{aligned}
&L_s \frac{di_{s1}}{dt} = -R_s I_{s1} - ss_{n1} V_{dc} + E_1 \\
&L_s \frac{di_{s2}}{dt} = -R_s I_{s2} - ss_{n2} V_{dc} + E_2 \\
&C \frac{dV_{dc}}{dt} = (2ss_{n1} + ss_{n2}) i_{s1} + (ss_{n1} + 2ss_{n2}) i_{s1}
\end{aligned}
\tag{11}
$$

The interaction between the three phases indicates the disadvantage of the ‘abc’ model. Therefore, for achieving control, this model can be converted to ‘dq’ reference frame. The positive-sequence components are made constant because of time-varying transformation, and there is no interaction effect between the phases at the switching state decision level.

2.3.2. The Model Transformed into the ‘dq’ Reference Frame

Using Park’s transformation, the three-phase quantities are converted to a ‘dq’ reference frame. The general transformation matrix is:

$$
PT_{dq}^{123} = \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta - 4\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta - 4\pi/3) \end{bmatrix}
\tag{12}
$$

Where $\theta = \omega t$represents the actual phase angle of the line voltage space vector and $PT_{123}^{dq} = (PT_{dq}^{123})^{-1} = (PT_{dq}^{123})^{T}$ coordinate matrix transformation.

The synchronous ‘dq’ frame obtained from the transformed model is denoted as:

$$
\begin{aligned}
&L_s \frac{di_d}{dt} = -R_s I_d - ss_{nd} V_{dc} + L_s \omega i_q + E_d \\
&L_s \frac{di_q}{dt} = -R_s i_q - ss_{nq} V_{dc} - L_s \omega i_q + E_q \\
&C \frac{dV_{dc}}{dt} = ss_{nd} i_d + ss_{nd} i_q
\end{aligned}
\tag{13}
$$

The resultant model from the synchronous orthogonal rotating frame is denoted as follows:

$$
\frac{d}{dt}\begin{pmatrix} i_d \\ i_q \\ V_{dc} \end{pmatrix} = \begin{pmatrix} -\frac{R_s}{L_s} & \omega & -\frac{ss_{nd}}{L_s} \\ -\omega & -\frac{R_s}{L_s} & -\frac{ss_{nq}}{L_s} \\ ss_{nd} & ss_{nq} & 0 \end{pmatrix} \begin{pmatrix} i_d \\ i_q \\ V_{dc} \end{pmatrix} + \begin{pmatrix} E_d \\ E_q \\ 0 \end{pmatrix}
\tag{14}
$$

The model given in (14) has nonlinear nature because of the multiplication terms present between the state variables {i_d, i_q, V_{dc}} and the inputs {ss_{nd}, ss_{nq}}. However, this model is independent of time for a given switching period. Here, these three variables should have an independent control. Therefore, the currents i_d and i_q should be made to follow a reference current {i_d, i_q} of varying nature .For maintaining the performance of the active filter in a compensatory manner, the DC voltage level V_{dc} is adjusted to a set point when there are dynamic variations.

2.3.3. Current Controller

In the current loop, one has the following expressions for switching functions ss_{nd} and ss_{nq} as:

$$
\begin{aligned}
&ss_{nd} = \frac{1}{V_{dc}}\left[-L_s \frac{di_d}{dt} - R_s i_d + \omega L_s i_q + E_d\right] \\
&ss_{nq} = \frac{1}{V_{dc}}\left[-L_s \frac{di_q}{dt} - R_s i_q - \omega L_s i_d + E_q\right]
\end{aligned}
\tag{15}
$$

Let,

$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

u_d and u_q can be used to control the currents i_d and i_q. An integrator is added for attenuating to track the steady-state error which is used as a tracking controller. It is designed by using the following expressions [13]:

$$u_d = \frac{di_d}{dt} = \frac{di_d^*}{dt} + k_p \tilde{i}_d + k_i \int \tilde{i}_d \, dt$$
$$u_q = \frac{di_q}{dt} = \frac{di_q^*}{dt} + k_p \tilde{i}_q + k_i \int \tilde{i}_q \, dt$$

Where $\tilde{i}_d = i_d^* - i_d \; and \; \tilde{i}_q = i_q^* - i_q$ are current errors and $\{i_d^*, i_q^*\}$ are the references of $\{i_d, i_q\}$ correspondingly. The proportional (k_{pc}) and integral (k_{ic}) gains are obtained as follows:

$$k_{pc} = 2\xi\omega_n$$
$$k_{ic} = 2\xi\omega_n^2$$

Where ξ is the damping factor, and ω_n is the current loop natural angular frequency.

2.3.4. DC Voltage Regulation

To maintain considerable level of V_{dc} across the SAPF dc capacitor, the losses through the active power filter's resistive–inductive branches can be managed by working on the source current. Ideally, it must work on the active component of current i_d. For this purpose, an outer control loop is designed by using a PI regulator:

$$I_{dc} = k_p (V_{dc}^* - V_{dc}) + k_i \int (V_{dc}^* - V_{dc}) dt \tag{16}$$

The closed-loop transfer function of the outer loop is given as follows:

$$k_{pv} = 2\xi\omega_v C_{dc} .$$
$$k_{iv} = 2\xi\omega_v^2 C_{dc}$$

Where ξ is the damping factor, and ω_v is the outer loop natural angular frequency.

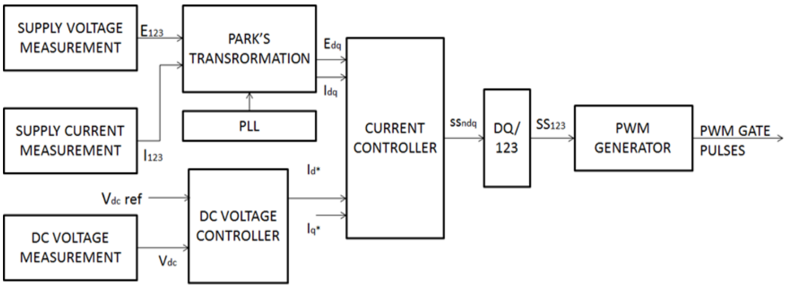

Figure 2. Control strategy of shunt active power filter

2.4. Modeling of shunt passive power filter

The passive power filter is tuned to eliminate 5th and 7th harmonics.The parameters are selected based on the following expression.

$$h = \sqrt{X_l / X_c}$$

Where h is the harmonics number, $X_l$and $X_c$are reactance of passive element.

3. RESULTS AND ANALYSIS

The proposed control strategy has been simulated under MATLAB-Simulink environment and its performance is verified. The nonlinear load consists of two three-phase rectifier, so that the effectiveness of the control scheme to compensate for unbalanced load was tested. The rectifiers are feeding *R*–*L*-type circuits.For variation in loads; the THD is obtained by analyzing the source current waveforms determined from the results of simulation. The main objective of the simulation is made to analyze different aspects such as: reactive power compensation and harmonic load currents compensation; for variations in load the corresponding dynamic response of the SHPF.Some results are presented to demonstrate the performance of non-linear function-based control scheme. The simulation results are shown in Figure 3-6. The parameters taken in these simulations are shown below in Table 1.

Table 1. Shunt Hybrid Filter Parameters

PARAMETERS	VALUE
Line voltage and frequency	V_s=230V(rms),f_s=50Hz
Active filter parameters	R=0.01Ω,L=0.1mH
	C_{dc}=750uF,V_{dc}=700V
Non Linear Load	R_1=10 Ω,L_1=10mH
	R_2=10 Ω,L_2=10mH
Regulator	K_{pc}=7K_{ic}=800
	K_{pv}=4.5K_{iv}=30
Series elements	R=0.01 Ω ,L=3mH
Passive elements	L_5=13mH C_5=30uF
	L_7=6.5mH C_7= 30uF

Figure 3 shows the system performance without hybrid filter. The THD level of voltage and current before compensation are shown in Figure 4. The current THD levels are observed to be 18.2% .voltage THD were 2.25%.The current THD levels are observed to be 8.71%, voltage THD were 1.71% with only passive filter being installed. The waveform and THD level are shown in Figure 5 and 6 respectively. The current THD level after compensation reduced to 1.32% and voltage THD level to 0.4% which can be seen with waveform and THD level in Figure 7 and 8. The dynamic performance of filter is seen in Figure 7. It can be observed that there is smooth changeover from one load value to another value,The DC bus voltage of SAPF settles to its steady-state value within two cycle of sine wave. From these results, it can be concluded that SHPF offers a very good dynamic performance for a stepped load current.

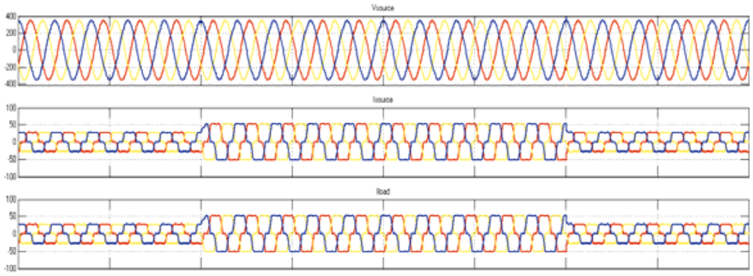

Figure 3. Voltage and current waveform before compensation

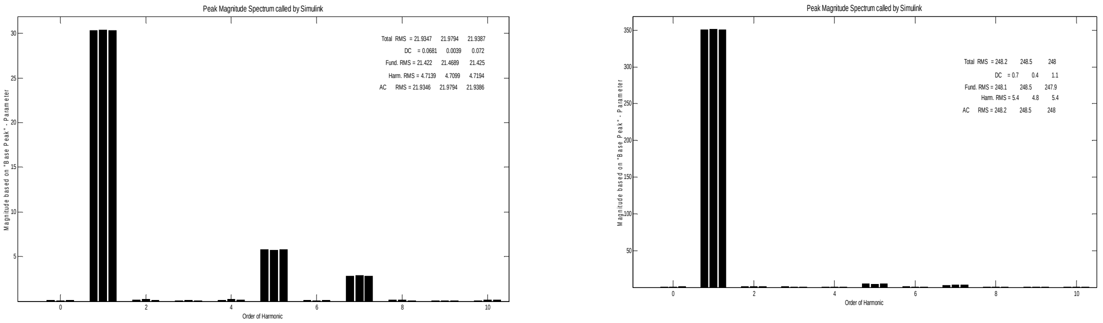

Figure 4. Current and Voltage THD before compenstion

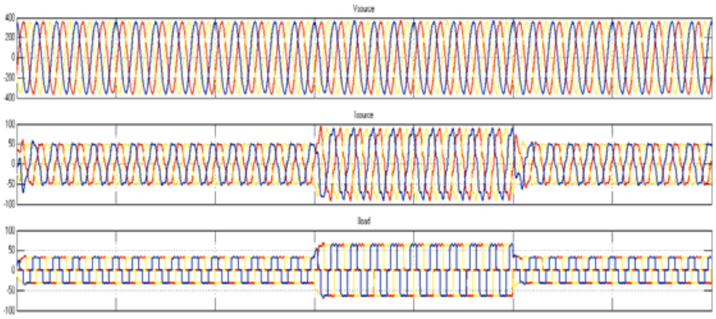

Figure 5. Voltage and current waveform with passive filter

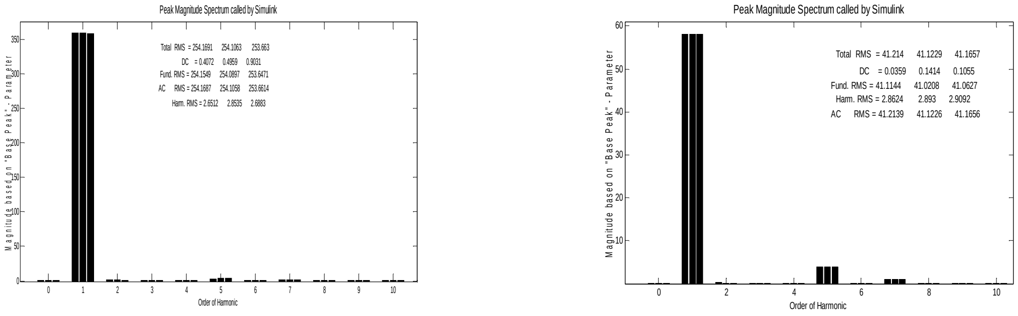

Figure 6. Current and Voltage THD with passive filter

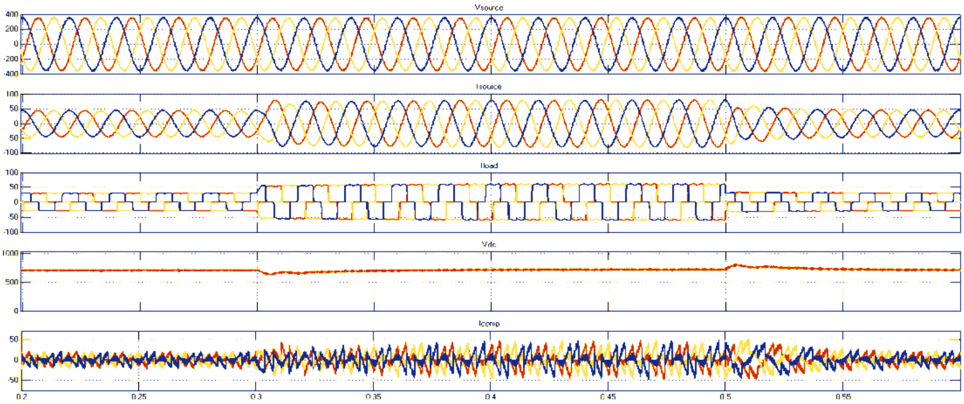

Figure 7. Voltage and current waveform after compensation

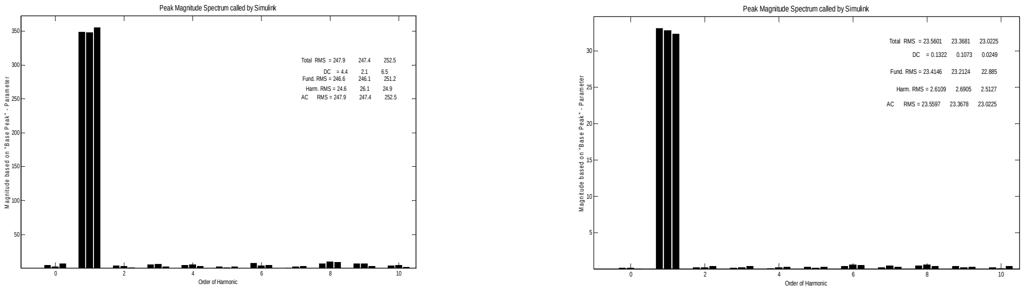

Figure 8. Current THD before and after compensation

4. CONCLUSION

The Shunt Hybrid Power Filter based on non-linear function control has been proposed and simulated under MATLAB environment to evaluate the dynamic performance for varying voltage-source type of nonlinear load conditions. From simulated results, it has also been shown that the control strategy has a fast dynamic response during large load variations and is capable of maintaining the THD of the voltage at PCC and the supply currents well below the mark of 5% specified in the IEEE-519 standard.

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