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Research Article

THE PERFORMANCE OF GA-BASED OPTIMIZED PASSIVE HARMONIC FILTER FOR HARMONIC COMPENSATION UNDER CPF AND DPF MODES

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ABSTRACT
Harmonic filtering is the most important method of preventing the harmonics from entering the distribution system and mitigating their adverse effects on electrical equipment. Use of passive filters is currently the method of choice, though much has been written on harmonic current control using advanced techniques such as magnetic flux compensation, harmonic current injection and dc ripple injection. Passive filters are inductance, capacitance, and resistance elements configured and tuned to control harmonics and can be classified into tuned filters and high-pass filters. Installation of such a passive filter in the vicinity of a non-linear load is to provide low-impedance paths for specific harmonic frequencies, thus resulting in absorbing the dominant harmonic currents flowing out of the load. In this research the performance of a single common passive filter (CPF) at the bus is investigated and the most effective method which could lead to improve voltage distortion and to decrease power losses is presented. Also in this study the performance of a dedicated passive filter (DPF) for each phase of non-linear load is investigated and the most effective method which could lead to improve voltage distortion and to decrease power losses is presented. In this research to optimize the passive filter under two operation mode including CPF and DPF modes, the genetic algorithm optimization approach is utilized. The simulation of proposed method under MATLAB/SIMULINK is analyzed in this research.

Keywords: *Non-linear Load, Voltage and Current Harmonics, Harmonic Compensation, Passive Filter*

INTRODUCTION
Increases in harmonic distortion will result in additional heating losses, shorter insulation lifetime, higher temperature and insulation stress, reduced power factor, lower productivity, efficiency, capacity and lack of system performance of the plant. Many researchers have been focuses on the passive filter design with aim of optimizing harmonic distortion due to nonlinear load and harmonics injection to power system. In (Almoataz, 2012), the harmonic passive filter planning in radial distribution systems using genetic algorithms with aim of voltage harmonic reduction is addressed. In this reference, the input parameters of programmed software include the number and the relevant order of these filters Between the different technical options available to reduce harmonic distortions and improve power quality, due to implementation of shunt capacitors to compensate the load power factor; it seems the passive power filters have proved to be an important method to compensate current and voltage disturbances in power distribution system (Daut *et al.,* 2006).
The results of related investigations show that the most of voltage and current distortions in distribution networks are arose to harmonics of third, fifth and seventh orders (Fuchs *et al.*, 1987). Due to that, in this case the implantation of three single tuned passive filters could solve this problem and therefore the sitting and sizing of filters is quite simple. However, because of distributed linear and nonlinear loads in distribution system, the passive filter planning is much difficult.
In (Jou *et al.*, 2001) the genetic-algorithm-based design of passive filters for offshore application is presented and discussed. In (Akagi *et al.*, 1983) a new genetic algorithm based approach to design a passive LC filter for a full-bridge rectifier with aim of finding maximum power factor of the ac mains is presented. In (Hamoudi and Labare, 2006) the calculation of the R-L-C parameters for a typical passive harmonic filter used in the customers' house is analyzed. Optimum location and sizing of two passive harmonic filters, whose harmonic tuning orders are 5 and 7 in distribution networks using genetic

algorithm is analyzed by (Akagi, 2007). Power loss reduction and minimization of total voltage harmonic distortion are considered as objective function in this reference.

Mathematical Modeling of Harmonics

As shown in Figure 1 in presence of sinusoidal source voltage due to non-linear load the current which drawn via source is harmonic distorted. Harmonic distortion is the corruption of the fundamental sine wave at frequencies that are multiples of the fundamental, (e.g., 180 Hz is the third harmonic of a 60 Hz fundamental frequency; 3 X 60 = 180).

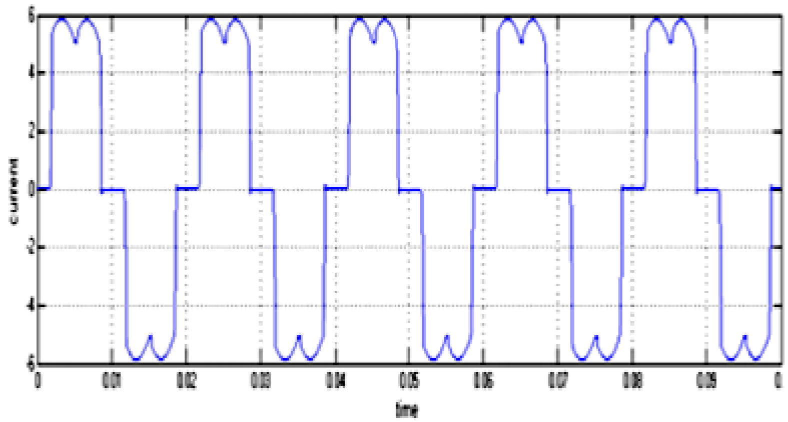


Figure 1: Harmonic distorted current wave

Now, consider non-sinusoidal situations, where network voltages and currents contain harmonics. While some harmonics are caused by system nonlinearities such as transformer saturation, most harmonics are produced by power electronic loads such as adjustable-speed drives and diode-bridge rectifiers. The significant harmonics (above the fundamental, i.e., the first harmonic) are usually the 3rd, 5th, and 7th multiples of fundamental component i.e. 50 Hz, so that the frequencies of interest in harmonics studies are in the low-audible range.

$$v(t) = \sum_{k=1}^{\infty} V_k \sin(\omega_0 t - \delta_k) \tag{1}$$

$$i(t) = \sum_{k=1}^{\infty} I_k \sin(\omega_0 t - \phi_k) \tag{2}$$

Whose rms values can be shown to be:

$$V_{rms} = \sqrt{\sum_{k=1}^{\infty} V_{k\,rms}^2} \tag{3}$$

$$I_{rms} = \sqrt{\sum_{k=1}^{\infty} I_{k\,rms}^2} \tag{4}$$

The average power is given by:

$$Pavg = \sum_{k=1}^{\infty} V_{k\,rms} I_{k\,rms} \cos(\delta_k - \phi_k) = P_{1avg} + P_{2avg} + P_{3avg} + \ldots. \tag{5}$$

Where, we see that each harmonic makes a contribution, plus or minus, to the average power.
A frequently-used measure of harmonic levels is total harmonic distortion (or distortion factor), which is the ratio of the rms value of the harmonics (above fundamental) to the rms value of the fundamental as follows (Juan *et al*., 2011):

$$THD_V = \frac{\sqrt{\sum_{k=2}^{\infty} V_{k\,rms}^2}}{V_{1rms}} \times 100\% \tag{6}$$

$$THD_I = \frac{\sqrt{\sum_{k=2}^{\infty} I_{k\,rms}^2}}{I_{1rms}} \times 100\% \tag{7}$$

Obviously, if no harmonics are present, then the THDs are zero. If we substitute equations, we find that:

$$V_{rms} = V_{1rms}\sqrt{1+(THD_V/100)^2} \tag{8}$$

$$I_{rms} = I_{1rms}\sqrt{1+(THD_I/100)^2} \tag{9}$$

Now, with substituting mentioned equations it yields the following exact form of true power factor, valid for both sinusoidal and non-sinusoidal situations:

$$PF_{true} = \frac{P_{avg}}{V_{1rms} I_{1rms}\sqrt{1+(THD_V/100)^2}\sqrt{1+(THD_I/100)^2}} \tag{10}$$

A useful simplification can be made by expressing (2) as a product of two components,

$$PF_{true} = \frac{P_{avg}}{V_{1rms} I_{1rms}} \times \frac{1}{\sqrt{1+(THD_V/100)^2}\sqrt{1+(THD_I/100)^2}} \tag{11}$$

And by making the following two assumptions:
1. In most cases, the contributions of harmonics above the fundamental to average power in (5) are small, so that Pavg ≈ P1avg.
2. Since THDV is usually less than 10%, then from (9) we see that Vrms ≈ V1rms.

Incorporating these two assumptions into (12) yields the following approximate form for true power factor:
When the fundamental component of a signal is zero, then the THD will be infinite, so in this condition this parameter does not have a engineering concept, therefore the another definition must be presented for total harmonic distortion. This new definition is DIN and can be defined as a percentage of the rms (used by the Canadian Standards Association and the IEC), and is calculated as follows:

$$DIN = \left[\sqrt{\sum_{i=2} M_i^2} \Big/ \sqrt{\sum_{i=1} M_i^2}\right] \tag{12}$$

The total power factor is called distortion power and results from the harmonic component of the current and voltages as follows (**Nastran *et al*., 1994**):

$$PF = \frac{P}{S} = \frac{\sum_{h=1} V_h\, I_h \cos\phi_h}{V_{rms}\, I_{rms}} \tag{13}$$

Where, h is the order of the hth harmonic and $\cos\phi_h$ is the angle between the hth harmonic voltage and the hth harmonic current.
It could be calculated easily as follows [6-7]:

$$PF = \frac{1}{\sqrt{1+THD_I^2}}.DPF \tag{14}$$

Where, THD_I demonstrates the total harmonic distortion of currents and DPF is the displacement power factor and is the cosine the angle of fundamental voltage and current component and assuming that for non-inductive or non-capacitive loads, the value can be considered as 1.

Passive Harmonic Filter

Precautionary solutions are not generally sufficient to eliminate the harmonics in power system, so we should use harmonic filters to eliminate or to reduce the effects of one or more orders of harmonic components. In a general context, we can refer to harmonic filters as passive and active filters.

Passive filters are inductance, capacitance, and resistance elements configured and tuned to control harmonics and can be classified into tuned filters and high-pass filters (Karuppanan and Kamala, 2012). They are connected in parallel with nonlinear loads such as diode/thyristor rectifiers, ac electric arc furnaces, and so in. Figure 2 and Figure 3 shows circuit configurations of the passive filters on a per phase base. Among them, the combination of two or three single-tuned filters to the 5th, 7th, 11th have been used in a high-power three-phase thyristor rectifiers in a nonlinear distribution system. Passive filter is a series combination of an inductance and a capacitance. In reality, in the absence of a physically designed resistor, there will always be a series resistance, which is the intrinsic resistance of the series reactor sometimes used as a means to avoid filter overheating. All harmonic currents whose frequency coincides with that of the tuned filter will find a low impedance path through the filter. Passive filter design must take into account expected growth in harmonic current sources or load reconfiguration because it can otherwise be exposed to overloading, which can rapidly develop into extreme overheating and thermal breakdown. The design of a passive filter requires a precise knowledge of the harmonic-producing load and of the power system.

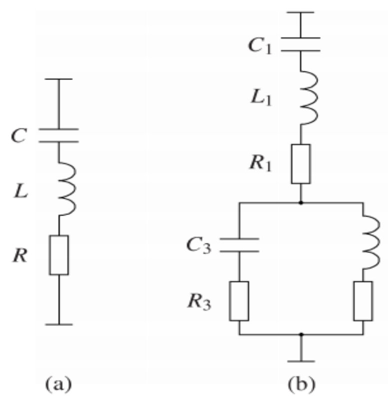


Figure 2: Passive tuned filters: (a) single tuned, and (b) double tuned

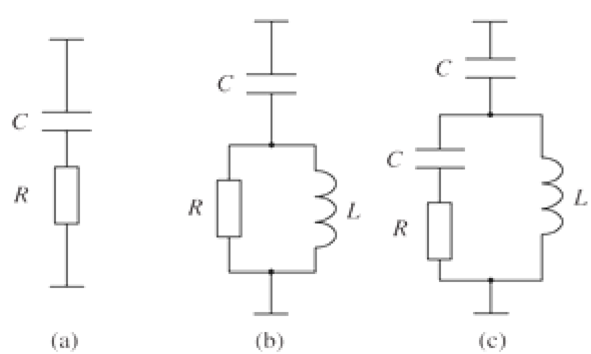


Figure 3: Passive high-pass filters: (a) first-order, (b) second-order and (c) third-order

Passive power filter is an appropriate combination of capacitor, inductor and resistor. It has been divided into single-tuned filter, high pass filter and double-tuned filter, and so on. Because double-tuned filter is complex in structure and difficult to tune, PPF usually consists of several single-tuned filters and a high pass filter in practice, which is showed in Figure 4. Here, SPFk and SPFm express single-tuned filters. HPF is a high pass filter.

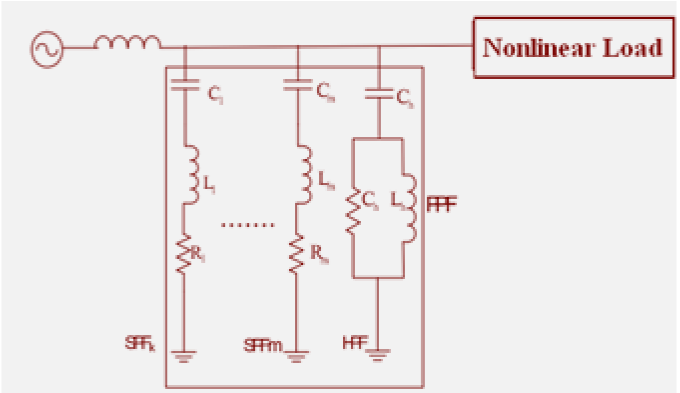


Figure 4: Typical structure of PPF

Harmonics Effects

Waveform distortions can drastically alter the shape of the sinusoid. However, no matter the level of complexity of the fundamental wave, it is actually just a composite of multiple waveforms called harmonics. Harmonics increase the equipment losses and thus the thermal stress. The triple harmonics result in the neutral carrying a current which might equal or exceed the phase currents even if the loads are balanced. This dictates the derating or over sizing of neutral wires. Moreover, harmonics caused resonance might damage the equipment. Harmonics further interfere with protective relays, metering devices, control and communication circuits, and customer electronic equipment. Sensitive equipment would experience mal-operation or component failure. Waveform distortions can drastically alter the shape of the sinusoid. However, no matter the level of complexity of the fundamental wave, it is actually just a composite of multiple waveforms called harmonics. This harmonics distorted voltages and currents have these disadvantages (Leszek and Herbert, 2005):

- Failure, tripping or overheating of capacitors, filters and related equipment.
- Abnormally high noise levels in capacitors, cables, transformers and lightning equipment.
- Overheating of transformers, cables, switchgear, conductors, etc.
- An abnormally high rate of failures of thyristors and converter equipment.
- Frequent failures of capacitors in lighting equipment or tripping of associated low voltage circuit breakers.
- "Nuisance failures" of fuses.
- "Nuisance tripping" of protection relays, in particular sensitive earth fault relays or earth leakage relays.
- Apparent errors in electronic power transducers.
- Apparent inconsistencies in metering equipment.
- Interference with computer equipment.
- An abnormally high cable failure rate or an increase in cable failures.

Once the harmonic sources are clearly defined, they must be interpreted in terms of their effects on the rest of the system and on personnel and equipment external to the power system. Each element of the power system must be examined for its sensitivity to harmonics as a basis for recommendations on the allowable levels. The main effects of voltage and current harmonics within the power system are (Morán *et al.*, 1997):

- Amplification of harmonic levels resulting from series and parallel resonances.
- Reduction in the efficiency of the generation, transmission and utilization of electrical energy.
- Ageing of the insulation of electrical plant components with consequent shortening of their useful life.
- Malfunction of system or plant components.

The effects of voltage distortion are:

- Thermal stress
- Load disruption
- Insulation stress

Genetic Algorithm Optimization Approach

GA is a search method based on the natural selection and genetics. GA is computationally simple yet powerful and it is not limited by assumptions about the search space. The most important goal of optimization should be improvement. Although GA cannot guarantee that the solution will converge to the optimum, it tries to find the optimum, that is, it works for the improvement. The GA is basically an evolutionary algorithm, analogous to a part of the physical world. Binary and floating-point representations are used to implement GA, for the sake of comparison. In the binary implementation, each element of a string (or chromosome) vector was coded using the same number of bits and each occupied its own fixed position.

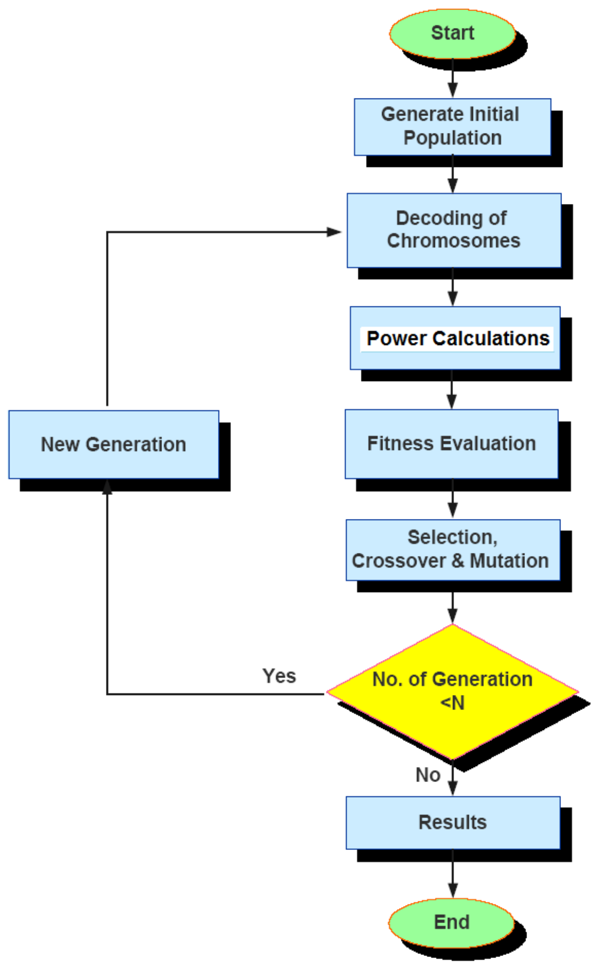


Figure 5: The block diagram of optimization problem

The minimization process in the binary representation used is characterized by the following. The implemented GA starts by randomly generating an initial population of possible solutions. For each solution a value of power generation units is chosen between 0 and a maximum limit, fixed by the planner on the ground of economically and technical justifications; then, a different size of passive harmonic filter is randomly chosen until the objective function is assigned. At this point, the objective function is evaluated verifying all the technical constraints. In order to solve the optimization problem, a modified GA has been used. In Figure 5 the block diagram of optimization problem has been shown (Zhou *et al*., 2009).

Parameters used for the GA with binary representation include: Population size 30, String length 10 bits, Reproduction rate 40% for the first preferred string; 30% for the second preferred string; 20% for the third preferred string. Crossover rate from exp (0.10) to exp (0.86), Mutation rate from exp (0.500) to exp (0.005), Maximum number of generations is 1500.

Problem Formulation

Harmonic filtering is the most important method of preventing the harmonics from entering the distribution system and mitigating their adverse effects on electrical equipment. Use of passive harmonic filters (PHF) is currently the method of choice. Passive filters are inductance, capacitance, and resistance elements configured and tuned to control harmonics and can be classified into tuned filters and high-pass filters (Ying-Pin and Chinyao, 2008). They are connected in parallel with nonlinear loads such as diode/thyristor rectifiers, ac electric arc furnaces. The target of PPF's optimal design is to meet requirements and to maximize overall efficiency. Optimal parameters shall meet the following requirements:

- Lower total harmonics distortion of voltage or current;
- Lower initial investment costs;
- Higher power factor, whereas reactive power can't be overcompensation;
- No series or parallel resonant with impedance of the system results in the amplification of harmonic;
- The design should ensure that in the normal fluctuation of frequency, the filter can also meet the technology

PPF should be installed to minimize the total distortion of current:

$$THD_i = \sqrt{\sum_{K=2}^{\infty}\left(\frac{I_k}{I_1}\right)^2} \tag{15}$$

The minimum total harmonic current distortion is taken as one optimal objective. For the asymmetric system, the total harmonic distortions of three-phase currents are not same. The optimal design of PPF shall achieve minimum total harmonic distortion of three-phase current as follows:

$$f_1(X) = THD_{ia} + THD_{ib} + THD_{ic} \tag{16}$$

This paper just takes the initial investment costs of PPF into account. The initial investment costs mainly consist of the costs of the resistor ($\boldsymbol{R}$), inductor ($\boldsymbol{L}$) and capacitor ($\boldsymbol{C}$) used in the passive power filter.

$$f_2(X) = \min \sum_{i=1}^{p}\left(\omega_1 R + \omega_2 X_C + \omega_3 X_L\right) \tag{17}$$

Where $\boldsymbol{p}$ is the number of the PPF; $\boldsymbol{C}_i$, $\boldsymbol{R}_i$, and $\boldsymbol{L}_i$ are corresponding parameters of single-tuned filter or high-pass filter respectively.

$$\begin{aligned} \omega_1 &= \mathrm{U_P} \times 10^3 \times \left[i_f^2 + \sum_{h=2}^{n} i_h^2 \right] \\ \omega_2 &= \left(\mathrm{U_P} \times K + \mathrm{U_C}\right) \times \left[i_f^2 + \sum_{h=2}^{n} \frac{i_h^2}{h} \right] \\ \omega_3 &= \left(\mathrm{U_P} \times K + \mathrm{U_L}\right) \times \left[i_f^2 + \sum_{h=2}^{n} h i_h^2 \right] \end{aligned} \tag{18}$$

*U*C the incremental cost of the capacitor and it is equal to 170×103 LE/MVAR; *U*L the incremental cost of the reactor and it is equal to 170×103 LE/MVAR; *n* the harmonic number; *K*= constant = 0.4KW/MVAR (Ying-Yi and Wun-Jhih, 2013); If the fundamental current component; *Ih* the harmonic current components; *U*P is a constant, and it is equal to (Ying-Yi and Wun-Jhih, 2013):

$$U_P = 8760\, P_v\, F_u\, U_u \tag{19}$$

Where F_u is the Filter utilization factor which is equal to 1.0 and U_u is the cost of power loss/KWH which is equal to 0.2 L.E.

$$P_v = \frac{(1+I)^N - 1}{I(1+I)^N} \tag{20}$$

The objective function is considered as follows:

$$F(x) = \alpha_1 f_1 + \alpha_2 f_2 \tag{21}$$

Matlab/Simulink Based Simulation

The optimized results of GA are presented in Figure 6. The result of this optimization is inserted to CPF and DPF modes. The simulation model of test system in order to analysis the performance of passive filter under CPF and DPF states are presented in Figures 7-8 respectively.

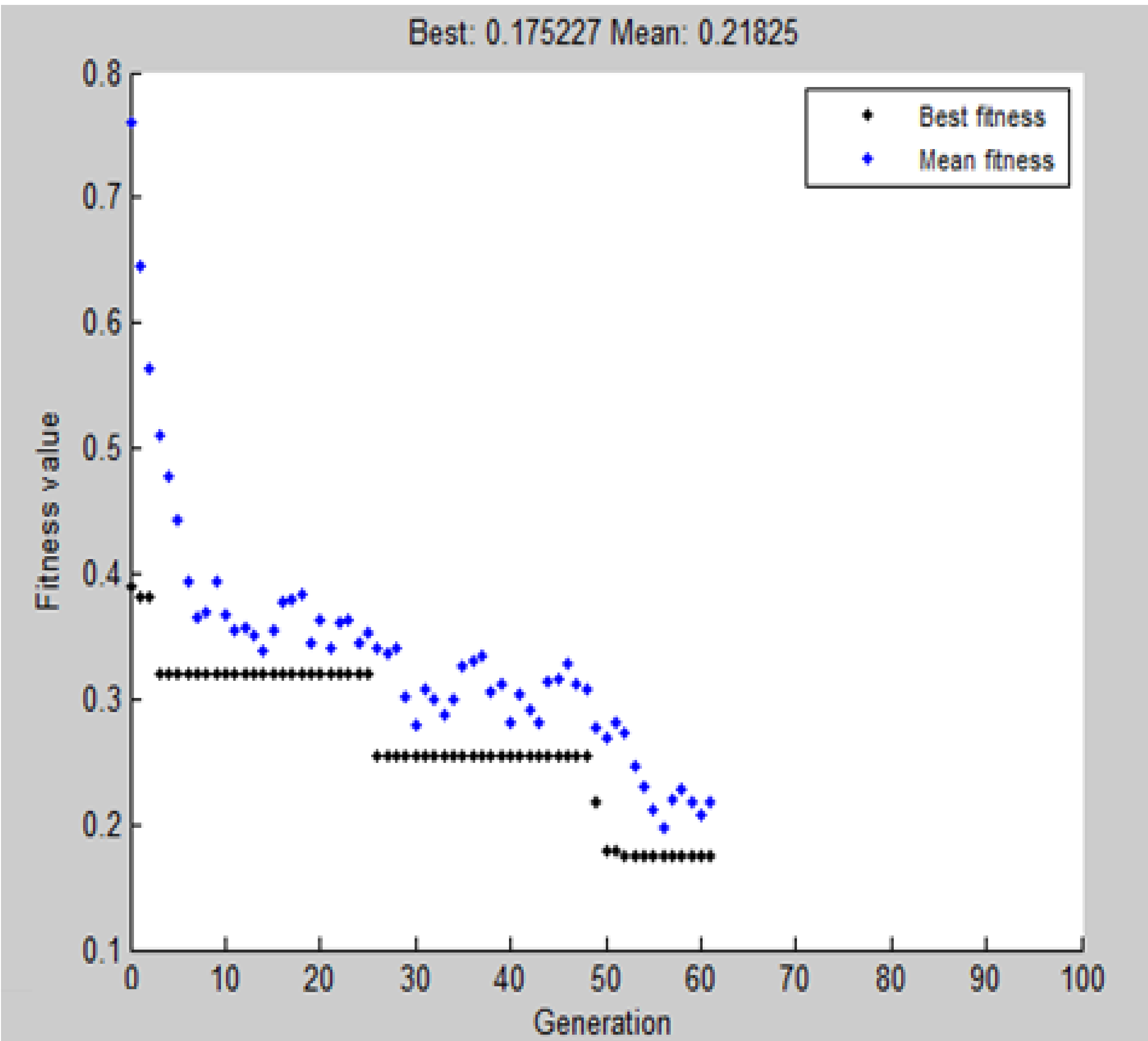


Figure 6: GA optimized Results

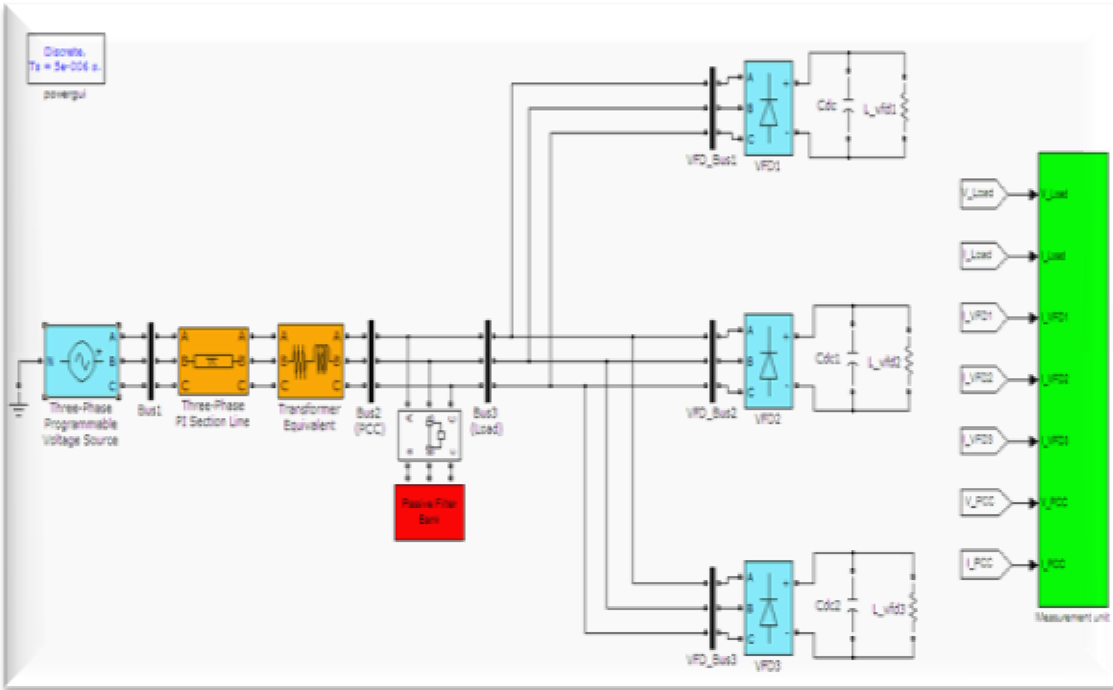


Figure 7: Matlab/Simulink developed model of the test system including of power system and VFD loads for passive filter in CPF state

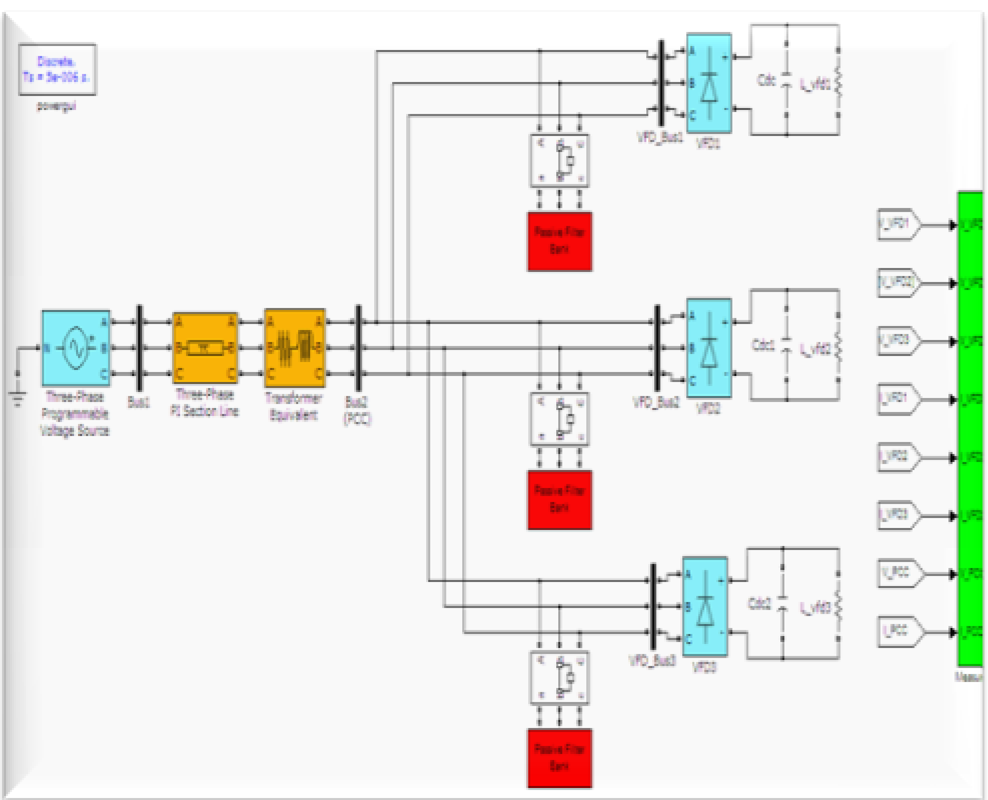


Figure 8:Matlab/Simulink developed model of the test system including of power system and VFD loads for passive filter in DPF state

The power system elements, including power source, interconnecting cable, transformer, variable frequency drives (VFDs) as non-linear load which is considered as harmonic source, and passive filter bank, is modeled in MATLAB. The non-linear load has been modeled with a diode rectifier with a smoothing capacitance of $300\ \mu F$ and an ac drive as equivalent resistance which represents the real power consumed by the load. This equivalent resistance corresponds to a 10.4-kW drive. The parameters of system including cable impedance, transformer equivalent parameters, passive filter parameters, main source and non-linear load are listed in Table 1.

Table 1: System parameters

Elements	Parameter Value
AC mains	230V, 50Hz
Load impedance	$VFD1: R_L = 15\Omega \quad C_L = 300\ \mu F$
	$VFD2: R_L = 15\Omega \quad C_L = 300\ \mu F$
	$VFD3: R_L = 10\Omega \quad C_L = 300\ \mu F$
Transformer equivalent	$0.15\Omega, \quad 6mH$
Passive filter	$L_5 = 10.34\, mH \quad C_5 = 36.34\ \mu F$
	$L_7 = 10.34\, mH \quad C_7 = 18.86\ \mu F$
Cable impedance	$0.6\Omega / km, 0.3mH / Km, 3\mu F / km$

In this study two conditions are considered. At first it is assumed that the main AC source is devoid from voltage harmonics and in second study it is assumed that due to injection of other harmonics current, the main source which feeds the nonlinear load is previously harmonic distorted.
The result of simulation when power source is devoid from voltage harmonics is presented in Table 2. It clearly shows that the application of passive filters reduces the net rms source current from 73.3 to 66.6 A for a single common passive filter (CPF) at the bus.

Table 2: Simulation result assuming main source is devoid of voltage harmonics

Current/Voltage	RMS value	THD%
Load current	73.29 A	38.13
Source current with CPF	66.64 A	2.11
Voltage at PCC	313.92 V	27.52
Voltage at PCC with CPF	317.24 V	9.35

When power source is distorted with voltage harmonics, the application of passive filters reduces the net rms source current from 82.11 to 72.76 A for a single common passive filter at the bus. This result is listed in Table 3.

Table 3: Simulation result assuming main source is distorted with voltage harmonics

Current/Voltage	RMS value	THD%
Load current	82.11	42.72
Source current with CPF	72.76	1.34
Voltage at PCC	312.4	31.09
Voltage at PCC with CPF	340.2	8.57

Table 4 clearly shows that the application of passive filters reduces the net rms source current from 73.3 to 72.8A for multiple DPFs for each VFD. It can be clearly seen that the THDs of current and voltage have been improved further with DPF performance of passive filters.

Table 4: Simulation results for DPF application of PPF

Current/Voltage	RMS value	THD%
Load current	73.29 A	38.13
Source current with DPF	72.88 A	1.27
Voltage at PCC	313.92 V	27.52
Voltage at PCC with DPF	328.57 V	6.93

Figure 9 shows the voltage at PCC without passive filter and Figure 10 presents the source and load current without passive filter.

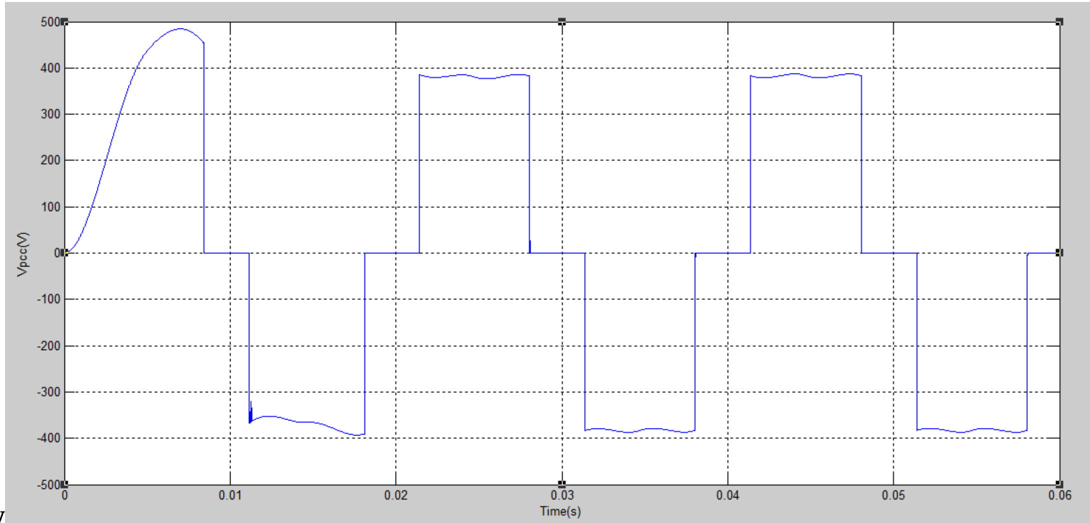
ew 

Figure 9: Voltage at PCC without passive filter

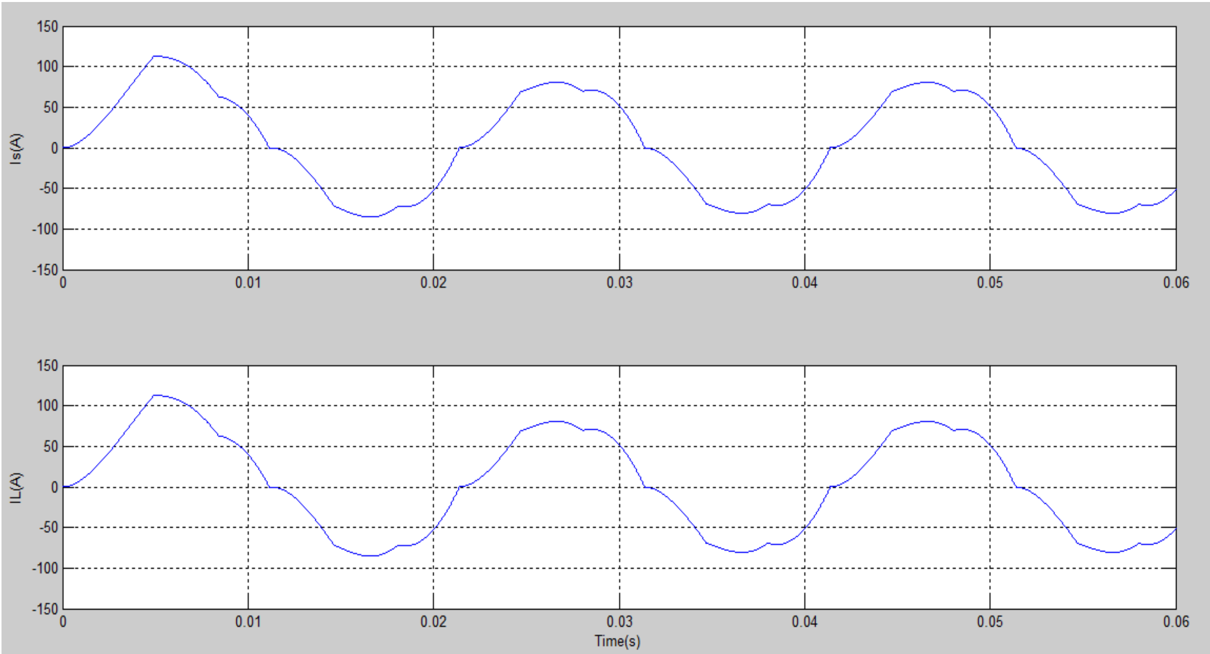


Figure 10: Source and load current without passive filter

In Figure 11 the non-linear phase a, b, c currents without passive filter is presented.

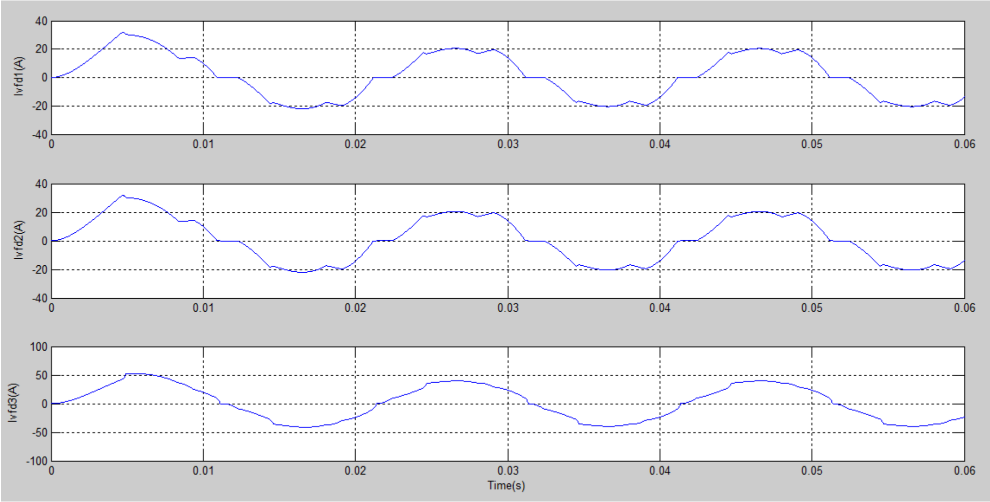


Figure 11: Non-linear phase a, b, c currents without passive filter

Figure 12 shows the voltage at PCC with passive filter under CPF state.
In figure 13 the source and load current with passive filter under CPF state is presented.
Also figure 14 shows the voltage at PCC without passive filter when main source is voltage harmonic distorted.

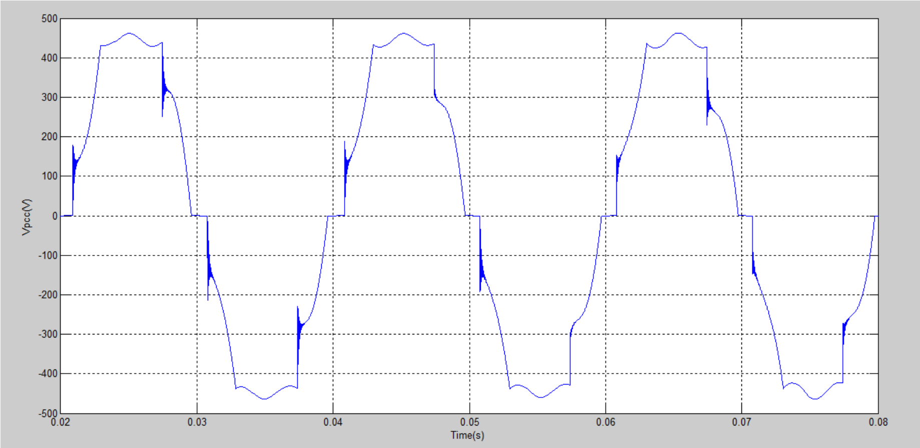


Figure 12: Voltage at PCC with passive filter under CPF state

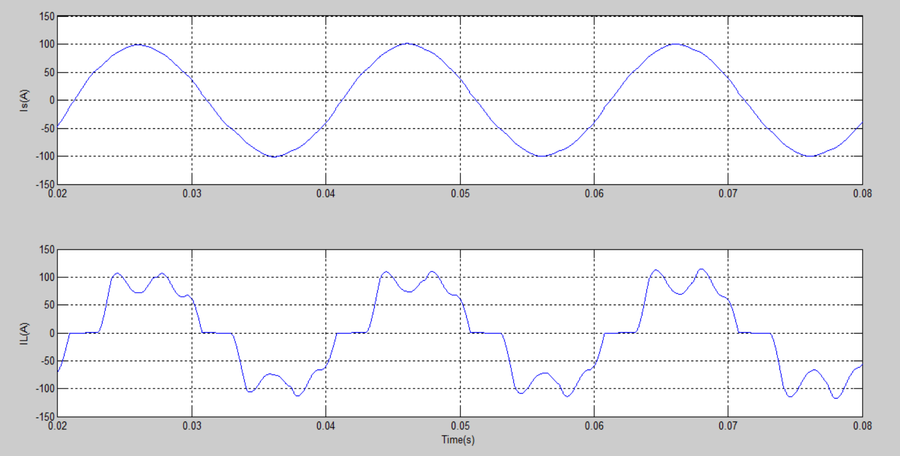


Figure 13: Source and load current with passive filter under CPF state

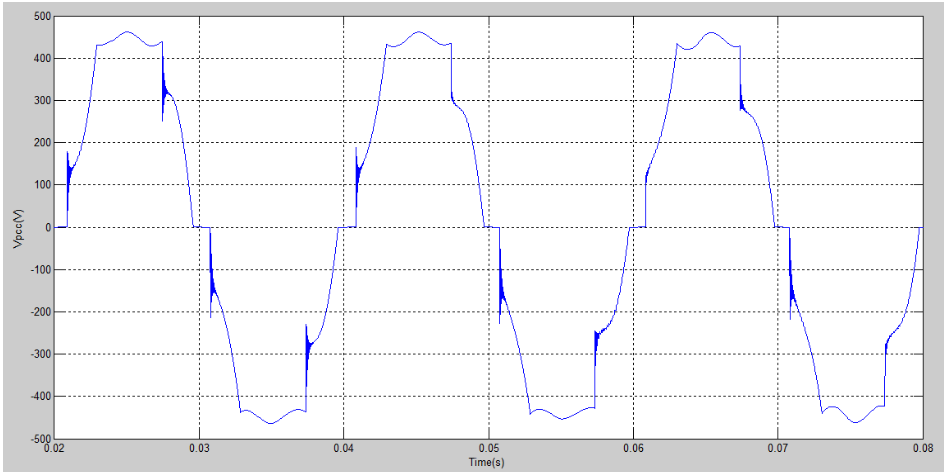


Figure 14: Voltage at PCC without passive filter when main source is voltage harmonic distorted

Figure 15 shows the voltage at PCC with passive filter under DPF state.

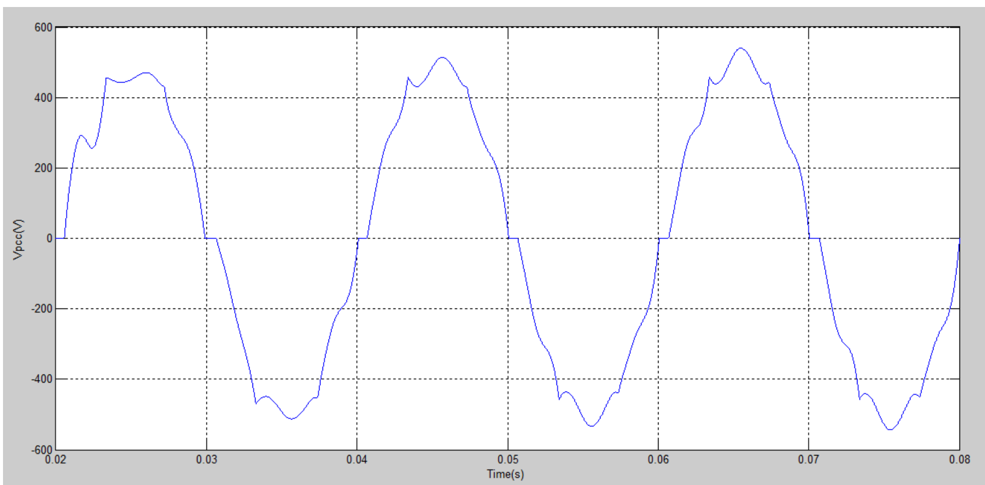


Figure 15: Voltage at PCC with passive filter under DPF state

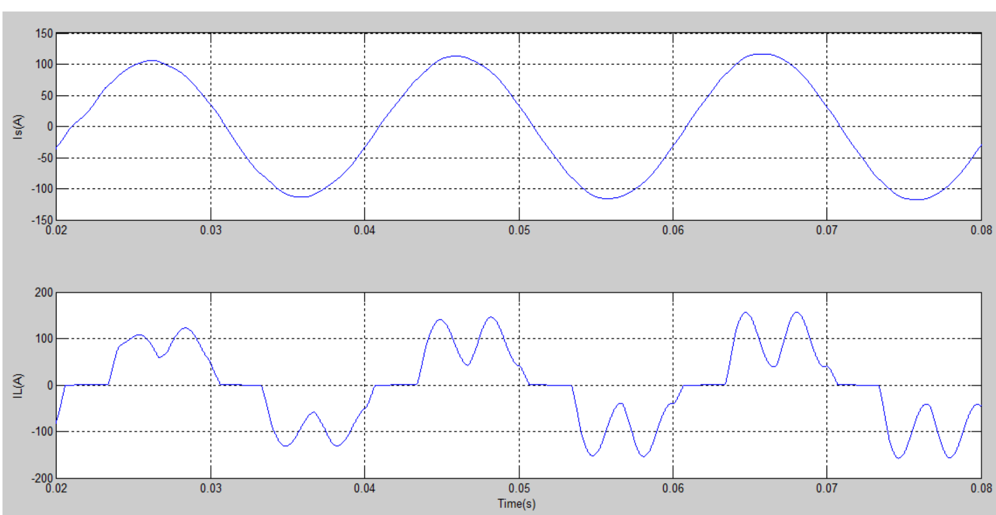


Figure 16: Source and load current with passive filter under DPF state

In Figure 16 the source and load current with passive filter under DPF state is shown

Conclusion

Harmonic distortion will result in additional heating losses, shorter insulation lifetime, higher temperature and insulation stress, reduced power factor, lower productivity, efficiency. In this research the performance of a common passive filter for non-linear load is investigated and the most effective method which could lead to improve voltage distortion and to decrease power losses is presented. Increases in harmonic distortion will result in additional heating losses, shorter insulation lifetime, higher temperature and insulation stress, reduced power factor, lower productivity, efficiency, capacity and lack of system performance of the plant. In this research the performance of a dedicated passive filter (DPF) for each phase of non-linear load is investigated and the most effective method which could lead to improve voltage distortion and to decrease power losses is presented.

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