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Modelling and validation of hybrid series active filter for power quality enhancement using OPAL-RT simulator

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ABSTRACT

It is a known fact that the quality of power is degrading at a very fast rate. The reason behind this is harmonics in the power supply. The main motive is to reduce the harmonic pollution in the system for various combinations of the load. The method proposed in this paper consists of hybrid series active power filter (HSAPF) which is a combination of an active power filter connected in series and the passive filter in parallel with the load. In order to generate the compensating signals, synchronous reference method has been used and the tuning of the proportional integral (PI) controller is performed with grey wolf optimization technique. It provides the optimized values of controller parameters that are very much necessary to improve not only the transient but also the steady state characteristics of the system. For comparison purposes the tuning of PI controller is also done using the well-known particle swarm optimization technique. A comparative simulation analysis is done in MATLAB as well as the results are verified by using OPAL-RT 4510 real time simulator which proves that the suggested topology gives better results in terms of total harmonic distortion (THD) reduction.

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1. INTRODUCTION

The sinusoidal nature of the power supply is affected when harmonics are present in the system [1]. All electric and electronic devices like transformers, compact fluorescent lamps (CFL), light emitting diodes (LED) lamps, high intensity discharge (HID) lamps, fluorescent tubes (FT), high voltage fluorescent lamps, air conditioners, rectifiers, inverters, lifts, mobile chargers, transformers cores, arc furnaces, switch mode power supplies (SMPS), adjustable speed drives (ASD), television (TV), chargers and computers produce harmonics. The phase relation between voltage and current which should be 0 degree is no more the same and there exists a phase difference which effects the point of common coupling between system and loads [2], [3]. To get rid of harmonics and enhance the power quality, filters are implemented in the circuit. Improving the quality of power and eliminating harmonics is a subject of research and has been addressed by many researchers in the past by suggesting several methods to implement passive and active filters. The passive filters suffer from the problem of resonance and large size and therefore are not popular [4], [5]. The inherent disadvantages of passive filters are resolved by using various types of active filters [6], [7]. The active filters work on the principle of harmonic compensation. The filtering characteristics are improved because the actual load current is monitored, and an exact opposite phase of the load current is injected to nullify the effect of harmonics. Thus, the supply waveform remains sinusoidal [8], [9]. Among the different types of active power filters (APF), shunt active power filters (ShAPF) gained popularity for eliminating harmonics, but they are not suitable for big systems [10]. Instead, series active power filters (SAPF) is another way to take care of the inherent disadvantages of ShAPF [11], [12]. A set of different combinations have been tested over the years to improve the filtering characteristics, out of which hybrid active power filters (HAPF) have been found to provide a viable solution at low cost. In HAPF, the output of the inverter is regulated to make the load voltage attain the set value [13], [14]. The inverters used are of high-power rating and also the inverter losses are reduced. But for some industrial applications still ShAPF are a preferred choice [15]–[18]. The aim of our proposed work is to formulate a technique which can eliminate harmonics in load voltage and also in source current.

In this paper, the hybrid series active power filter (HSAPF) is designed using optimized proportional integral (PI) controller gain. In general, the controller does two operations *i.e.*, initiate the switching pulses which is required for the inverter and generate reference current [19]–[21]. The selection of proper reference control voltage algorithm is important to reduce harmonics and get improved results. To generate the reference compensating voltage many methods can be found in the literature and one of them is instantaneous power theory (p-q) which is also known as synchronous reference frame theory [22].

Till now, the DC link capacitor voltage was controlled using the conventional PI controller because of its simple design and also it can be easily applied [23]. Even though with the many advantages of the conventional PI controller it fails to give the desired results and hence PI controller tuned with the grey wolf optimization (GWO) and particle swarm optimization technique (PSO) is tested in this research work. It is found to be more effective, and it gives better performance when compared with the conventional PI controller. The main aim of using the optimization technique is to find the PI controller gain parameters as per our requirement.

Apart from the optimization algorithms such as genetic algorithm [24], bacterial forging [25], particle swarm optimization [26], firefly algorithm [27], teaching learning-based optimization [28] the use of neural networks [29], neural network with fuzzy interface system [30] and the hybrid combination of the different optimization techniques such as PSO-GWO [31] and GA-PSO are also found in literature that can optimize the controller gains to give the required result. The basic idea behind using this optimization techniques is to estimate the PI controller gains as per minimum objective function. So, the GWO technique is proposed here to tune the controller parameters and to improve the DC link capacitor accuracy. The GWO technique makes the DC-link voltage more stable and faster as compared to other techniques. The optimized value of PI controller gains obtained from GWO technique is used in the HSAPF control scheme to mitigate power quality issues. The HSAPF with control algorithm is built in MATLAB Simulink and its performance is analysed for different types of non-linear loads. To verify the simulation results, the experimental set up has been done and the OPAL-RT 4510 simulator is used to validate the performance of the designed system. The total harmonic distortion (THD) in source current and load voltage are shown and compared with the results obtained from the existing technique. The harmonic spectrums justify that the proposed topology restricts the harmonics level well under 5% for medium voltage application as per IEEE 519-2014 Standards. The nonlinear load which consumes some reactive power is also mitigated to ensure the unity power factor operation of the system.

The sequence of the remaining part of the paper is aligned as follows: the optimization techniques and the objective function is given in Section 2. The overview of system topology and synchronous reference method is explained in section 3. In Section 4 all the simulation results are discussed in detail whereas the Section 5 includes the experimental results obtained using OPAL-RT 4510 simulator. Section 6 gives the conclusion.

2. OPTIMIZATION TECHNIQUES

This section presents a brief algorithm of PSO, GWO and the objective function which is designed as the minimum function for obtaining PI controller gains.

2.1. Particle swarm optimization

In this technique all individuals are given a position in the solution space which is continuously updated till the desired objective is reached [32]. The best position is obtained as per the defined objective function for which the controller gains are optimized and the error between the desired reference voltage and the voltage obtained across the DC link capacitor reaches to a minimum value. The error can be described as:

$$Error(e) = \text{Reference voltage} - V_{dc} \quad (1)$$

where V_{dc} is capacitor voltage. The controller output is as given in (2):

$$O_{cont} = K_{prop} e_r(t) + K \int_0^t e_r(t)_{int} \quad (2)$$

The tuning of PI parameters is a major issue since the load is variable in nature and in such varying load conditions the DC link voltage should remain constant. The application of PSO in our proposed system is explained in section 2.3. PSO searches for best position in the entire search space and rely on mathematical expression as given in (4).

$$V_q(m+1) = w * V_q(m) + c_1 * r_1 * [X_{qLB}(m) - X_q(m)] + c_2 * r_2 * [X_{qGB}(m) - X_q(m)] \quad (3)$$

and

$$X_q(m+1) = X_q(m) + V_q(m+1) \quad (4)$$

The notations m and q denote number of iterations and q is the particle number. The term $V_q(m)$ and $X_q(m)$ defines the velocity and position of the particle at m^{th} iteration. The other constants such as c_1 and c_2 are basically the cognitive part and r is the random number in range [0,1]. $X_{qLB}(m)$ and $X_{qGB}(m)$ are the local and global optima of the q^{th} particle attained so far in the entire search space. The corresponding flowchart is shown in Figure 1.

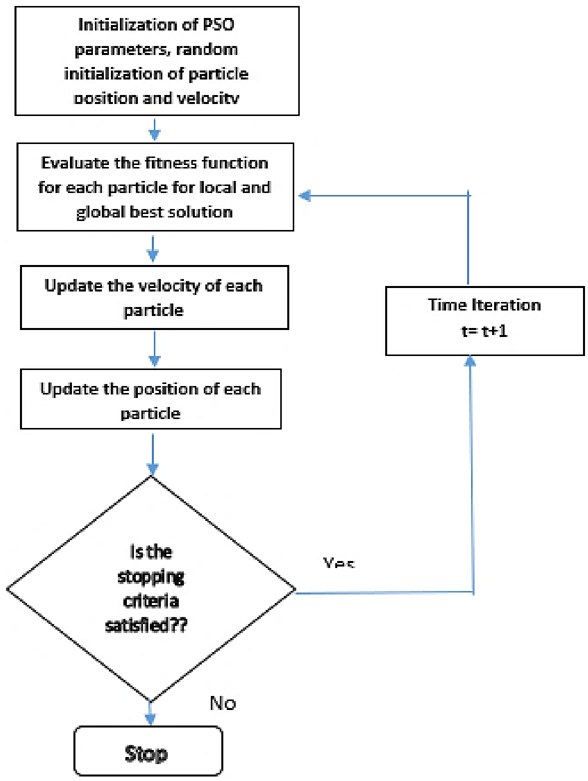

Figure 1. Flow chart of PSO technique

2.2. Grey wolf optimization

In GWO technique the first step is to select the population of grey wolves which are termed as the candidates [33]. The prey which is at a distance is designated as the optimum solution. The random members (A and C) support the candidates encircling the prey. The method adopted for hunting is given as,

$$\vec{D} = |\vec{C} * \vec{X_p}(g) - \vec{X}(g)| \quad (5)$$

$$\vec{X}(g+1) = \vec{X_p}(g) - \vec{A} * \vec{D} \quad (6)$$

where g represents the current iteration, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\overrightarrow{X_p}$ is the position vector of the prey, $\vec{D}$ and $\vec{X}$ indicates the distance and position vector of grey wolf. $\vec{A} = 2\vec{a} * \overrightarrow{r_1} - \vec{a}$ and $\vec{C} = 2 * \overrightarrow{r_2}$. Here value of $\vec{a}$ is linearly decreased from 2 to 0 and r_1 and r_2 are basically the random vectors defined in the range [0,1]. The corresponding flowchart is shown in Figure 2.

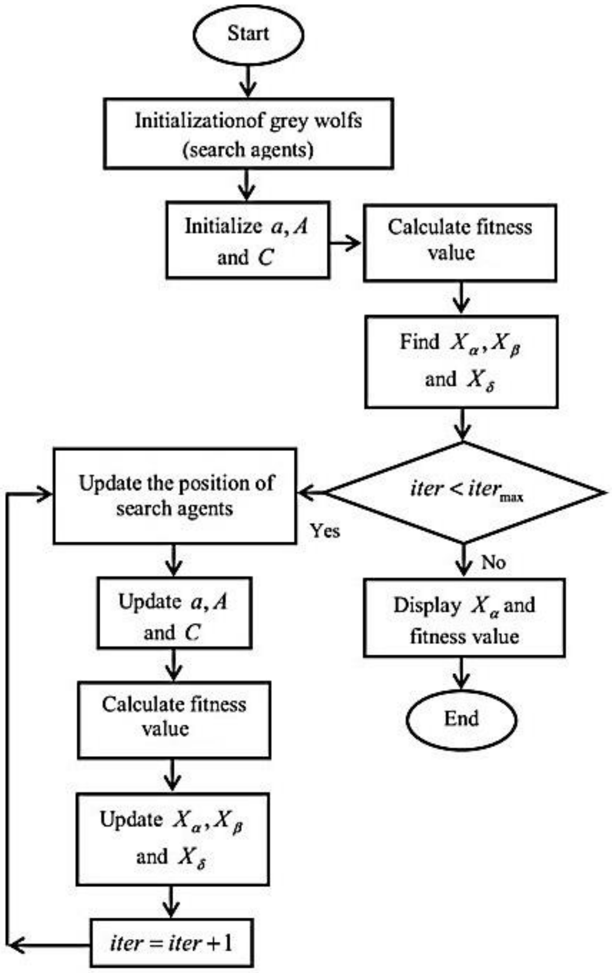

Figure 2. Flow chart of GWO technique

2.3. Objective function

As per the requirement, $m(x)$ is used to minimize PI controller gains (Kp, Ki). After g^{th} iterations optimal result is considered as the best solution from the given population size. It is represented mathematically as (7):

$$ITSE = m(x) = \int_0^\infty e^2(t)dt \tag{7}$$

The ITSE is the integral time square error, which when minimized gives the optimal values of controller parameters. The error (e) is $e = V_{dc}^* - V_{dc}$ where V_{dc} is DC link voltage and V_{dc}^* is the reference voltage. It has two variables K_p and K_i which needs to be tuned. The controller variables are defined as $x = \left(K_p, K_i\right)^T \in R$. The search space is given by $S = \{x \in R, xmax_{min}\}$ and R is the positive real number. The workspace data of ITSE which is the fitness function is extracted at every step and provided to optimization algorithm so that fine tuning of K_p and K_i is obtained. Hence the optimization technique minimizes the fitness function and is represented as (8).

$$Minimize\{ITSE\left(K_p, K_i\right)\} \tag{8}$$

3. OVERVIEW OF SYSTEM TOPOLOGY

HSAPF consists of two types of filters connected to the load: one type is connected in series whereas the other in parallel. Figure 3 shows the block diagram of HSAPF. Series connected filter is known as active filter and has three components, namely: i) full bridge inverter, ii) DC link capacitor, and iii) three-phase LC filter. Parallel connected filter is known as passive filter. It helps to get rid of 5th, 7th, 11th, and 13th harmonics from the system.

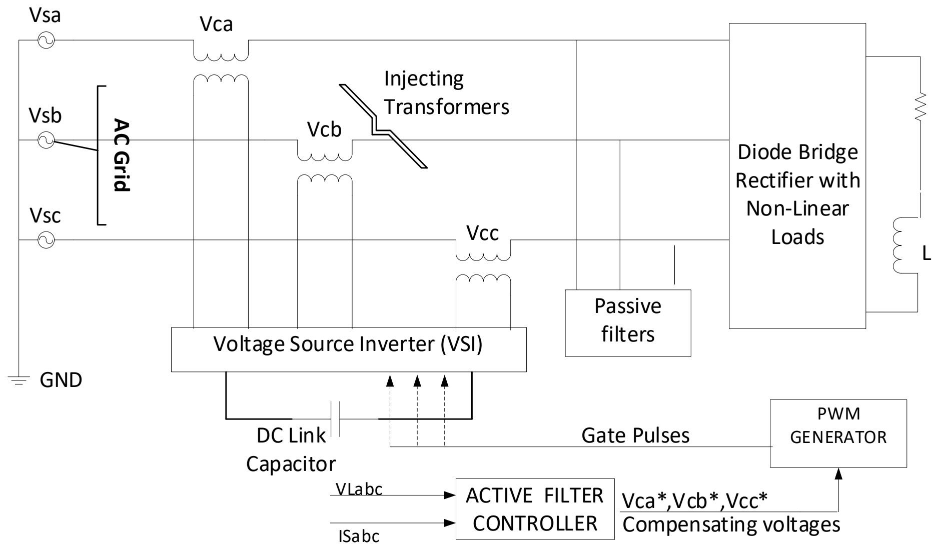

Figure 3. Block diagram of HSAPF

4. SIMULATION RESULTS

In this section the performance of PI controller based HSAPF for two types of non-linear load conditions–RL and RLC loads are presented. The simulation is performed in MATLAB. The Simulink model of the designed system is as shown in Figure 4 and the system parameters are given in Table 1. To evaluate the % THD of load voltage and the source current FFT analysis is done, and it is found to be as per IEEE 519 Standard for the proposed model. The reference voltage is calculated as 85 volts.

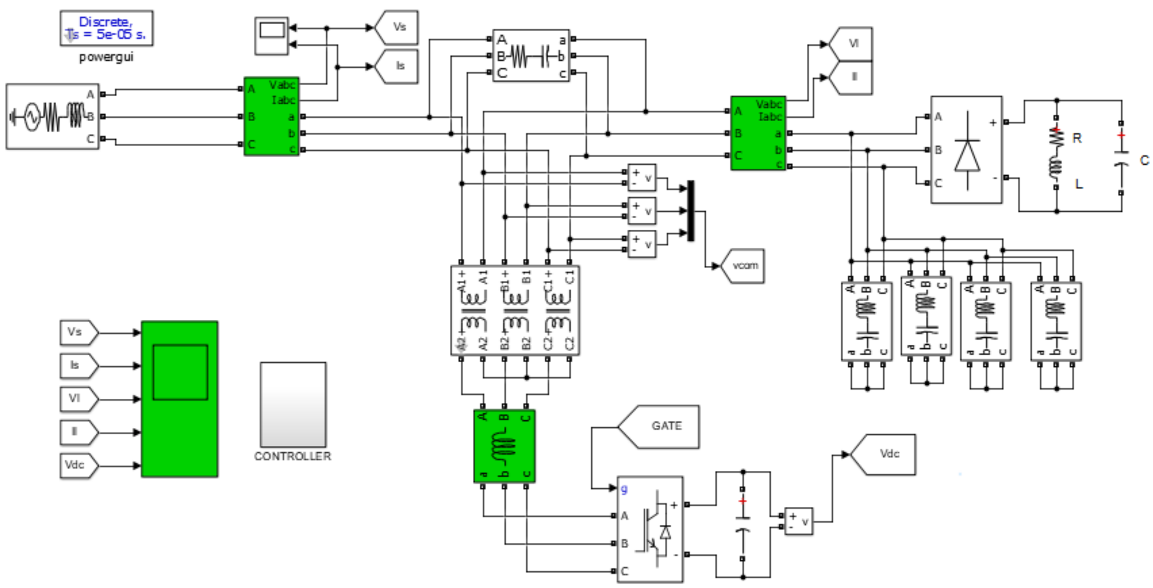

Figure 4. Simulink model of the desired system

Table 1. System parameters

Parameters	Values
Line voltage and frequency	$V_s = 220\,V(rms), F_s = 50\,hz$
Line impedance	$L_s = 0.5\,mH, R_{s==}0.1 = ohm$
Non-linear load	$L_L = 30\,mH, R_L = 25\,ohm, C_L = 50\,\mu F$
Series active filter parameter	$C_c = 60\,\mu F, L_c = 1.35\,mH$
	$C_{dc} = 1200\,\mu F, V_{dc} = 85\,V$
Passive filter parameter	$L_f = 2.36\,mH, C_f = 70\,\mu F$
PI controller parameter tuned with GWO	$K_{p1} = 1.3922, K_{i1} = 1.2181, K_{p2} = 1.3446, K_{i2} = 1.2253$
Ts and switching frequency	$T_s = 50e^{-6}, f_s = 1\,Khz$

The discussion presented here is divided into four cases, case 1 and 2 debates about the performance of HSAPF with PI controller tuned using PSO and GWO technique respectively for RLC load. Case 3 and 4 is devoted for assessing the effectiveness of PSO and GWO tuned HSAPF with PI controller respectively for RL load. The performance characteristics of DC link voltage is also evaluated in time domain for RLC load. For the purpose of comparison, %THD of source current and load voltage is calculated before applying compensation for both the types of load conditions. Also, to show the effectiveness of the optimization technique %THD is calculated for the system with HSAPF tuned with conventional PI controller.

4.1. Case 1: PI controller tuned with PSO technique (RLC load)

In this case, the controller parameters are tuned with the PSO technique. The % THD is drastically reduced to 4.53% in source current and 4.92% in the load voltage. Figure 5 represents the source current and load voltage waveform under steady state conditions. Figures 6 to 9 give an idea about the harmonic pollution before and after compensation in current and voltage waveform.

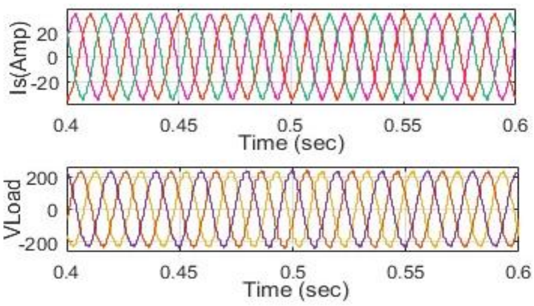

Figure 5. Steady state source current and load voltage

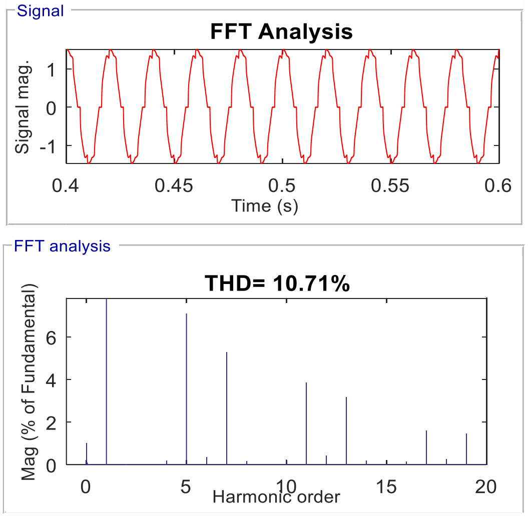

Figure 6. THD (%) source current before compensation

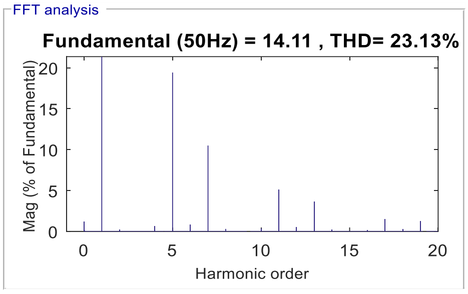

Figure 7. THD (%) load voltage before compensation

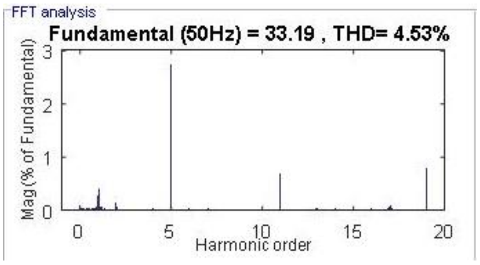

Figure 8. THD (%) source current after compensation

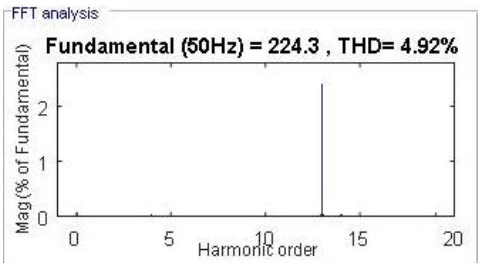

Figure 9. THD load voltage after compensation

Figure 10 represents the capacitor accuracy. Figure 10(a) shows the graph of DC link voltage (V_{dc}) and reference voltage. Figure 10(b) shows the resultant error plot. It can be seen that the error is almost reduced to zero. Figure 11 shows the time response graph of DC link capacitor voltage. The system parameters as shown in the graph are evaluated for 2% tolerance band. The % peak overshoot is 49.88%, rise time is 0.0184 s and the settling time is 2.19 s. These specifications indicates that the system performance needs to be improved and it could be done only when all these parameters are reduced further to give a better time response characteristic.

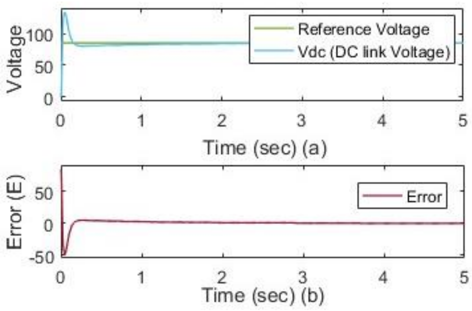

Figure 10. Capacitor accuracy of (a) reference and DC link voltage and (b) resultant error plot

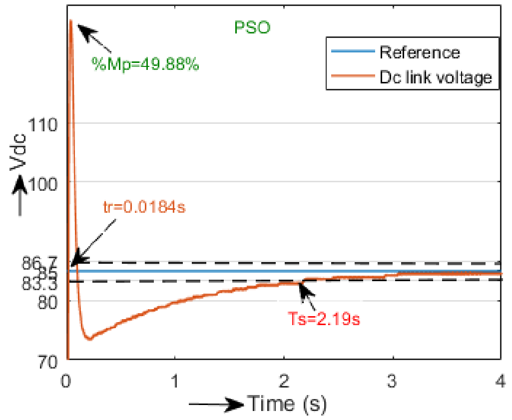

Figure 11. Performance characteristics of DC link voltage using PSO technique

4.2. Case 2: PI controller tuned with GWO technique (RLC load)

In the proposed system the PI controller is tuned with the GWO technique since the PSO has the disadvantage that under heavy optimization constraint it gets struck in the local minima and therefore that problem can be resolved with the GWO technique. The results obtained prove the efficacy of the system over the existing optimization techniques used to tune the controller parameters. Figure 12 shows that the THD in the source current is now reduced to 3.89% as compared to 4.53% and Figure 13 describes the harmonic pollution in the load voltage is now 4.54% as it was 4.92% in case when the controller parameters were obtained through PSO. The accuracy of DC link capacitor voltage (V_{dc}) is shown in Figure 14 and its performance in terms of % peak overshot, rise time and settling time is depicted in Figure 15. The % peak overshoot is 36.7%, rise time is 0.018sec and the settling time is 0.99sec which is far better than the time domain specifications obtained while the swarm optimization technique is used to tune the controller gains.

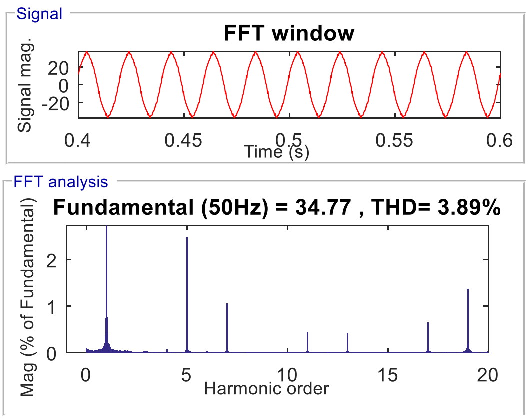

Figure 12. THD (%) source current using GWO technique

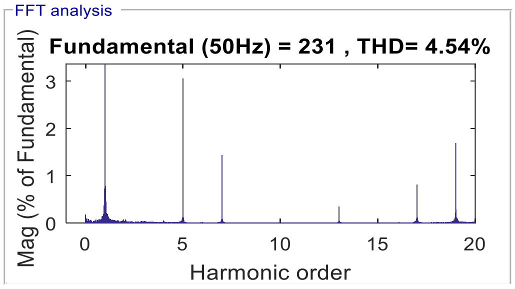

Figure 13. THD (%) load voltage using GWO technique

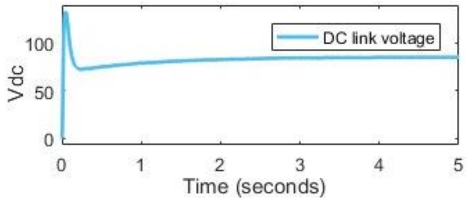

Figure 14. DC link voltage

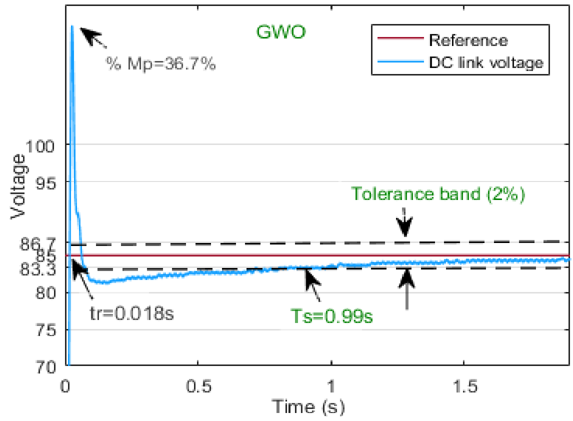

Figure 15. Performance characteristics of DC link voltage using GWO technique

4.3. Case 3: PI controller tuned with PSO technique (RL load)

In this case the results are obtained for the RL load while considering that the conventional PI controller is tuned with the PSO technique, and it was observed from Figures 16 and 17 that the harmonic pollution in both the current and the voltage is now 4.35% and 4.22%. Although the results obtained are quite satisfactory but still further improvement can be done to reduce the THD and improve the quality of the waveform. The gain parameters obtained by tuning the controller with the PSO technique are given as:

$$K_{p1} = 4.855$$
$$K_{i1} = 2.489$$
$$K_{p2} = 3.569$$
$$K_{i2} = 8.759$$

These gains are obtained when the fitness function that is ITSE reaches the minimum value.

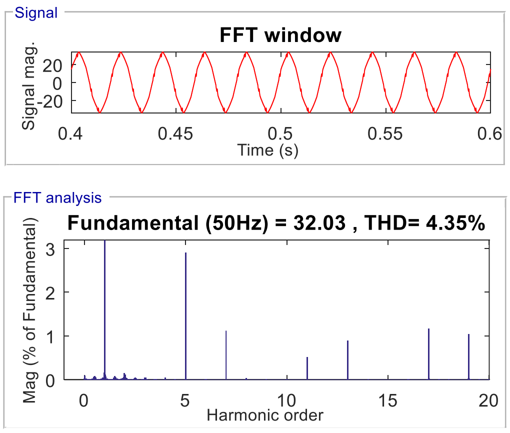

Figure 16. THD (%) source current using PSO technique

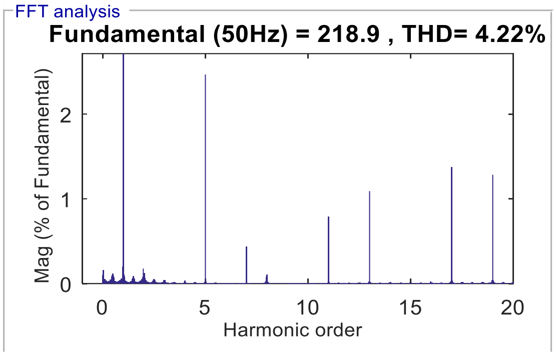

Figure 17. THD (%) load voltage using PSO technique

4.4. Case 4: PI controller tuned with GWO technique (RL load)

It is clear that the proposed system is effective even for the RL load since Figure 18 shows that the % THD is now 3.63% in the source current when PI controller parameters are tuned with the GWO technique and the Figure 19 represents THD in the load voltage which has been dropped down from 4.22% to 4.20%. Since, there is a marginal reduction in the THD of the load voltage but the results are quite satisfactory for the source current and the THD drops down to a minimum value that's 3.63% which strongly supports the proposed algorithm and exceeds over the conventional algorithms.

A comparison of % peak overshoot, rise time and settling time for RLC load is tabulated in Table 2. It can be seen that the time response characteristics is improved when PI controller is tuned with GWO technique. Similar analysis is performed for RL load and it is found that the proposed method (GWO-PI) gives improved results.

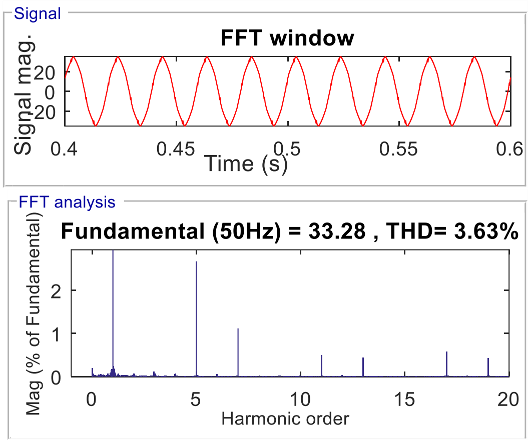

Figure 18. THD in source current using GWO technique

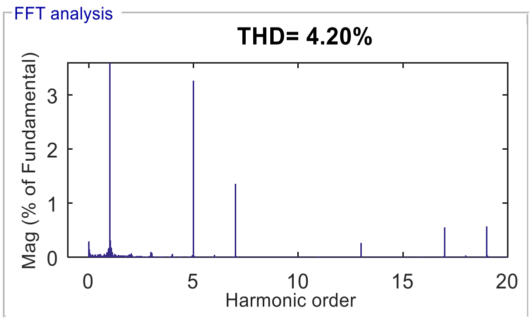

Figure 19. THD in load voltage using GWO technique

Table 2. Time response characteristics for RLC load

S. No	Tuning method	% Peak overshoot	Rise time (s)	Settling time (s)
1	PSO-PI	49.88	0.0184	2.19
2	GWO-PI	36.70	0.0180	0.99

5. EXPERIMENTAL RESULTS

In order to verify the results obtained through simulation an experimental set up has been done and the results are validated by the use of real time OPAL RT-4510 simulator. Figure 20 shows the experimental set up of the simulator. Figure 21 shows the OpComm block required to see the output of the real time simulator which consists of source current and source voltage for two different loading conditions (RL and RLC load).

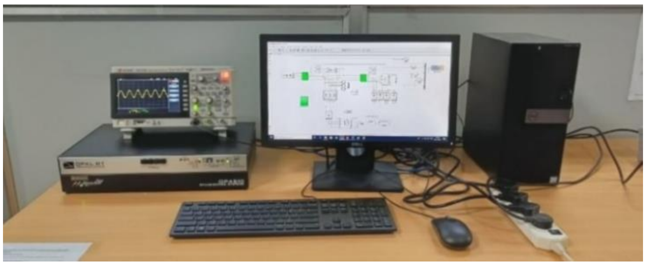

Figure 20. Experimental set up of software in the loop model

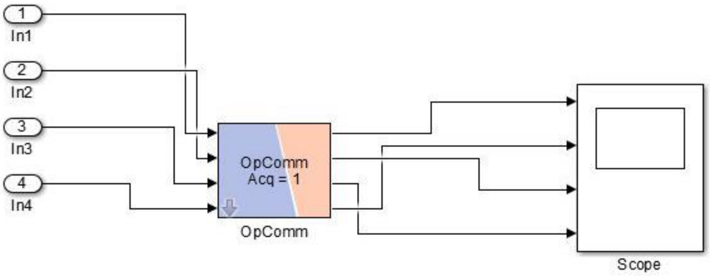

Figure 21. OpComm block

5.1. Case 1: RLC load (software synchronized results)

In this case the results are validated for the RLC load using the real time simulator. It is clear from the analysis that the THD is minimum and as per the IEEE Standard 519. Figures 22 and 23 shows the steady state characteristics of the load current and the source voltage for RLC load respectively.

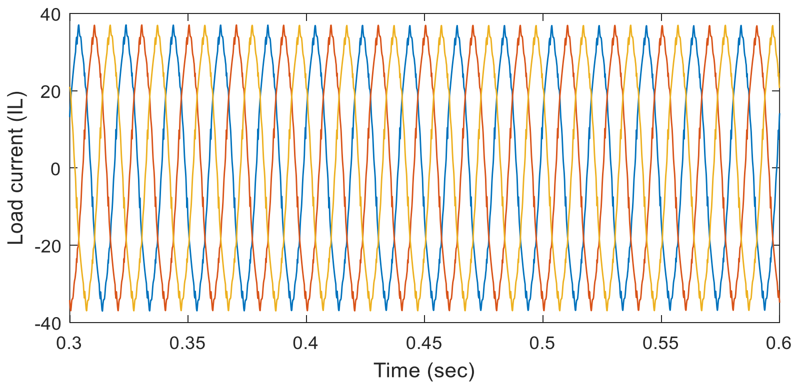

Figure 22. Steady state characteristics of load current using OPAL RT–4510 for RLC load

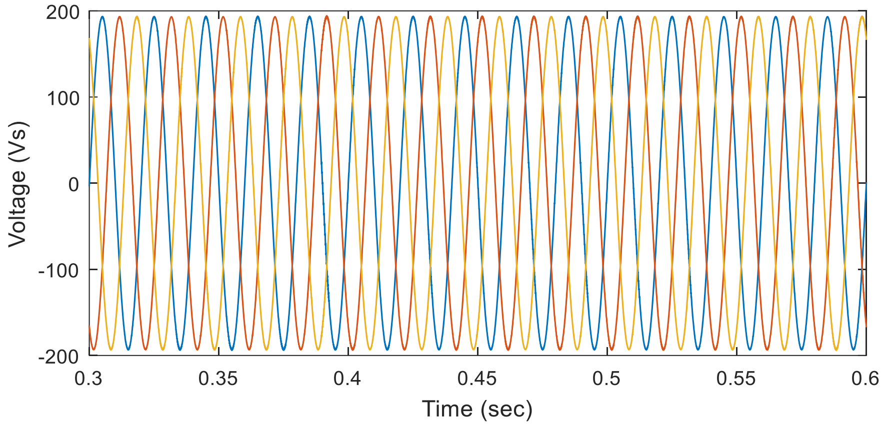

Figure 23. Steady state characteristics of source voltage using OPAL RT–4510 for RLC load

5.2. Case 2: RL load (software synchronized results)

Figures 24 and 25 shows the steady state characteristics of the load current and the source voltage for RL load. A comparison of % THD for both RLC and RL loads is tabulated in Table 3. It can be seen that the THD is least when PI controller is tuned with GWO technique. Since, it is clear that for the RLC load THD in source current is 3.89% which is minimum using the proposed GWO technique and similarly it is minimum for the RL load in case of source current.

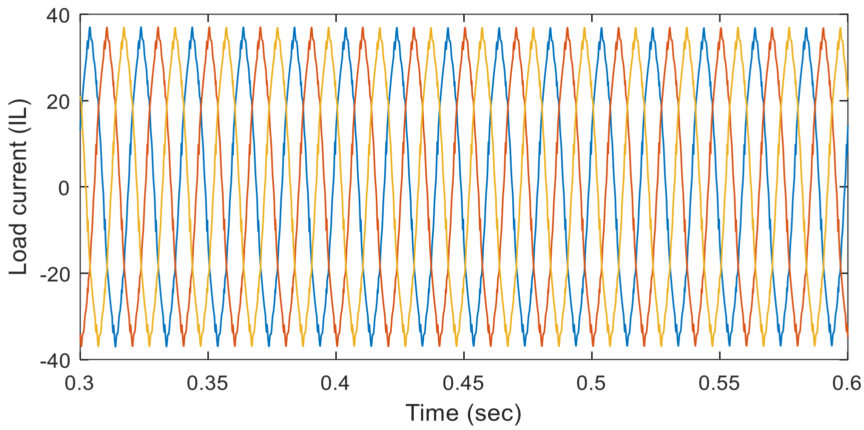

Figure 24. Steady state characteristics of load current using OPAL RT–4510 for RL load

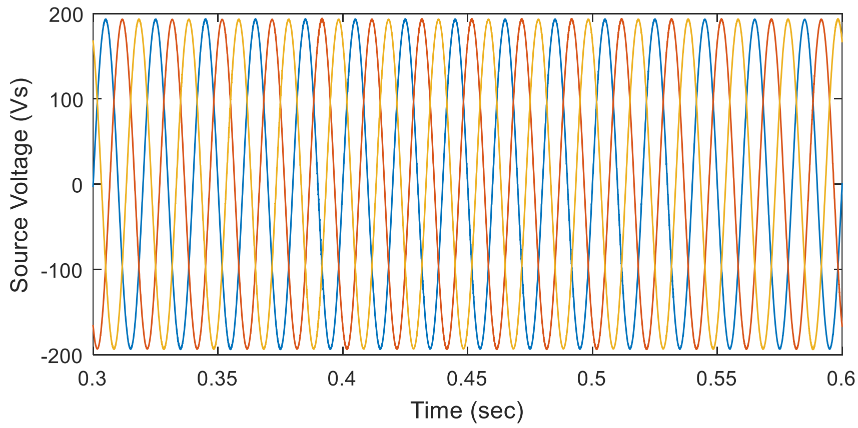

Figure 25. Steady state characteristics of source voltage using OPAL RT–4510 for RL load

Table 3. THD comparison (%)

Loads	THD (before compensation)	THD (PI)	THD (PI-GWO)	THD (PI-PSO)
RLC load (source current)	10.71%	6.93%	3.89%	4.53%
RLC load (load voltage)	23.13%	6.19%	4.70%	4.92%
RL load (source current)	14.29%	6.50%	3.63%	4.35%
RL load (load voltage)	36.14%	4.74%	4.20%	4.22%

Further, the comparison has been made for the THD in the load voltage for RL and RLC load and the results clearly shows the edge the optimization technique has over the existing conventional algorithms. Similarly, the analysis is carried out for load voltage and the source current and it was observed that the experimental results are well according to the simulation results obtained using MATLAB. Further, a table is given below summarizes the THD in different cases obtained using OPAL RT 4510 simulator.

The effect of harmonics introduced in the system due to non-linear loads is such that it deteriorates the quality of power delivered to the consumer. These power quality issues reduce the life and efficiency of the equipment as it causes overheating, insulation breakdown, over speeding of motors etc. The harmonic mitigation method proposed in this paper to snub harmonics is a grey wolf optimizer controlled HSAPF. The four cases considered here to examine the performance of HSAPF are all non-linear loads. The synchronous reference frame method-based control has been used to produce reference signals for supply voltages from evaluated fundamental components of load voltages. Inside the control algorithm, the GWO technique is used for achieving the best numerical value of PI controller gains. Therefore, tuning of PI-controller gain values is the considered as the most important factor for the efficient operation of HSAPF. The numeric values obtained by tuning the PI controller gains with the grey wolf optimization technique are chosen as the gains values corresponding to the minimum objective function that is integral time square error (ITSE). This has further resulted in improved DC link characteristics in terms of time domain specifications when compared to conventional tuning method. The simulations results show that the %THD in load voltage and source current is drastically reduced for both types of loads–RL and RLC. The results tabulated in Table 3 compare the response of the proposed method with the response of the system before applying any compensation, by using conventional PI controller and by using PSO-PI controller. The simulations have been performed in MATLAB and the results contained are also validated through an experimental set up using real time OPAL RT-4510 simulator.

6. CONCLUSION

Harmonics are created by nonlinear loads and switched devices which are majorly used in industries. However now a days many residential and building lighting loads produce more harmonics. Zillions of people hooked to computers and mobiles continuously inject harmonics back into the power distribution system. As is known, the use of inductors and capacitors in loads or in supply sources reduces current in harmonics. Performing harmonic analysis and mitigation studies also helps in integration of renewable energy sources for sustainable power system operation. The harmonic mitigation method proposed in this paper to snub harmonics is a grey wolf optimizer controlled HSAPF. The proposed design mitigates the harmonics in the source current and the load voltage to the desired level as set by the IEEE Standard 519 for the different categories of nonlinear load conditions–RL and RLC. It is further observed that the proposed GWO optimized based hybrid series APF gives better harmonic elimination as compared to the existing hybrid filters tuned with the conventional techniques as available in the literature. It is also shown in the proposed work that the implemented GWO-PI tuned method is better than PSO-PI tuned method in terms of improving the time response specifications of DC link capacitor voltage. The simulation results presented in this paper are validated using real time OPAL-RT 4510 simulator which proves the effectiveness of the designed approach when compared to the results obtained by MATLAB. The designed system effectively reduces the harmonics in the supply waveform.

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