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DESIGN OF PASSIVE FILTERS FOR REDUCING HARMONIC DISTORTION AND CORRECTING POWER FACTOR IN TWO PULSE RECTIFIER SYSTEMS USING OPTIMIZATION

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ABSTRACT

This work presents a method capable of designing passive filters to reduce harmonic distortion and correct the power factor in two pulse Rectifier system. The optimization process considers the discrete nature of the size of the element of the filter. This new formulation is a combinatorial optimization problem with a non-differentiable objective function. In addition a solution methodology based on an optimization technique Genetic Algorithm (GA) is proposed to determine the size of filters. The steps involved in GA are clearly explained. Simulation and experimental results for GA based design are presented.

Keywords: *Filters, Optimization, Power System Harmonics, Power Quality, Total Harmonic Distortion.*

1. INTRODUCTION

Nowadays, the most common practice for harmonic mitigation is the installation of passive harmonic filters. Passive filters exhibit the best relationship cost-benefit among all other mitigation techniques when dealing with low and medium voltage rectifier system [1-4]. They supply reactive power to the system while being highly effective in attenuating harmonic components. Typically, filter banks installed in medium-voltage systems are able to provide satisfactory reduction in voltages and currents distortions after their planning and design the other solution is the application of active filters [5-7]. These devices operate by rectifying the waveform and storing its energy in the DC side; then, an inverter typically transforms this energy to AC to reconstruct the waveform at a desirable magnitude and angle. Active filters operate very well in low voltage systems, but their cost and complexity when operating at medium- and high-voltage systems usually make them not regarded as viable [8]. Therefore, passive filters are still the most suitable mitigating scheme, even though they are a mature subject. The objectives of this paper are to provide the steps involved in GA are clearly explained. Simulation and experimental results for GA based design are presented [9, 10].

2. OPERATION OF TWO PULSE RECTIFIER

A single phase diode bridge rectifier connected to R load and its voltage and current waveform shown in fig.1. It consists of four diodes D1, D2, D3 & D4. At the input side, the source impedance is represented by series RL circuit.
Capacitor at the output end maintains constant output voltage and minimizes voltage harmonics. For analysis purpose the load specifications are taken to be 100W, 4A and 24V from a regulated power supply. The bridge circuit is characterized by 3 different modes [11-13].

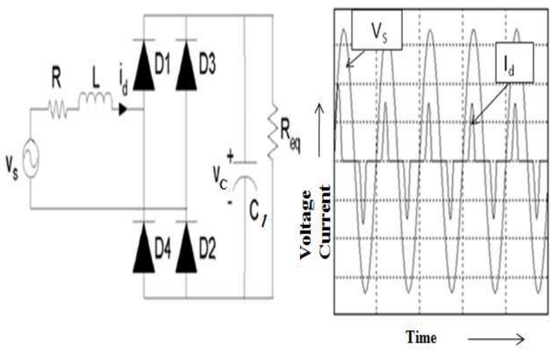

Figure 1: Two Pulse Circuit And Waveform

Mode 1:

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During mode 1, diode D1 and D2 conducts and the load resistance is connected to input voltage. A positive current flows in the circuit through the 2 diodes of the rectifier charging up the output dc capacitor. This mode is characterized by the following equations

$$\begin{bmatrix} \dot{i}_s \\ \dot{v}_c \end{bmatrix} = \begin{bmatrix} -R_s/L_s & -1/L_s \\ 1/C_l & -1/R_dC_l \end{bmatrix} \begin{bmatrix} i_s \\ v_c \end{bmatrix} + \begin{bmatrix} 1/L_s \\ 0 \end{bmatrix} [V_s] \quad (1)$$

Mode 2:

In this mode, all the rectifier diodes are off and the current becomes zero. While the DC output voltage is maintained constant by discharging the stored capacitor voltage. The equation representing this mode is given by

$$\left[\dot{v}_c \right] = \left[-1/R_dC_l \right] \left[v_c \right] \quad (2)$$

Mode 3:

A negative current flows in the circuit charging up the output dc capacitor with the other set of diodes conducting.

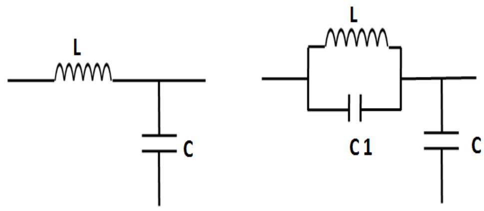
$$\begin{bmatrix} \dot{i}_s \\ \dot{v}_c \end{bmatrix} = \begin{bmatrix} R_s/L_s & 1/L_s \\ -1/C_l & -1/R_dC_l \end{bmatrix} \begin{bmatrix} i_s \\ v_c \end{bmatrix} + \begin{bmatrix} 1/L_s \\ 0 \end{bmatrix} [V_s] \quad (3)$$

Where:

V_s= source voltage
i_s = input source current
v_c= output capacitor voltage
R_s = source resistance
L_s = source impedance
C_l = output capacitor
R_d = diode resistance

3. PASSIVE HARMONICS FILTER

The input filter has four primary functions. One is to prevent electromagnetic interference, generated by the switching source, from reaching the power line and affecting other equipment. The second is to prevent high-frequency voltage on the power line from passing through the output of the power supply. Third is to improve the power factor and forth one is eliminate the harmonic. The passive filter consists of elements like inductor, capacitor and resistor for the filtration purpose. This makes the filter configuration simple and easy to implement. The filter is connected with the power distribution system and is tuned to present low impedance to particular harmonics so that these harmonics are diverted from their normal flow path through the filter or is tuned to present high impedance to particular harmonics to stop them from affecting the circuit. The tuning depends on the configuration of the filter designed. The passive filter is a very good choice for constant loads and is a cost effective solution to harmonic reduction and power factor improvement. All these advantages can be lost if the input filter is not properly designed. An oversized input filter unnecessarily adds cost and volume to the design and compromises system performance [14-18].



a) b)

Figure 2: Proposed Filter Connections

This paper explains how to choose and design the optimal input filter for a two pulse diode rectifier application using optimization. For a two pulse diode rectifier circuit with low power rating, using a passive filter is best suited. In most of the cases a passive filter involves an LC combination tuned to serve the purpose. Fig.2 shows the proposed LC filter approach to reduce line current harmonics generated by two pulse diode rectifier.

The simple passive-filter solution is the L-C passive filter equivalent circuit shown in fig.3. The transfer functions of the filter:

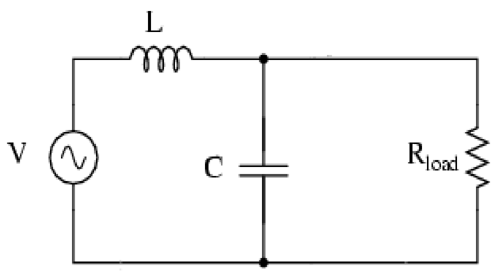


Figure 3: Filter Equivalent Circuit

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$$F_{filter}(S) = \frac{V_{out}(S)}{V_{in}(S)} = \frac{1}{1 + s.\frac{L}{R} + LC.s^2} \quad (4)$$

Due to limited space the cut off frequency, damping factor and quality factor expressions are not presented in this paper. This paper mainly focused only GA based design method.

4. GENETIC ALGORITHM BASED FILTER DESIGN

In this section an overview about genetic algorithm is given. Steps involved with genetic algorithm are explained. The objective of power factor improvement together with harmonic elimination is framed as an optimization task and the same is solved using Genetic Algorithm.

Problem Formulation

The objective of power factor improvement is drafted as an optimization task and it is given by
Maximize

$$F(\phi) = \frac{1}{power\ factor} \quad (5)$$

Subject to,

$$\phi_{\min} \leq \phi \leq \phi_{\max}$$

Where, $\phi = \{L, C\}$ and the subscript indicate the values of boundary values of filter components. In the GA based design emphasis is also given to minimize the size of the filter components as well.

Genetic Algorithm
Genetic Algorithm generates solutions to optimize problems using techniques inspired by natural evolution, such as inheritance, selection, crossover and mutation. It is a biologically inspired population based algorithm and was developed by JOHN HOLLAND, University Of Michigan to understand the process of natural systems [19-25]. It is widely used in scientific and engineering fields. The main steps involved are:

- Initializing Population.
- Evaluation of Fitness.
- Selection of Survivors based on fitness.
- Cross-Over & Mutation operation on the survivors.

Here, a population of strings (called chromosomes), which encode candidate solutions (called individuals) to an optimization problem, evolve toward better solutions. Usually, the algorithm terminates when either a maximum number of generations has been produced, or a satisfactory fitness level has been reached for the population. If the algorithm terminates due to a maximum number of generations, a satisfactory solution may or may not have been reached.

A typical genetic algorithm requires:

- representation of the solution domain
- fitness function to evaluate the solution domain

Flow Chart for GA
Flowchart representing the various steps involved is presented in fig.4. Only the fitter individuals in the population are allowed to pass their chromosome to the next generation. Random individual values are initialized and made to run till the best solution is reached.

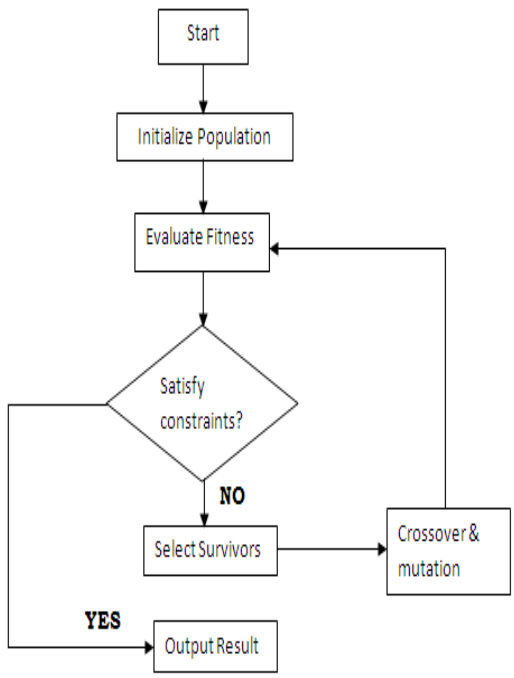

Figure 4: Flowchart Of Genetic Algorithm

Steps involved in GA based filter design
The following section explains how Genetic Algorithm is used for design of filter components:

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Step1: Create a population of initial solution of parameters (L and C)

This step primarily requires the population size. Each variable in the problem is called as a gene and in the present problem, there are two (i.e., L and C) genes. A Chromosome consists of the genes and thus each chromosome represents a solution to the problem. This is illustrated in fig.5. The population consists of a set of chromosomes. It is well articulated in literature that a population size of 10-30 is an ideal one and hence population size is selected as 15 in this work.

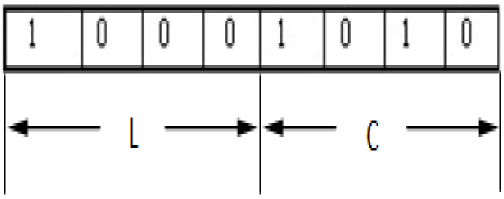


Figure 5: Chromosome Structure

Step 2: Evaluation of objective function

In the present problem, input power factor is to maximized and the corresponding objective function, F (L, C) is computed using.

$$F\ (L, C)\ =\ Power\ factor \qquad (6)$$

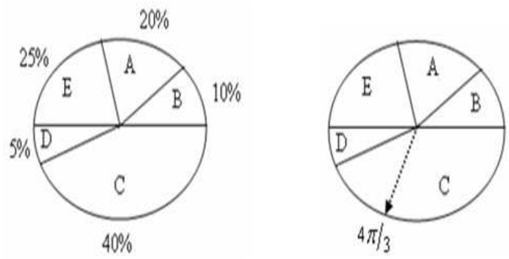
Step 3: Evaluation of fitness function

The degree of "goodness" of a solution is qualified by assigning a value to it. This is done by defining a proper fitness function to the problem. Since GA can be used only for maximization problems, the following fitness function is used:

$$Fitness\ function = \frac{1}{F\,(\phi)} \qquad (7)$$

Step 4: Generation of offspring

Offspring is a new chromosome obtained through the steps of selection, crossover and mutation. After fitness of each chromosome is computed, parent solutions are selected for reproduction. It emulates the survival of the fittest mechanism in nature. The Roulette wheel selection is the most common and easy-to-implement selection mechanism. A virtual wheel is implemented for this selection process. Each chromosome is assigned a sector in this virtual wheel and the area of the sector is proportional to their fitness value. Thus the chromosome with largest fitness value will occupy largest area, while the chromosome with a lower value takes the slot of a smaller sector. Let there be five chromosomes labeled as A, B, C, D and E and their fitness value increases in the order of D, B, A, E and C. Then Fig. 6(a) shows a typical allocation of five sectors of chromosomes in the Roulette wheel. In Roulette wheel selection, an angle is generated randomly and the chromosome corresponding to this angle is selected. Fig. 6(b) shows a randomly generated angle of 4 /3 rad.



6(a) 6(b)

Figure 6: Roulette Wheel Selections

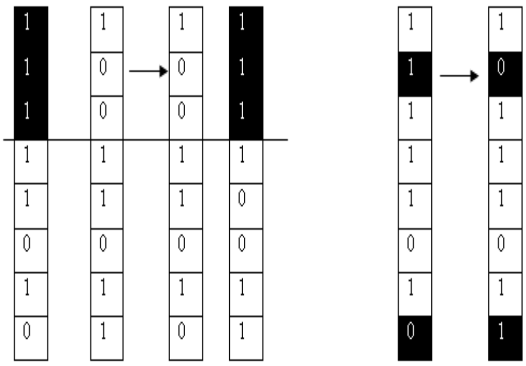


Figure 7: Crossover And Mutation

In this case, chromosome C is selected. The chromosomes thus selected are called parent population and are subjected to undergo crossover and mutation to produce offspring for the next generation. Conventional method adopted in GA is Roulette wheel selection and in this work, this selection method is modified by combining it with Elitism. Using Elitism, a definite number of best solutions are retained and are re-used in the next generation without undergoing the steps of mutation and crossover. Following the selection of

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parent population, crossover and mutation are performed to generate offspring population. In crossover, randomly selected sub-sections of two individual chromosomes are swapped to produce the offspring. In this work, multipoint crossover is adopted for increased efficiency since three variables are embedded in one chromosome mutation is another genetic operation by which a bit within a chromosome may toggle to the opposite binary. Fig.7 illustrates crossover and mutation. The crossover and mutation are performed based on the probability of crossover and mutation.

Step5: Replace the current population with the new population

Step6: Terminate the program if termination criterion is reached; else go to step 2.

The genetic algorithm method offers advantages in terms of Computational burden. The optimal values of L and C using conventional method are obtained after trying out many combinations of L and C where as they are obtained very easily through GA method.

5. SIMULATION AND EXPERIMENTAL RESULTS

A dedicated software program has been written to implement Genetic Algorithm in MATLAB. To validate GA design method, power factor and harmonic spectra are computed the different LC filter combinations like parallel LC filter, series LC filter, Shunt LC filter and Parallel and shunt LC filter. The computed harmonic spectra taken all four combinations are shown in fig.9 and power factor values and Total Harmonics Distraction (THD) are presented in table II. The following GA parameters are considered for simulation

- Population size : 15
- Coding : Binary
- Number of generations : 200
- Selection scheme: Combination of Roulette wheel selection with elitism.
- Crossover operator :Multipoint crossover
- Crossover probability : 0.7
- Mutation probability : 0.01

The convergence characteristics of Genetic Algorithm for typical case of LC passive filter is shown in fig.8. From the characteristics it is clear that the GA converges to objective function of 1 at 10^{th} iteration. The convergence obtained is seemed to be satisfactory as the objective function in our case i.e. 1/PF is converges within few iterations.

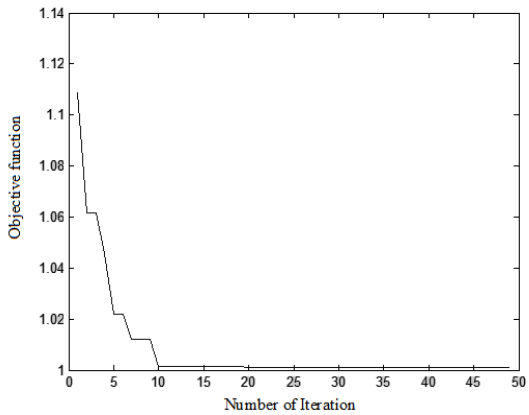

Figure 8: Convergence Characteristics Of GA

The above described algorithm is implemented for design of LC filter and the simulated results are presented in table.

TABLE I. SIMULATED RESULTS FOR SHUNT LC FILTER

L (mH)	C (uF)	PF	Vo	Irms	THD (%)
14.3	220.00	0.9915	23.13	4.96	6.99
15.5	254.59	0.9966	25.29	4.50	6.95
16.7	266.24	0.9972	25.77	4.68	6.10
17.0	250.71	0.9966	25.13	4.45	6.35

The proposed various passive filter harmonic reduction approaches has been implemented on a laboratory prototype. Figs 10(a) shows the experimental results without filter. The two pulse rectifier is in discontinuous operation resulting in high current harmonics. The measured THD of input current is 71.9 %.Figs 10(b) shows the experimental results with Shunt LC filter. Notice the near sinusoidal shape of the input current. The measured THD of the input current is reduced to 14.3% (fig.10 (b)). Fig. 11 shows the Current Harmonics spectrum for Combination of Parallel and shunt filter. The measured THD of the input current is reduced from71.9 to 8.9%

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SIMULATION RESULTS

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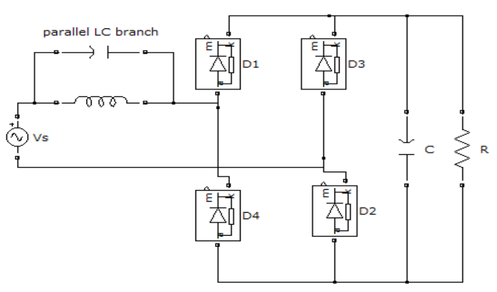
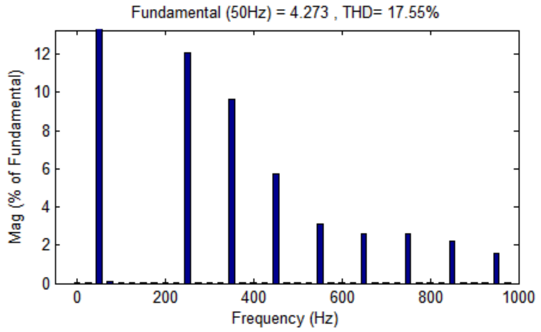
<tr><th></th><th>Passive Filter circuits</th><th>Harmonic Spectrums</th></tr>
<tr><td>a)</td><td>
</td><td>
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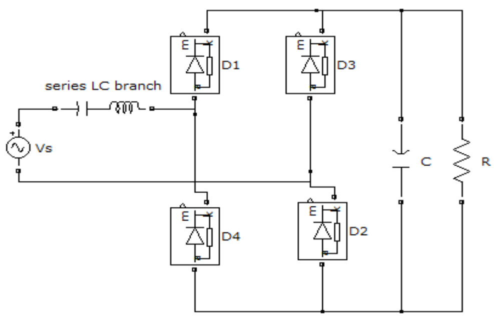
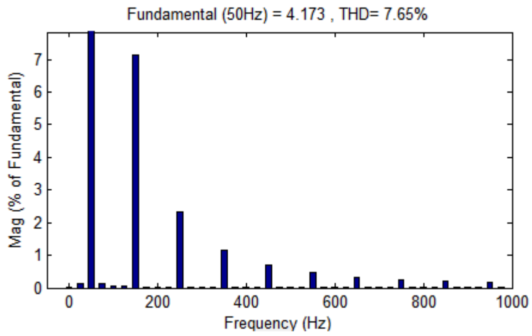
<tr><td>b)</td><td>
</td><td>
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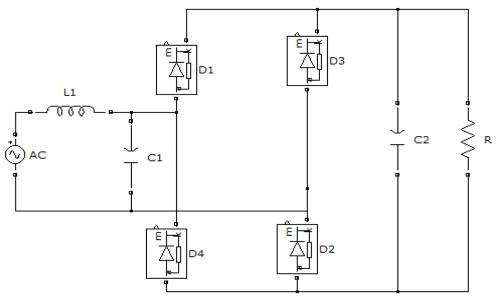
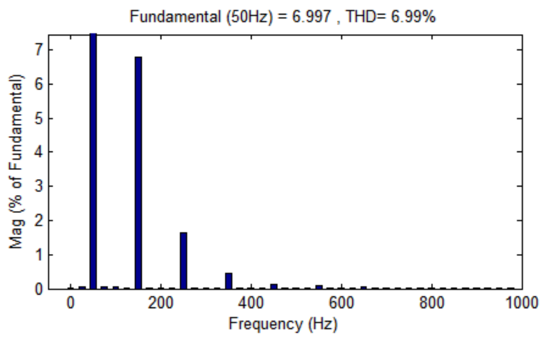
<tr><td>c)</td><td>
</td><td>
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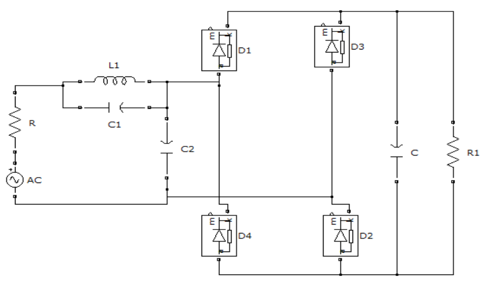
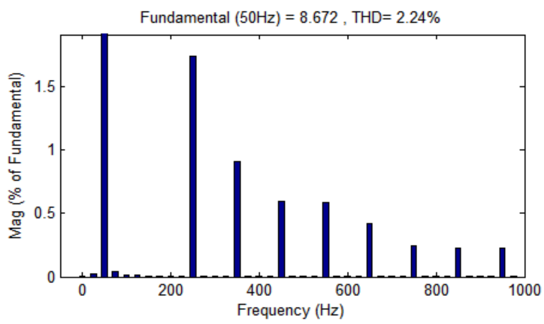
<tr><td>d)</td><td>
</td><td>
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Figure 9: Simulation Circuits And Current Harmonics Spectrum Of A) Parallel LC Filter B) Series LC Filter C) Shunt LC Filter D) Combination Of Parallel And Shunt Filter

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EXPERIMENTAL RESULTS

Current waveforms **Harmonic Spectrums**

a)

b)

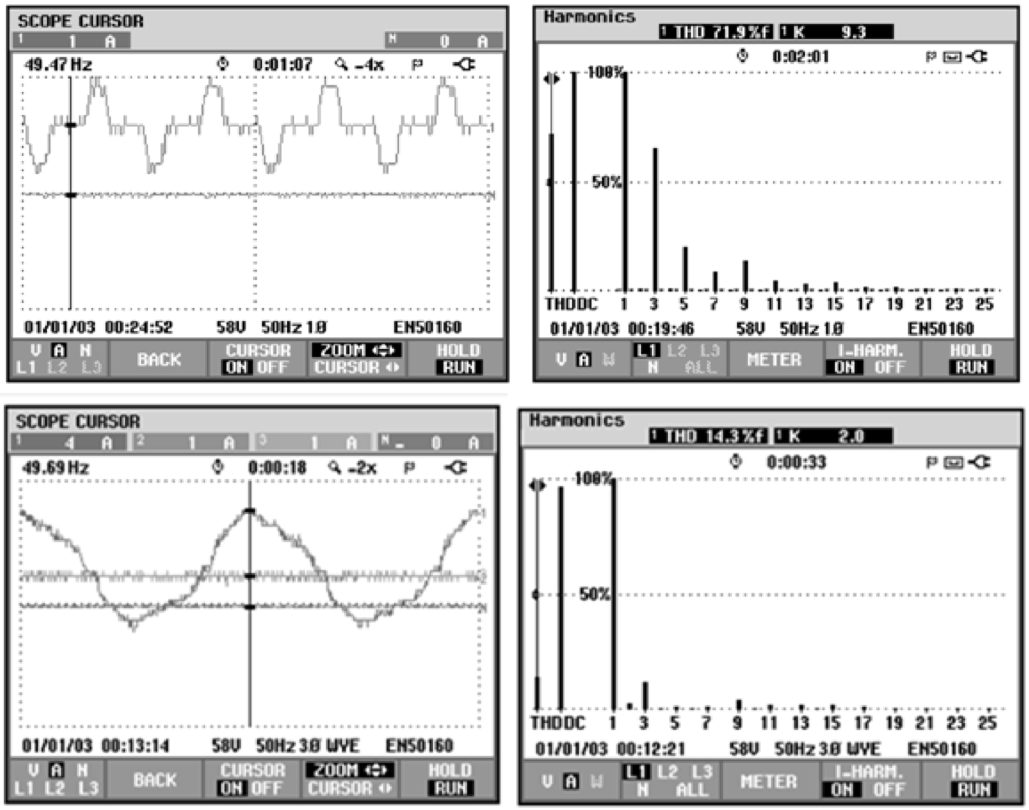

Figure 10: Measured Current Waveform And Current Harmonics Spectrum Of A) Without LC Filter B) Shunt LC Filter

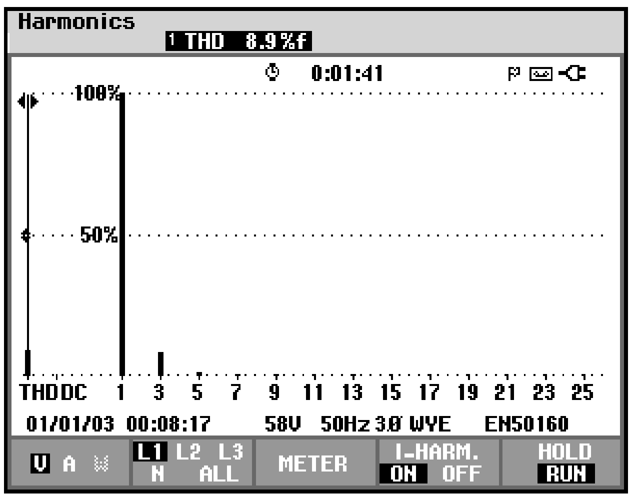

Figure 11: Current Harmonics Spectrum For Combination Of Parallel And Shunt Filter

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Table 2 Simulated Comparative Results

Configuration	Power Factor	THD (%)
Without filter	0.66	105.7
Parallel LC	0.9827	17.79
Series LC	0.99	7.011
Shunt LC	0.997	6.11
Parallel and shunt filter	0.9998	3.45

6. CONCLUSION

Analysis of the above results gives a clear validation to the idea of inserting a filter at the input side of the two pulse diode rectifier circuit. By insertion of a well designed filter it is observed that the power factor of the circuit has improved to a great extent and the THD has reduced to a very low value compared to that of without a filter. After observing the results it can be now concluded that the proposed configuration of Shunt LC and parallel & shunt combination filter produces the best results. Harmonic values are well within the harmonic limits and the output voltage is maintained constant for all the values. However future work and research is still needed in this filter designing process where in it is possible that the other different optimization techniques can be used to design the filter values and secondly an active filter can be used which can help the achievement of unity power factor and very high reduction in harmonics.

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