A Detailed Current Harmonic Analysis and GA Based Passive LC Filter Design In Six-Pulse Variable Frequency Drive

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ABSTRACT

This paper describes the detailed current harmonic analysis from six pulse variable frequency drive in Pulp and Paper Industry. It is also demonstrated that converters operating in the continuous conduction mode (CCM) and discontinuous conduction mode (DCM). The harmonics are validated by real measurements for the six pulse drive. 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. The experimental results for GA based LC Filter design are presented.

Introduction

The application of cost effective power converter circuits which enhance the overall performance, efficiency, and reliability of industrial processes is common in all industry. The industrial applications of AC/DC and DC/AC power conversion have increased gradually since the advent of silicon controlled rectifiers (SCR) in 1957. However, the wide use of single and three phase diode/thyristor rectifiers, for DC power supplies and Variable Frequency Drives (VFDs) in industrial appliances. With an estimated 65% of industrial electrical energy used by electric motors, the major users in industry increasingly see energy reduction as a key to improve their profitability and competitiveness.

Because variable speed drives reduce energy consumption 20-30% savings and decrease pollutant emission levels to environment while increasing productivity, their proliferation is inevitable. For variable speed applications, VFDs are widely employed in driving induction and permanent magnet motors due to the high static and dynamic performance obtained in such systems. High energy efficiency and high motion quality, low starting torque, etc. are the positive attributes of the VFDs. Unfortunately VFDs produce high levels of harmonic current distortion and their interaction with the supply system is not fully understood nor described in literature. As a result, VFDs are often installed with little regard to the effect they will have on the total harmonic voltage distortion (THDV) and current harmonic distortion (THDI) at the point of common coupling (PCC). It is therefore not until after the installation is complete that the harmonic problems are realised requiring expensive retrofit solutions such as the installation of harmonic filters or phase-shifting transformers.

When a distorting load such as VFDs is added to a power system, the THDV and THDI at the PCC is dependent on the existing supply distortion, the supply impedance and the harmonic currents produced by the load. In order to be able to predict the harmonic effects of installing VFDs, accurate information about the magnitude and phase of the harmonic currents produced by the VFDs, is required. This paper deals detailed Current Harmonic Analysis of the VFDs operation. This analysis is then used to investigate the dependence of the line side harmonic currents on both the circuit parameters of the VFD and Genetic Algorithm (GA) based LC filter design.

Voltage Source Variable Frequency Drive

The most widely used type of variable speed drive is the voltage source inverter (VSI) base variable frequency drive (VFD). VFDs are composed of three main components: a rectifier, a DC link and an inverter. The front end of a three-phase VSI VFD is composed of an uncontrolled bridge rectifier and a DC link which contains a shunt capacitor to provide a smooth voltage supply to the inverter. These circuits generally have little or no DC link inductance and therefore the assumption of constant DC current the rectifier current typically has a high ripple component and may even decay to zero periodically for smaller drives thus producing high levels of harmonic current distortion.

When looking at the line side harmonics of a VFD in steady state operation, the inverter is typically modelled as a DC current source or a constant DC power. In this paper it is assumed that the DC voltage for smaller VFDs has little ripple. Therefore a resistive load has been used to approximate and assumed that the three-phase supply is balanced and sinusoidal, for preliminary investigations. The simplified VFD model is shown in Figure 1.

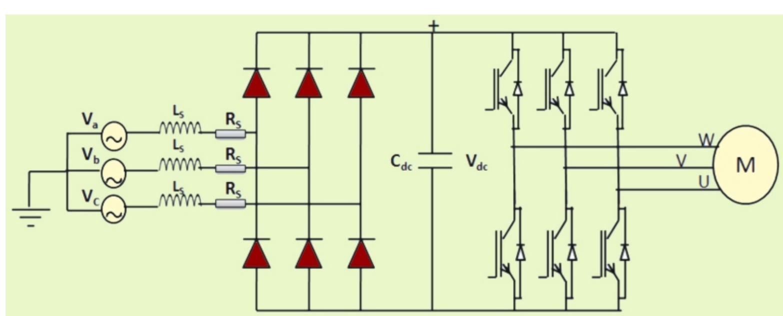

Fig.1. Voltage source variable frequency drive power structure

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Circuit Operation

Rectifier circuits with capacitive DC links have three possible modes of operation, each of which has associated linear differential equations for the capacitor voltage, V_{dc}, and DC current, I_{dc}, as described below. The operation of the circuit at any point in time may be determined by solving for these state variables by analysing the natural and forced response of the differential equations. The final expressions for V_{dc} and I_{dc} are not presented in this paper

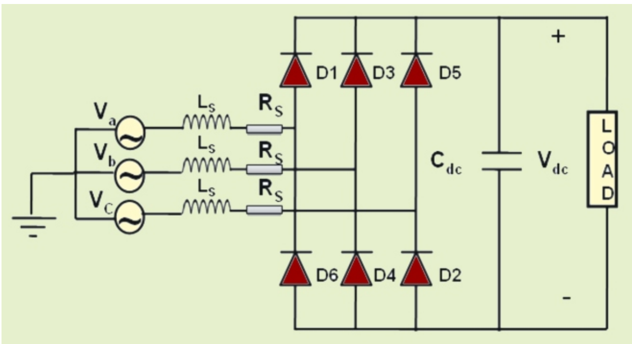


Fig.2. Phase Rectifier with Voltage Smoothing DC Link

Conducting

The rectifier diodes are forward biased and current flows from the supply into the capacitor and the load. The equivalent circuit is shown in Figure 3.

Discharging

Rectifier diodes are reversed biased so no current flows from the supply. The load current is supplied from the capacitor. The equivalent circuit is shown in Figure 4.

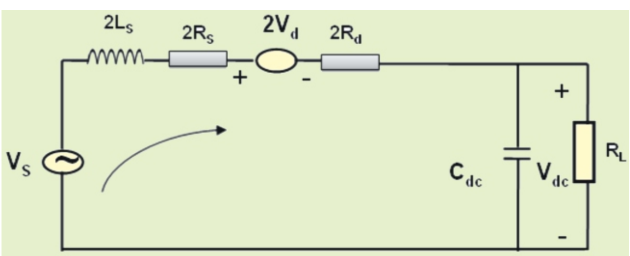


Fig.3. Conducting Mode Equivalent Circuit

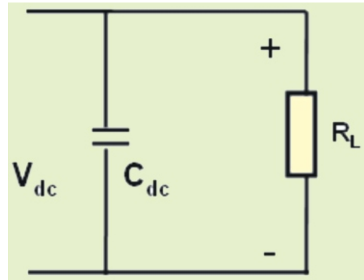


Fig.4. Discharge Mode Equivalent Circuit

Commutation

When current is transferred from one phase to the next there is a period of commutation due to the inductance in the supply. By way of illustration, Figure 5 shows the equivalent circuit for the positive commutation from C phase (D5) to A phase (D1) which occurs at θ = π /3.

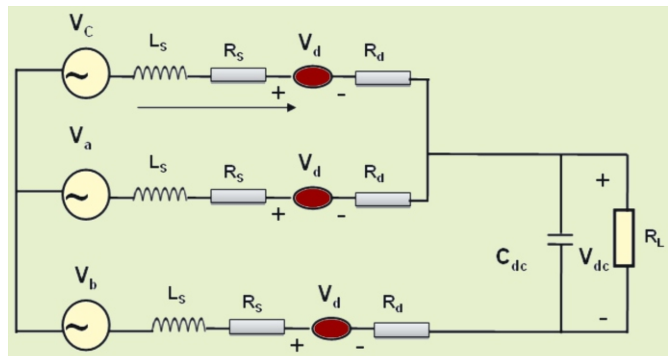


Fig.5. Commutation Mode Equivalent Circuit

Mode of Operation

Discontinuous Conduction mode

Due to cost constraints, smaller VFDs often have little or no DC link inductance. In these cases the rectifier circuit periodically becomes reversed biased. To illustrate this take the circuit shown in Figures 2 and 3. The waveforms for the DC voltage, V_{dc}, and phase current, I_a, for this case are given in Figure 6. It can be seen that when the rectifier is reversed biased (ie. Vo > Vin) no current flows from the

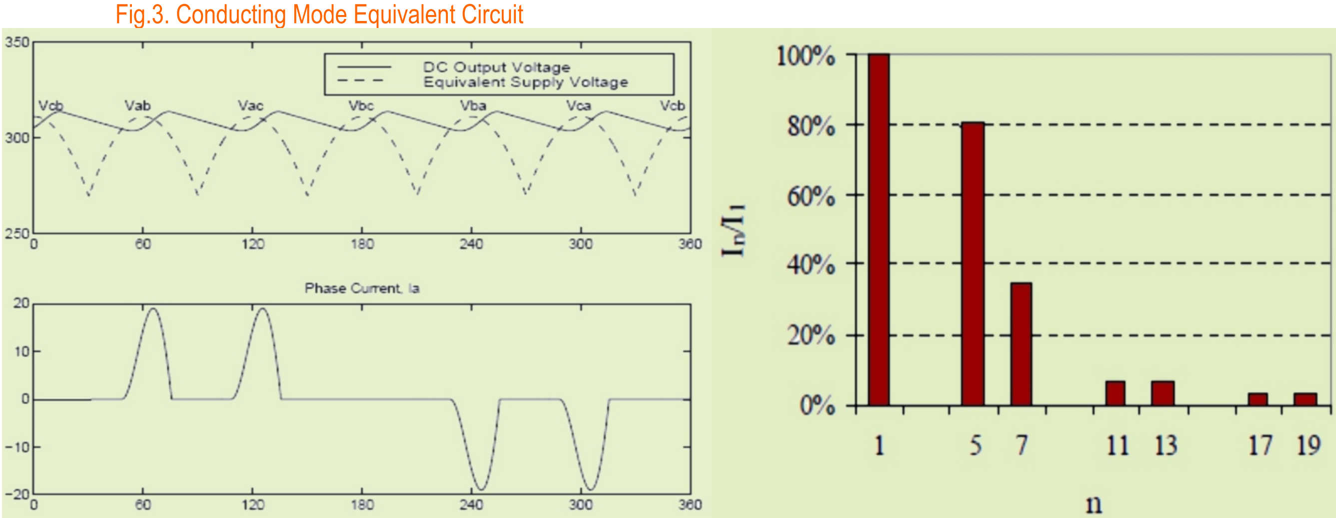
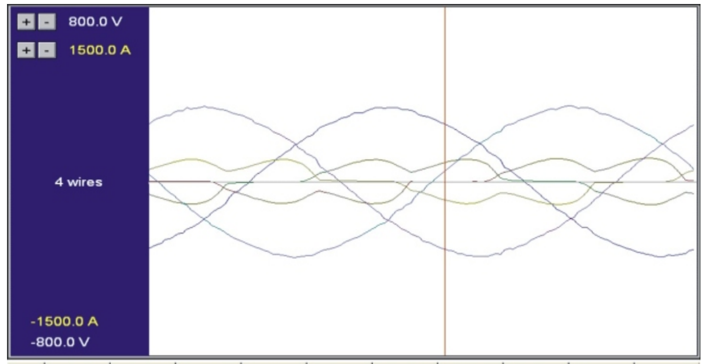


Fig.6. Discontinuous Conduction waveform and its Harmonic spectrum

supply and when the rectifier is forward biased (ie. Vin > Vo) the phase current is characterised by high amplitude pulses. The total harmonic current distortion (THDI) for this case is 60-90%.

Continuous Conduction mode

The DC link chokes which is electrically present after the diode rectifier bridge and before the dc bus capacitor. The dc link choke performs very similar to the three phase line inductance. The ripple frequency that the dc link choke has to handle is six times the input ac frequency for a six-pulse drive. Inductance in the DC link significantly reduces the supply current distortion. Figure 7 gives the waveforms for V_{dc} and I_a. It can be seen that the rectifier circuit remains forward biased so the current flow from the supply is continuous. There is, however, still a high ripple component in the phase current. The THDI in this case is 39%. The attenuation effect is more significant in this case with the THDI decreasing from 60-90% to 39%. The variation in phase angle is also more pronounced.



	Urms (V)	Irms (A)	thdU (%)	thdI (%)	Uxx	S (kVA)	P (kW)	Q (kVAR)	Pf	Freq
Ph1	237.35	122.919	1.85	33.87	412.54	29.175	26.630	11.916	0.913 i	
Ph2	239.20	123.084	1.89	35.94	411.68	29.442	26.727	12.349	0.908 i	
Ph3	237.07	122.512	1.91	33.52	411.77	29.044	26.417	12.070	0.910 i	
Tot	I null:	0.666				87.660	79.774	36.336	0.91 i	49.74

Fig.8. Line Voltage and Current Waveform

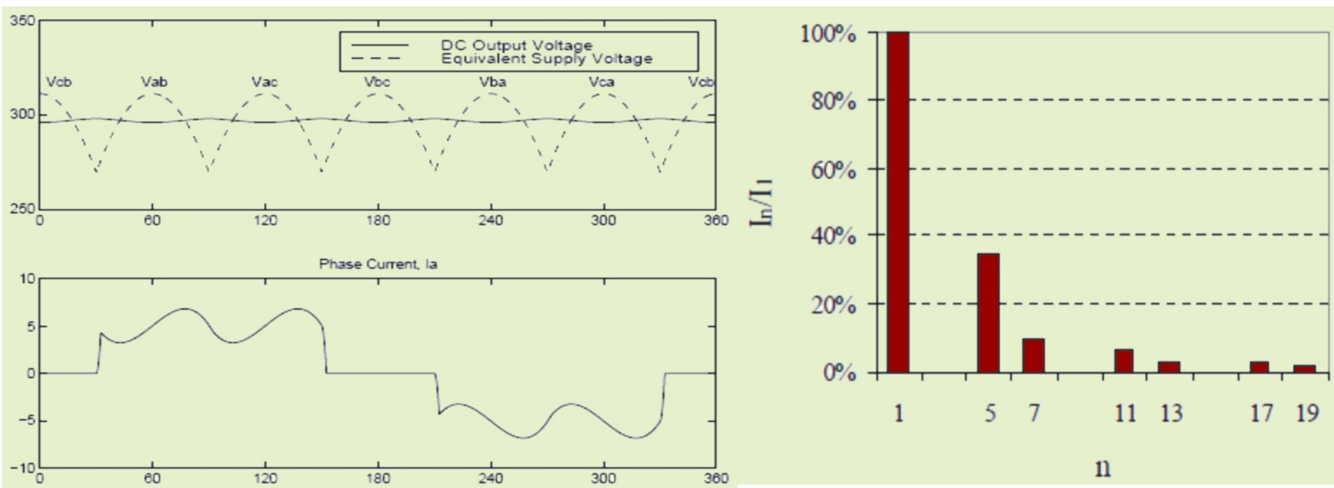


Fig.7. Discontinuous Conduction waveform and its Harmonic spectrum

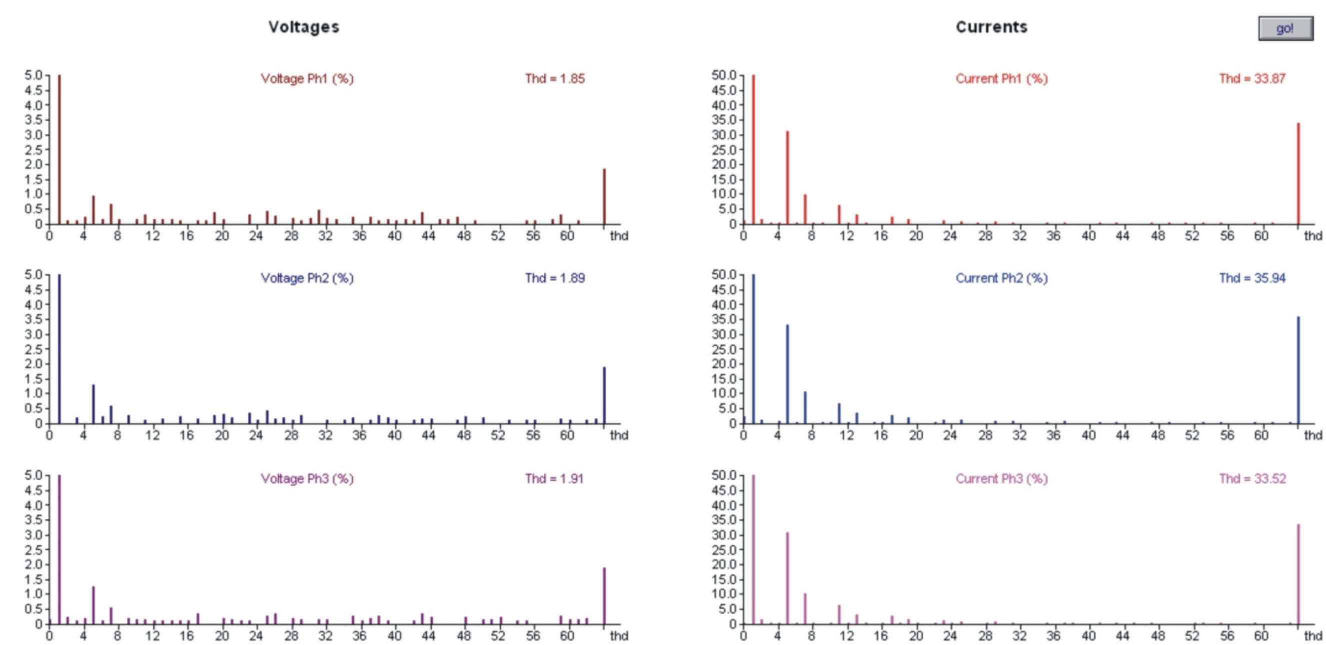


Fig.9. Line Voltage and Current Harmonic spectrum

Case Study

The harmonic study conducted in TNPL and results of a harmonic study are presented in table I. To provide detailed analysis of the system, one of the 132 KW Primary Air fan six pulse drive was investigated in Boiler. The three phase line voltage and current wave form measured by using power quality analyzer and its harmonic spectrum are shown in figure-8 and 9 .A six pulse converter would generate harmonic current of the order 5th, 7th, 11th, 13th,17th,19th 23rd,25th,etc.

Table - 1

Harmonic order	Case study Result	
	Phase Current	% distortion
1	116.41	100
5	36.45	31.31
7	11.62	9.98
11	7.33	6.30
13	3.72	3.19
17	2.88	2.48
19	2.01	1.72
%THD	%THDV	% THD I
%	1.83	33.87

Figure 10 and 11 shows the phase current waveform and its FFT components with respect to phase voltage Vab. It is clear from this figure that the supply current has very high THD mostly of 5th and 7th harmonics.It is clear from this figure that the supply current becomes to non sin-wave with 33.87%THD.

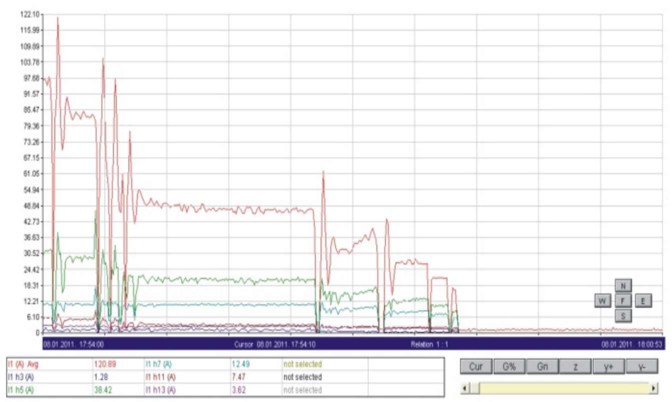


Fig.10. Average current and 3rd ,5th ,7th ,11th and 13th harmonics current.

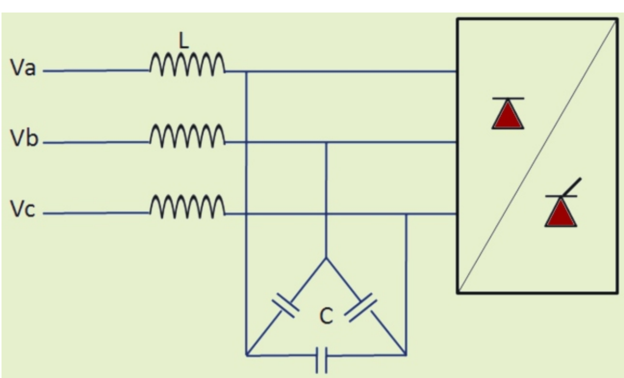


Fig.11. Proposed filters

Figure 10 shows the average current and 3rd ,5th ,7th ,11th and 13th order harmonics current with respect to varying load current. It is clear from the figure 3rd order harmonic current is not presented and very high THD 5th and 7th harmonics current.

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.

This paper explains how to choose and design the optimal input filter for six pulse-v**ariable frequency** drives application using GA **optimization**. For a six pulse-v**ariable frequency** drives 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.11 shows the LC filter approach to reduce line current harmonics generated for six pulse-v**ariable frequency** drives. This paper mainly focused only GA based design method.

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

$$F(\Phi) = \frac{1}{Power\ factor} \qquad (1)$$

Subject to,

$$\Phi_{min} \leq \Phi \geq \Phi_{max}$$

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. 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.12. 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.

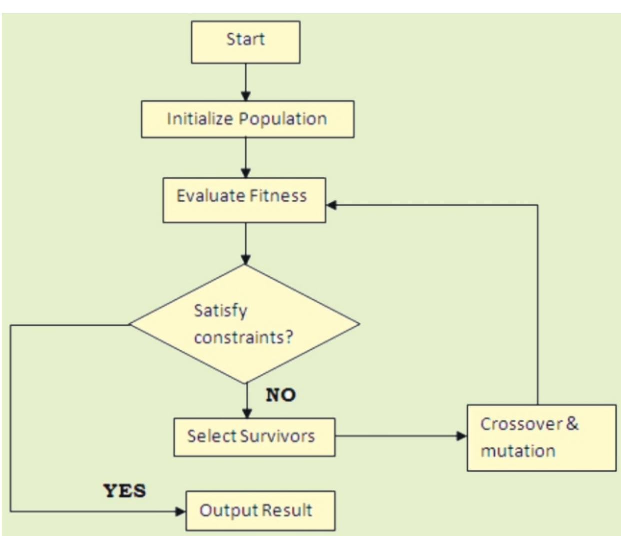


Fig.12. Flowchart of Genetic Algorithm

Steps involved in GA based filter design

The following section explains how Genetic Algorithm is used for design of filter components:

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.13. 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.

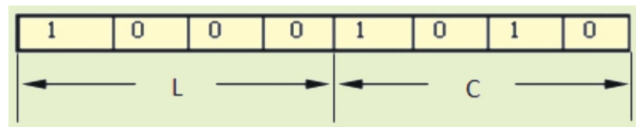


Fig.13. Chromosome structure

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 (2)

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:

$$\text{Fitness Function} = \frac{1}{F(\Phi)} \qquad (3)$$

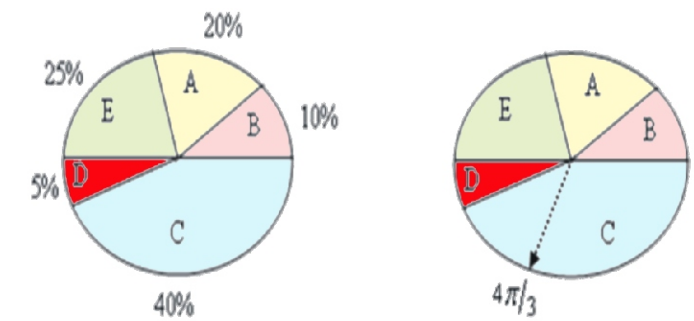
Step 4: Generation of offspring

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. 14(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. 14(b) shows a randomly generated angle of 4π/3 rad. 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 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.15 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.



14 (a) *14 (b)*

Fig.14. Roulette wheel selections

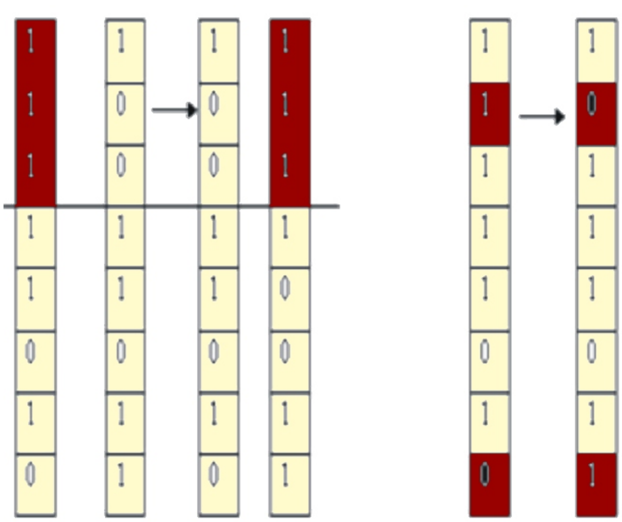


Fig.15. Crossover and mutation

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 in LC filter. The computed harmonic spectra 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 shunt LC passive filter is shown in fig.16. From the characteristics it is clear that the GA converges to objective function of 1 at 10th 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.

The above described algorithm is implemented for design of LC

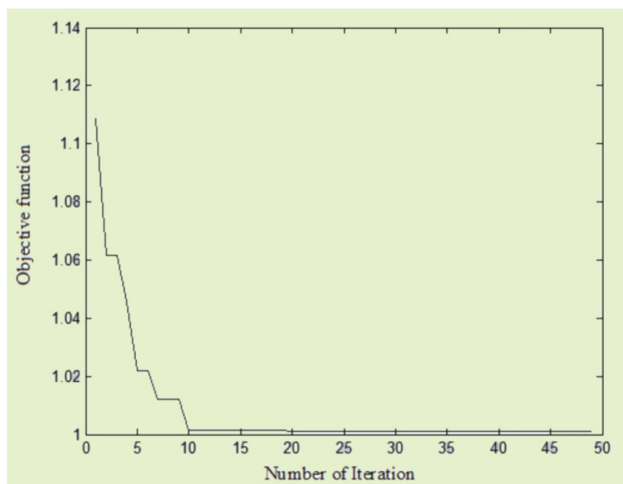
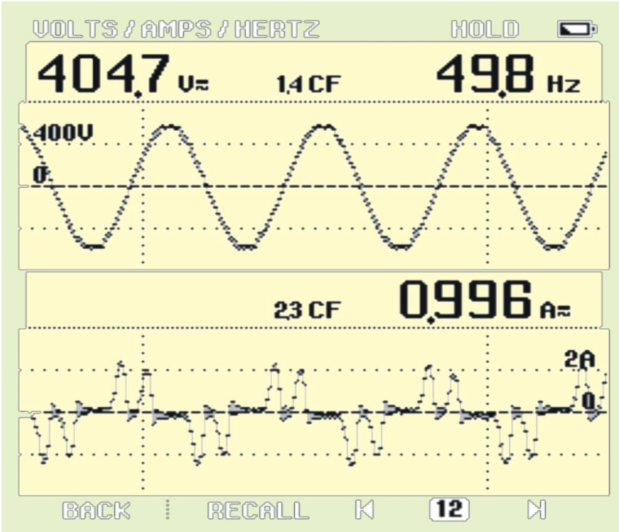


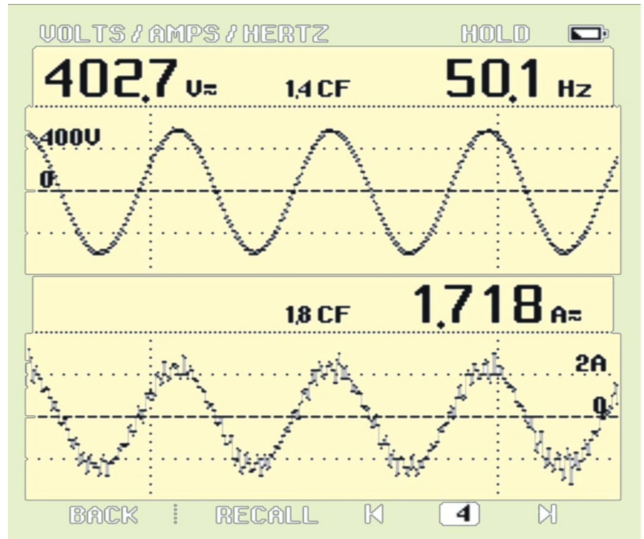
Fig.16. Convergence characteristics of GA

Table II. Simulated REsults for LC Filter

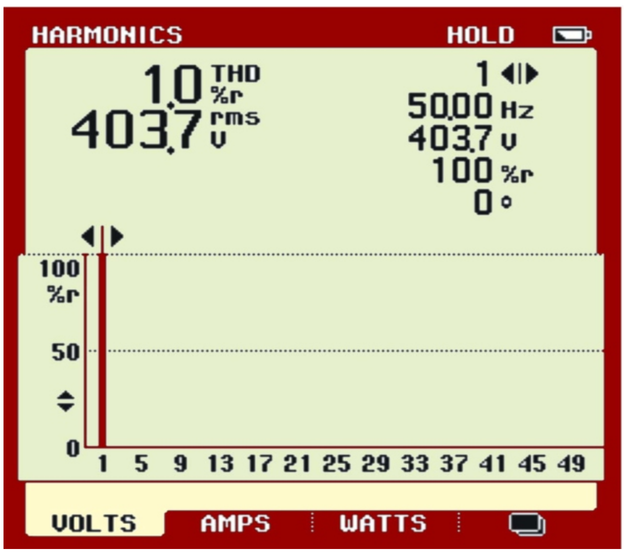
Sl No.	L (mH)	C (uF)	PF	Vo	Irms	THD (%)
1.	14.3	220.00	0.9915	23.13	4.960	6.99
2.	15.5	254.59	0.9966	25.29	4.505	6.95
3.	16.7	266.24	0.9972	25.77	4.686	6.10
4.	17.0	250.71	0.9966	25.13	4.451	6.35



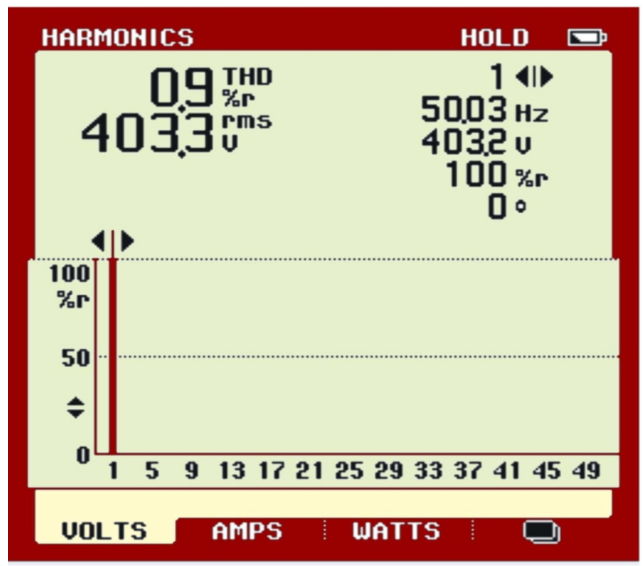
Voltage and current wave froms with out filter



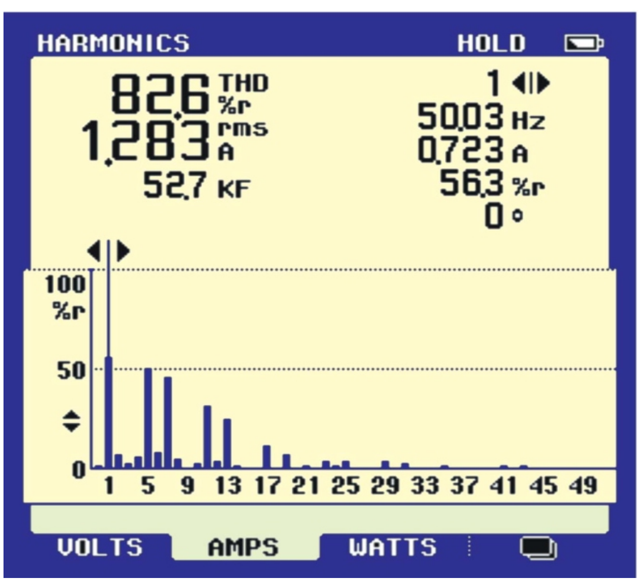
Voltage and current wave froms with filter



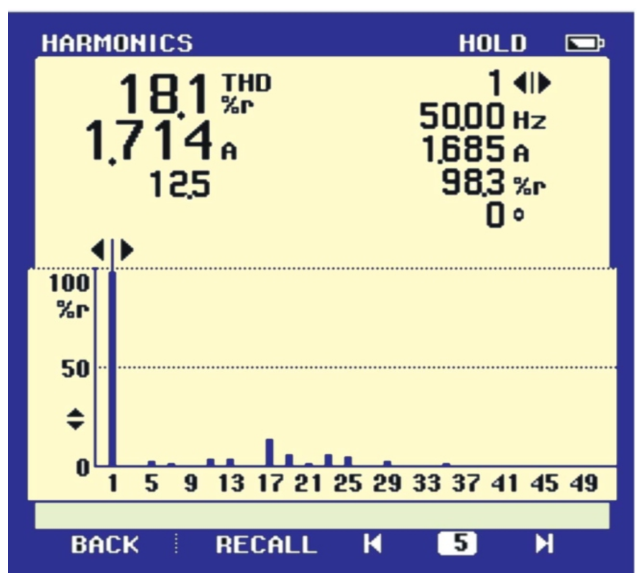
Voltage Harmonics Spectrum with filter



Voltage Harmonics Spectrum with out filter



Current Harmonics Spectrum with out filter



Current Harmonics Spectrum with filter

Fig.17. Experimental Results without filter and with filter

filter and the simulated results are presented in table II.

In order to validate the theoretical findings a hardware prototype was fabricated and the same was used to drive a 415V; 5.5 KW, 1500RPM three phase induction motor. The voltage and current harmonics are measured, the measured harmonic spectra are shown in Fig. 17. As compared experimental results, the current harmonics Ithd% were reduced from 82.6% to 18.1% and 5^{th}, 7th, 11th and 13^{th} order harmonics are reduced grate extant. The fig.18 shows the power factor values of the experiment. The simulation and experimental result are matched. **The objective of power factor improvement is drafted as an optimization; it's also satisfied from** simulation and experimental results and also compared with 3% line reactor output (fig.8) power factor were improved from 0.91 to 0.99 by using LC filter. The total harmonics distraction without filter, 3% line reactor and LC filter comparison results are presented table III.

Table III.- EXPRIMENTAL Results COMPARsION

Total Harmonic Distortion	Without filter		With 3% Line Reator		With LC Filter	
	Voltage	Current	Voltage	Current	Voltage	Current
%THD	% THDV	% THD I	% THDV	% THD I	% THDV	% THD I
%	1.8	82.6	1.0	33.8	0.9	18.1

Fig.18. Power factor Exprimental Results .

CONCLUSION

Harmonic analysis of power system is performed to study the system behavior under harmonics IEEE 519 norms. This paper presents the modeling of six pulses converters in industrial applications. Case study of harmonic analysis is performed at TNPL, Tamilnadu, India. THD is used as the harmonic index and harmonic spectrum is presented for six pulse-variable frequency drives. These models can hence be employed for harmonic analysis of a practical system and used to design a suitable filter to mitigate harmonics.Analysis of the results obtained gives a clear validation to the idea of inserting a filter at the input side of the six pulse-variable frequency drives. By insertion of a well designed filter it is observed that the power factor of the circuit is improved to a great extent, THD is reduced to a very low value and the output voltage is maintained constant for all the values compared to a circuit having no filter. From the results, it is concluded that the proposed configuration of LC filter gives improved performance.

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