Selective Harmonic Elimination in PWM Inverter Using Fire Fly and Fire Works Algorithm

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Abstract— ***This work considers new applications of Firefly and Fireworks algorithm for solving the selective harmonic elimination problem in inverter output waveforms. The higher order harmonics in the output of the inverter can be eliminated easily by using small passive filters. Lower order harmonic elimination requires selecting a pre-specified firing angle. That angle is one of the many solutions of a non-linear transcendental equation of PWM output. The lower order harmonics are eliminated in the generation stage by proper switching of PWM inverter switches. The effectiveness of an algorithm is judged based on many parameters like the rate of convergence, number of iterations, accuracy etc. The power of the two algorithms are evaluated for this application and found to be better than those found in the literature.***

Keywords— selective harmonic elimination, PWM, Firefly and Fireworks algorithm

I. INTRODUCTION

Harmonics are non-power frequency pollutants present in the pulse width modulated (PWM) inverter output. PWM is one of the most widely used method in inverters due to its improved steady state performance. However the harmonics from the PWM output have to be eliminated because they are the source of many power quality problems [3, 4] like excessive heating of neutral conductor, blinking of incandescent lamps, nuisance tripping of circuit breakers, bursting of capacitors used for power factor correction and switching malfunction in variable frequency drives (VFD). The VFD or adjustable speed drives (ASD) are currently used in industries for improving the performance of the drive / system and saving energy [11]. The traditional valve or damper throttling for flow control in pumps and blowers are now replaced by VFD / ASD running at various speeds with valve or damper fully open thereby saving energy [15].

There are many methods for harmonic elimination such as phase shifting transformer, passive harmonic filter, active filters, D.C choke and harmonic trap filters. The elimination of lower order harmonics by optimal firing angle selection has been originally proposed four decades back by Hasmukh S.Patel and Richard G.Hoft [1,2] using iterative methods. The iterative methods like Newton Raphsons method suffers from a disadvantage of speed of convergence which depends mainly on taking good initial values. The main challenge is to quickly find one of the many solutions for the multimodal non-linear transcendental equation of PWM output which satisfies the objective function. Walsh function was used as an analytical method of solution by converting PWM equations into to linear algebraic equations (T.J. Lang et al [5]).The next major contribution was solving the equation using Genetic Algorithm (GA) by Maswood et al[6]. GA works on the concept of survival of the fittest offsprings which was generated by mating of parents. Mutation and / or crossover were applied using roulette wheel to generate various offsprings. Only the fittest offsprings were retained while others were discarded. Convergence even with a random start was enabled in GA but the disadvantage is crowding in which many values were getting converged not at global minima but around global minima.

The crowding problem was overcome later by Sundareswaran. K et al by employing Ant Colony algorithm [9], Bees foraging and Bees Genetic Algorithm [10]. The new algorithms also converged with random initial start, crowding was overcome and the rate of convergence was also fast when compared to previous ones which has been elaborated much in literature. Contemporary contributions were made for this problem by different techniques by R. A. Villarreal et al, B. J. Rabi et al, R. A. Jabr et al, Chiasan et al and V. G. Agelidis et al [7,8].

The contribution of this paper lies in employing Firefly algorithm formulated by Prof. Xin She Yang and Fireworks algorithm formulated by Prof. Yin Tan with slight modifications to suit our application for finding the optimal firing angles subject to constraints. The simulation results were validated in a prototype inverter fabricated in the laboratory and a few conclusions were derived from the simulation and hardware results.

II. PROBLEM FORMULATION

The output voltage of a single phase PWM inverter is shown in fig. 1. The output is symmetrical to $\pi/2$, where k is the number of pulses per half cycle which is an odd number, the output voltage can be expressed using Fourier series as

$$V_0 = a_0 + \sum_1^n A_n \cos(n\omega t) + \sum_1^n B_n \sin(n\omega t) \qquad \text{Where n=1, 2, 3, 4, 5,......} \qquad (1)$$

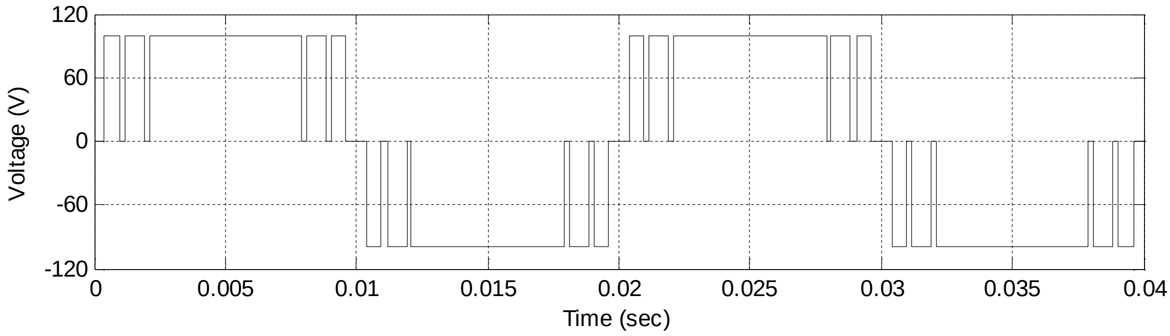

Fig-1 Theoretical output waveform of PWM inverter

Due to symmetry of the wave the even harmonics, A_n and a_0 are zero,
The equation (1) can be rewritten as

$$V_0 = \sum_1^n B_n \sin(n\omega t) \qquad \text{Where n=1, 3, 5,...} \qquad (2)$$

The value of B_n is computed as

$$B_n(\alpha_1, \alpha_2, ..., \alpha_{k-1}, \alpha_k) = \frac{4V_{dc}}{n\pi} \sum_{k=1}^{k} (-1)^{k+1} \left[\cos(n\alpha_k)\right] \qquad (3)$$

The fundamental component is given by

$$B_1(\alpha_1, \alpha_2, ..., \alpha_{k-1}, \alpha_k) = \frac{4V_{dc}}{\pi} \sum_{k=1}^{k} (-1)^{k+1} \left[\cos(\alpha_k)\right] \qquad (4)$$

The objective of the problem is to find the switching angles to make *B1 = Vo** and along with selective harmonic elimination (SHE). Here *Vo** is the reference output voltage.
The optimization problem for k number of pulses per half cycle is to minimize the difference between reference output voltage and the fundamental in addition to eliminating selected harmonics.

The objective function is $F(\alpha)$

Minimize

$$F(\alpha)=F(\alpha_1, \alpha_2, \alpha_3, ..., \alpha_{k-1}, \alpha_k)=e_r+hc \qquad (5)$$

Subject to

$\alpha_1 \le \alpha_2 \le \alpha_3 \le ....\le \alpha_{k-1} \le \alpha_k \le \pi/2$

In the above equation

$$e_r = \left| V_0^* - \frac{B_1}{\sqrt{2}} \right| \qquad (6)$$

$$hc = |B_3| + |B_5| + |B_7| + ... + |B_{2k-1}| \qquad (7)$$

III. OPTIMIZATION BASED ON FIREFLY AND FIREWORKS ALGORITHM

The fire fly algorithm available in the literature [12,13,14] with a little modification has been found to be more suitable for our problem of constrained continuous search because there is a difference in steps followed for discrete and continuous optimization algorithms.

Minimization of *F(α)* is a discrete optimization problem with multiple solutions. The iterations are stopped when the objective function is converged with minimum error whereas for continuous optimization the search within bounded space is done continuously for the best solution.

A. Modified Firefly algorithm:

The swarm intelligence is a kind of problem solving ability that emerges from interactions between simple information processing units of which the firefly algorithm is an example.

Many fireflies are deployed and it is assumed that all are unisexual. So each one can attract any other firefly. The amount of light emitted by bioluminescence from each firefly is inversely proportional to the distance from the food source. Attraction is based on brightness between any two fireflies and less bright fireflies will move towards a brighter ones. The distance between fireflies may sometime cause the actual brightest firefly (global minima) to appear less bright, some fireflies may crowd near less bright ones (local minima) than the brightest firefly (due to distance). So we are deploying some fireflies randomly to avoid local minima and crowding. This is the modification of the firefly algorithm in this work. This Fire Fly algorithm is a metaheuristic optimization algorithm formulated and deployed for optimization problems by Prof. Xin-She Yang [12-14] and numerous applications currently indicate that it is better than particle swarm optimization algorithm formulated by Ebert et al [16] for applications in problems with stochastic test functions [17]. The different steps of the firefly algorithm are given as,

Step(1) : Deploying fireflies

In the initial step fireflies are deployed initially in a feasible solution space with constraint of $0 \le \alpha_1 \le \alpha_2, ..., \le \alpha_k \le \pi/2$, here the positions of fireflies refer to one complete solution set to the problem. For example three switching pulses per half cycle are mapped as the location of a typical firefly in three dimensions as α_1, α_2 and α_3.

Step (2): Evaluation of the objective function:

For our problem the harmonic error (hc) is to be minimized where as maximizing the fundamental frequency output voltage (B_1). The objective function $F(\alpha)$ at each firefly position is evaluated using the following equation to find whether minima have been achieved.

$F(\alpha)=F(\alpha_1, \alpha 2, \alpha 3, \dots\dots\dots, \alpha k\text{-}1, \alpha k)=e_r+hc$

Step (3): Computing the brightness of each firefly

The brightness is inversely proportional to the distance to food. $L = 1/F(\alpha)$

Step (4): Identification of brightest fire fly

The fire fly which gives maximum brightness is designated as the brightest firefly which is the global minima and our search is to identify it among all the fireflies.

Step (5) Adding new Fireflies

Majority of fireflies follow the brightest firefly but some fireflies may fly to other less bright ones which may seem to be brighter (local minima) due to less distance between them. The distance between fireflies may cause sometime the actual brightest firefly (global minima) to appear less bright, some fireflies may crowd near less bright ones (local minima) than the brightest firefly (due to distance). So we are deploying again some fireflies randomly to avoid local minima and crowding [6], this redeployment of fire flies is the modification over the conventional algorithm [12-14].

Step (6) End the program

The program can be stopped on achieving the objective function or after doing a pre-specified number of iterations.

B. Fire Works Algorithm:

The inspiration by observing fireworks explosion prompted Prof. **Yin Tan** to formulate a novel swarm intelligence algorithm called fireworks algorithm for optimization problems of complex functions [18,19]. As done in Firefly algorithm randomness is introduced to avoid getting stuck up in local minima to get a modified algorithm.

The sparks are viewed as a search in local space around a specific point where the firework is setoff. The sparks are evaluated based on the distance from the centre. A large number of sparks near the centre is considered good fireworks and others are bad fireworks. More clearly a good fireworks produce more sparks within more vicinity to centre whereas a bad fireworks produces less sparks away from the vicinity to centre. After evaluation good fireworks are retained and random search is continued until optimum values are obtained or after a certain number of iterations.

Step (1) Deploying firework sparks at random locations

The sparks are generated in space by setting off fireworks subject to constraints of $0 \leq \alpha_1 \leq \alpha_2, ..., \leq \alpha_k \leq \pi/2$.

Step (2) Evaluation of the location of sparks:

The optimization problem for k number of pulses per half cycle is to minimize the difference between reference fundamental output voltage and actual fundamental output voltage in addition to eliminating k-1 selected harmonics.

The objective function $F(\alpha)$ is evaluated using equation

$$F(\alpha)=F(\alpha_1, \alpha_2, \alpha_3, \ldots\ldots\ldots, \alpha_{k-1}, \alpha_k)=e_r+hc \tag{5}$$

Subject to

$\alpha_1 \leq \alpha_2 \leq \alpha_3 \leq \ldots\ldots\ldots \leq \alpha_{k-1} \leq \alpha_k \leq \pi/2$

In the above equation

$$e_r = \left| V_0^* - \frac{B_1}{\sqrt{2}} \right| \tag{6}$$

$$hc = |B_3| + |B_5| + |B_7| + ... + |B_{2k-1}| \tag{7}$$

Step (3): Evaluating the quality of location

The firework quality is evaluated by number of sparks produced and its vicinity to the centre of the sparks produced. As described above the good fireworks are retained and bad ones are not considered to the next iteration.

Step (4) Adding new fireworks

New fireworks are setoff in every iterations which is the modification over the conventional Fireworks Algorithm in order not to get stuck up in local Minima values and to avoid crowding [6]

Step (5) Termination

The program can be stopped on achieving the desired objective function or after doing a pre-specified number of iterations.

IV. SIMULATED RESULTS

A dedicated software using m-codes in MATLAB is developed for the implementation of the proposed algorithms. The addition of random particles in place of worst particles in every iteration is taken to yield the best solution. It is observed that fireflies start from different locations after their deployment but start to converge towards global minima. Initially fireworks starts with random locations so that the need for good initial starting as required in Newton Raphson's method is eliminated for these Meta Heuristic search algorithms.

It is observed that for this constrained optimization problem the modified Fireworks works faster than modified Firefly algorithm which is shown in Fig-2. It is also observed that the number of iterations and total required are greatly reduced when compared to the existing algorithms of Ant colony, PSO, GA and NR.

The harmonic spectra of output voltage for inverter of K=5 are shown in Fig 3 for Fire Fly algorithm and in Fig-4 for Fire Works algorithm. It is found that values obtained from theoretical simulation matches well with practical values, the difference being less and mainly due to the switching transients. Desired harmonics are reduced to a great extent and complete elimination is also possible by fine tuning and increasing the iterations.

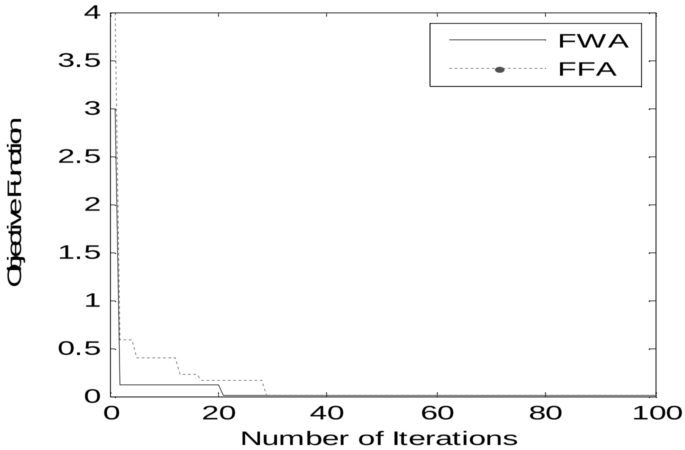

Fig-2 The convergence graph of Fire Fly Algorithm(FFA) and Fire Works Algorithm(FWA)

Specific comparisons with other methods in the literature like GA [6], OBF, Ant colony, Bees G.A[9,10] suggest that Fireworks algorithm works excellent and Fire Fly is also good for our application.

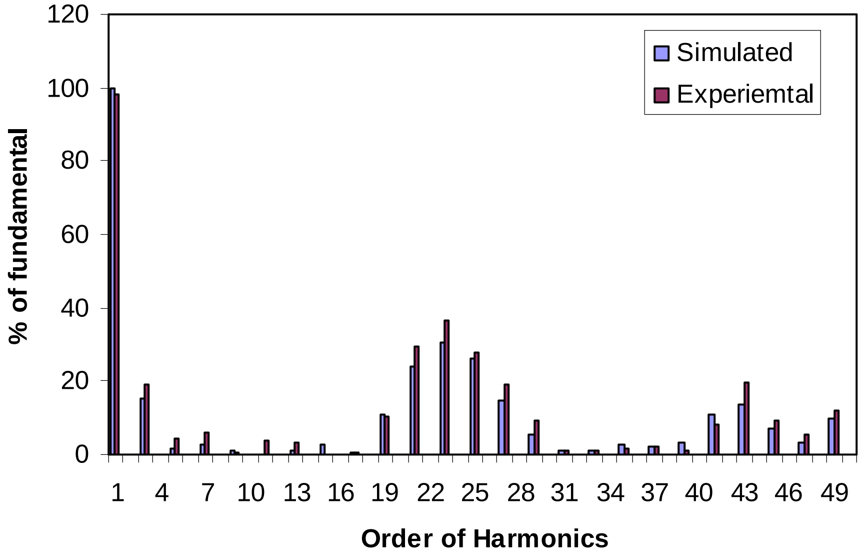

Fig-3 Harmonic Spectra of FFA

V. EXPERIMENTAL RESULTS

In order to verify the theoretical predictions Insulated Gate Bipolar junction Transistor (IGBT) based single phase H bridge PWM inverter was fabricated in the laboratory and used to feed a resistive load. The firing pulses were generated using DSP TMS 320 F28335 of Texas Instruments and Code composer studio version 3.3 interfacing software was used to generate codes for DSP from Mat Lab simulink models.

The inverter was supplied from a constant D C source of 10 Volts. The firefly and fireworks optimization algorithms were run and the switching angles that were obtained were used to generate the switching pulses of the inverter output voltage for k=5 (eliminating the harmonics of order 5, 7, 11, 13 and fundamental output voltage maximization).

Since the triple-n harmonics are eliminated in the transformer delta connection so triple- n harmonics are not considered for elimination and due to quarter wave symmetry even harmonics are absent.

The optimum switching angle pulses were generated using Texas instruments DSP processor (F-28335) interfaced to IGBT through optocoupler based driver circuit to get power outputs. The experimental waveforms Fig 5(Firefly) and Fig 6 (Fireworks) were recorded using Agilent Mixed Signal Oscilloscope cum analyzer (model 3014A) using which experimental values of harmonic spectra were obtained and a good agreement between computed and measured values was observed. Switching transients were observed in measured values which were absent in matlab simulations. The outputs demonstrate that the selected harmonics were eliminated successfully while maintaining desired output voltage.

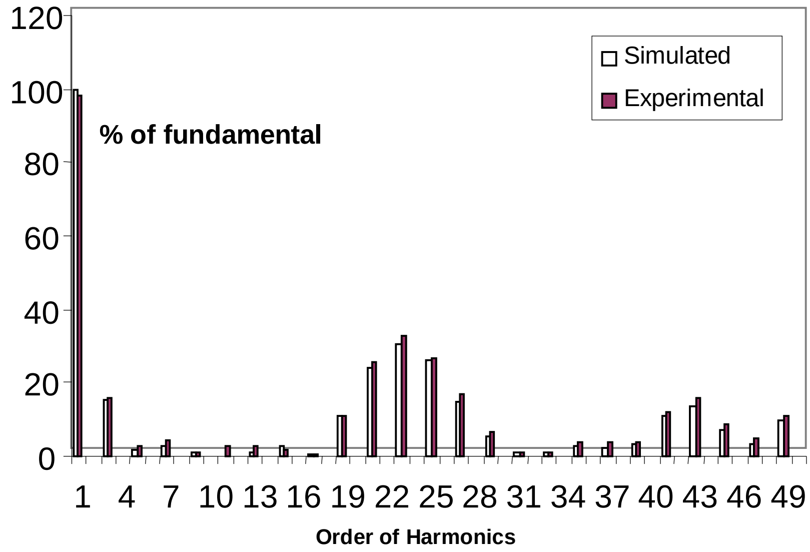

Fig-4 Harmonic Spectra of FWA

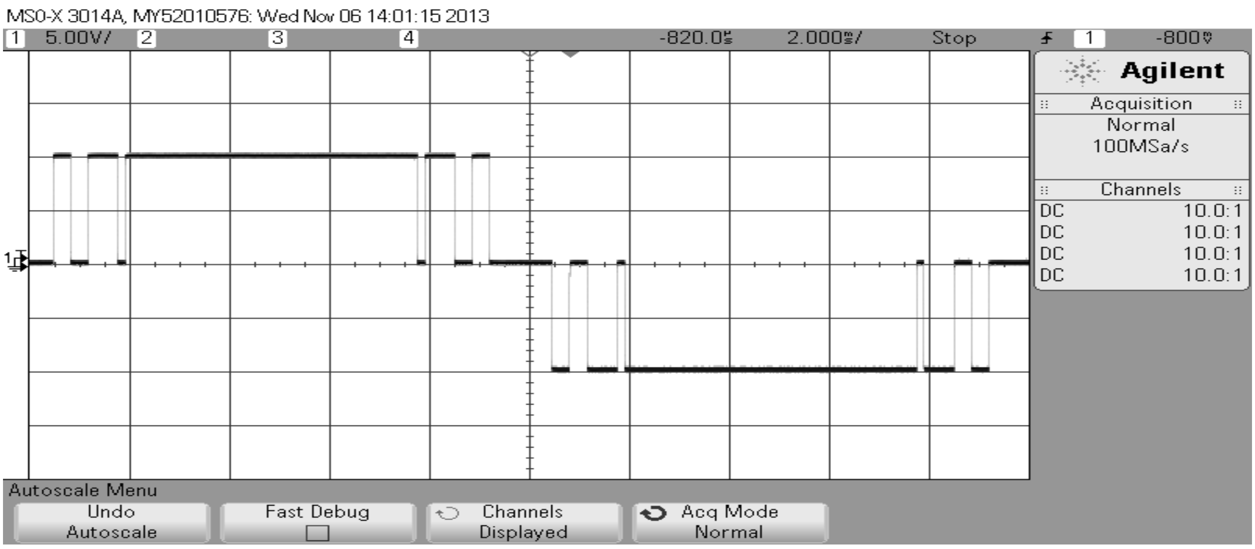

Fig-5 Experimental waveform of PWM inverter using angles generated using FFA

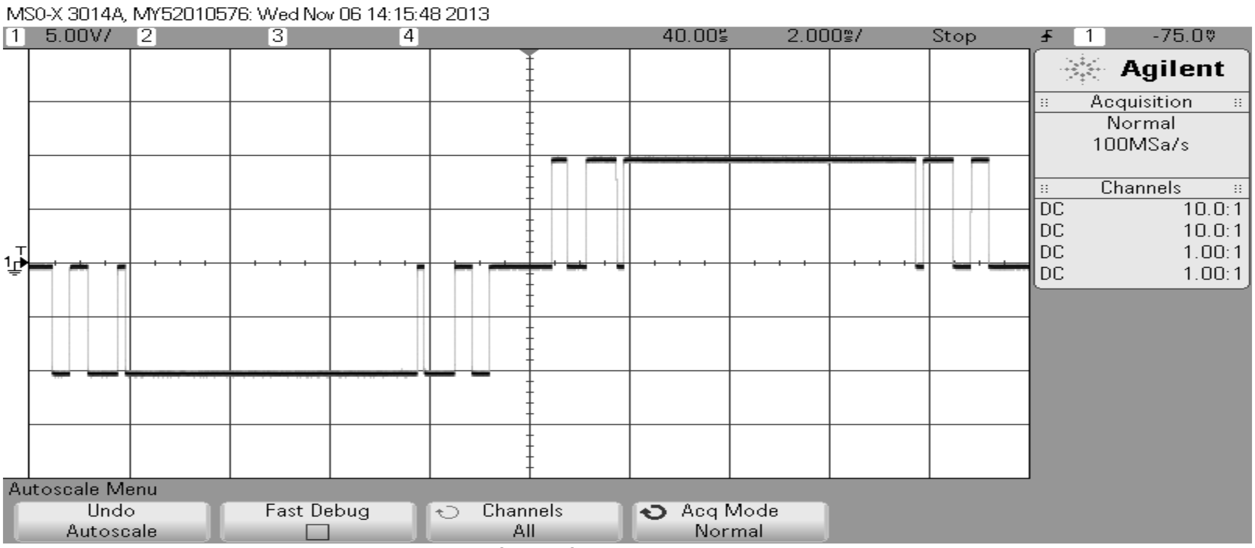

Fig-6 Experimental waveform of PWM inverter using angles generated using FWA.

TABLE I COMPARISON TABLE FOR THE SELECTIVE HARMONIC ELIMINATION OF DIFFERENT METHODS
(k = 5 and Vo^* = 0.6 pu.)

The magnitude of lower order harmonics – which are desired to be eliminated – expressed in percentage	OBF	Bees GA	Standard GA	NR	Firelfly	Fireworks
fifth harmonic	1.21	1.19	1.28	0.0	1.16	1.1
seventh harmonic	1.4	1.05	1.96	0.0	1.03	0.9
eleventh harmonic	1.01	0.9	0.86	0.0	0.92	0.85
thirteenth harmonic	1.014	1.084	1.014	0.0	1.03	1.010
Objective function Value	0.08	0.06	0.21	0.001	0.05	0.04
Magnitude (Vo pu) of the fundamental component	0.6	0.594	0.602	0.598	0.594	0.601
No of iterations taken for convergence	28	16	78	14	27	8

Table I shows the comparison of algorithms in terms of lower order harmonic elimination as well as objective function and fundamental magnitude. The table also gives the comparison of number of iterations required to converge the objective function of different algorithms. From the table, it is clear that the two new algorithm firefly and fireworks shows better performance in terms of three parameters such as selective harmonic elimination, desired fundamental magnitude and quick convergence. The authors are currently trying to implement this algorithm for ASD or Variable Frequency Drives which has penetrated the industry currently 15-20% [11].

VI. CONCLUSIONS

SHE in a PWM inverter is carried out using two optimization techniques one based on attraction of unisexual fireflies by its bio-luminescent brightness and another based on generation of sparks around a firework. The two prospective methods supplement the present wealth of recently developed optimization techniques and knowledge and its application to harmonic elimination.

These algorithms confirm quick convergence with random initial guess, simple computational steps and derivative free operation. The theoretical and experimental results on a proto type PWM inverter are given to show the effectiveness of the new applications for emerging two new algorithms to be better than Ant colony, bees G.A and OBF algorithms.

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