Uludağ University Journal of The Faculty of Engineering, Vol. 24, No. 3, 2019 RESEARCH

DOI: 10.17482/uumfd.595233

THE HARMONIC ELIMINATION IN INVERTERS WITH METAHEURISTIC APPROACHES

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Received: 22.07.2019; revised: 13.11.2019; accepted: 21.11.2019

Abstract: Inverters which convert DC voltage into AC voltage are widely used in the field of power electronics. During the conversion from DC voltage to AC voltage, some of the harmonics can occur. Harmonics which are one of the most important parameters in the field of energy/power systems determine the power quality. Therefore, one of the crucial steps is the elimination/suppression of harmonics in the outputs of the inverters. It is required to solve complex equations with multiple variables in this elimination process. In this study, a software is developed and eight different metaheuristic algorithms/approaches (backtracking search, cuckoo search, electromagnetic field optimization, harmony search, Harris hawks optimization, interior search, vortex search, Yin-Yang-pair optimization) are used for the elimination of the chosen harmonics by determining suitable switching angles. The desired harmonics are eliminated in the chosen inverter circuits via the software with a user-friendly interface easily, fast and effectively, and the results can be observed both numerically and graphically through the this software.

Keywords: Inverter, harmonic elimination, metaheuristic algorithms.

Metasezgisel Yaklaşımlarla Eviricilerde Harmonik Eliminasyonu

Öz: DC gerilimi AC gerilime dönüştüren eviriciler (invertörler), güç elektroniği alanında en çok kullanılan devre türlerinin başında gelmektedir. Anahtarlamalarla DC gerilimden AC gerilime dönüşüm esnasında, çıkış geriliminde harmonikler oluşmaktadır. Harmonikler ise enerji/güç sistemlerinde güç kalitesini belirleyen parametrelerin başında yer almaktadır. Dolayısıyla evirici devrelerinin çıkışındaki harmoniklerin elenmesi/bastırılması önem arz etmektedir. Bu eleme işleminde ise çok değişkenli karmaşık denklem sistemlerinin çözülmesi gerekmektedir. Gerçekleştirilen çalışmada, seçilen harmonikleri elemek için en uygun anahtarlama açılarını, sekiz farklı metasezgisel algoritma/yaklaşım (geri izleme arama, guguk kuşu arama, elektromanyetik alan optimizasyonu, harmoni arama, Harris şahinleri optimizasyonu, dahili/iç arama, girdap arama, Yin-Yang-çifti optimizasyonu) ile hesaplayan yazılım geliştirilmiştir. Kullanıcı dostu arayüze sahip yazılım ile seçilen türdeki evirici devrelerinde, belirlenen harmonikler hızlı, kolay ve etkin bir şekilde elenebilmekte; sonuçlar hem sayısal hem de grafiksel olarak gözlenebilmektedir.

Anahtar Kelimeler: Evirici, harmonik eliminasyon, metasezgisel algoritmalar.

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1. INTRODUCTION

In the past decade, the usage of power electronics circuits/systems has been increased with the developments of industry. One of these systems is the inverters that convert energy. These systems have been widely used in many areas, such as flexible AC transmission system (FACTS) devices, high voltage direct current lines, electrical drives etc. and can also be used for an energy conversion as the inverters. Performances of the systems which convert DC voltage to AC voltage can be determined depend on harmonics at output voltage. There are many different techniques and applications to eliminate the harmonics at the output. Pulse width modulation (PWM) control is one of the important techniques based on the calculation/optimization of switching angles of inverter for the desired output voltage (Ahmadi et al., 2011; Amjad and Salam, 2014; Babu et al., 2015; Dahidah and Agelidis, 2008; Dahidah et al., 2015; Kavousi et al., 2012; Liu et al., 2009). Calculation/optimization of the triggering angles of the switching elements for the output voltage of the desired characteristic forms the basis of this control. The solution of large systems of equations (linear/nonlinear) is required if the structure of the circuit becomes more complex, meaning that manual analytical solutions for such problems are extremely difficult. A wide various of problems can be solved quickly and easily with metaheuristic algorithms, therefore, these algorithms can be utilized effectively and efficiently in these optimization processes.

In this work, eight different metaheuristic algorithms, which are backtracking search (BS), cuckoo search (CS), electromagnetic field optimization (EFO), harmony search (HS), Harris hawks optimization (HHO), interior search (ISA), vortex search (VS), Yin-Yang-pair optimization (YYPO), are used to calculate switching angles by solving the related equations for the elimination of desired harmonics. The main aim of this study is to solve harmonic elimination problems, which are hard to solve analytically, within a reasonable process time and to find switching angles automatically and easily by combining a lot of metaheuristics with a software. Using the software developed for this purpose, undesired harmonics can be eliminated at the output and optimal switching angles can also be determined fast and effectively.

This paper is organized as follows: Inverters and the used metaheuristic algorithms are briefly described in Section 2-3. The designed simulator and applications (results) are given in Section 4 and finally, the conclusions are outlined in Section 5.

2. INVERTERS

The inverters or DC-AC inverters which are frequently used in the industry convert DC power into AC power in the desired frequency and amplitude (Fig 1). In theory, the output of the inverters is sinusoidal, but, in the real-world applications, it cannot be sinusoidal as it includes harmonics. Besides, the harmonics can be reduced by using the switching techniques with the high-speed semiconductor components used in the inverters.

Undesirable harmonics in single-phase inverters can be eliminated by using a unipolar or bipolar voltage chops. The both conditions are summarized in Table 1 (Gürdal, 2008; Patel and Hoft, 1973; Rashid, 2013).

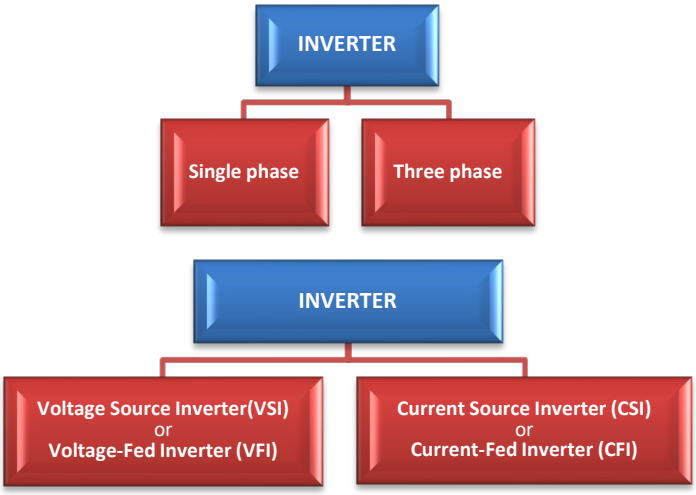


Figure 1:
Types of inverters

3. METAHEURISTIC ALGORITHMS/APPROACHES

The use of metaheuristic algorithms in many areas has been rapidly increased with the developments of the technologies in recent years. Especially, these algorithms are frequently used in the area of optimization related to social and engineering sciences in solving optimization problems. The flowcharts of the algorithms used in this work are given in Table 2 (Abedinpourshotorban et al., 2016; Civicioglu, 2013; Dogan and Olmez, 2015; Gandomi, 2014; Geem et al., 2001; Heidari et al., 2019; Punnathanam and Kotecha, 2016; Yang, 2009; Yang and Deb, 2009).

Table 1. The harmonics at the output

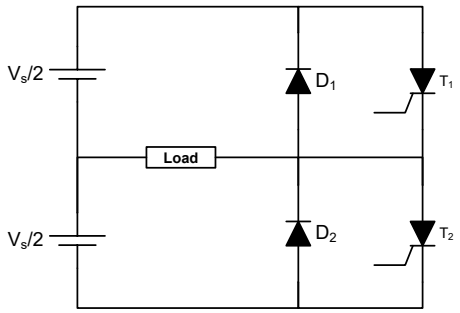
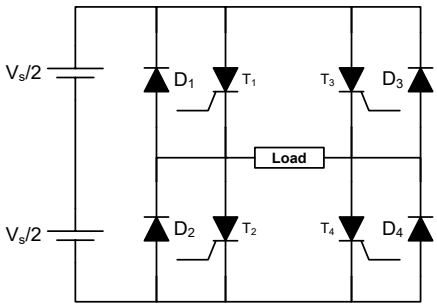
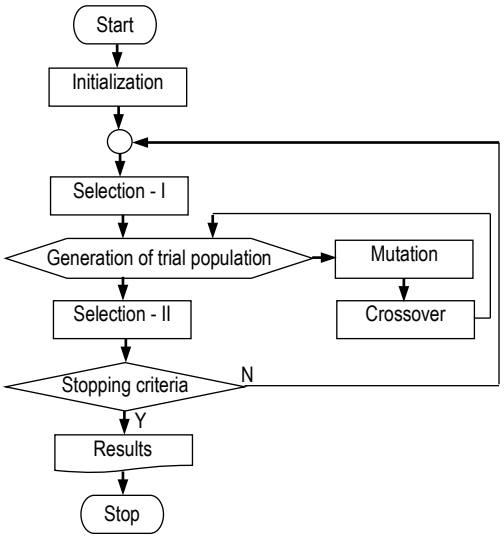
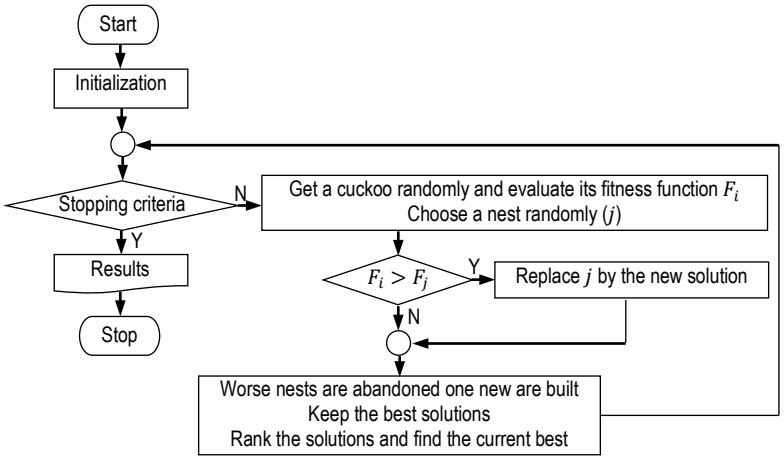
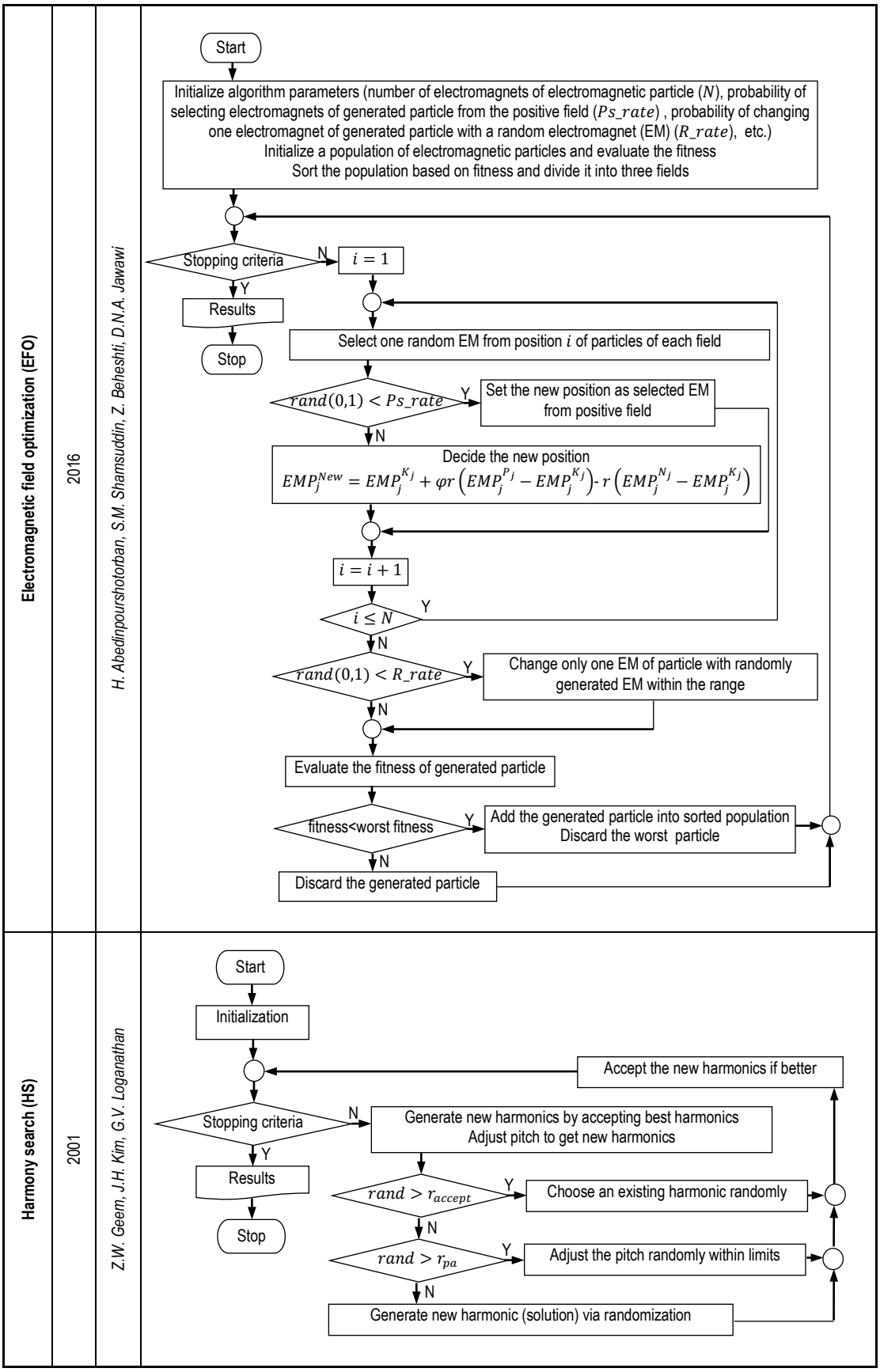
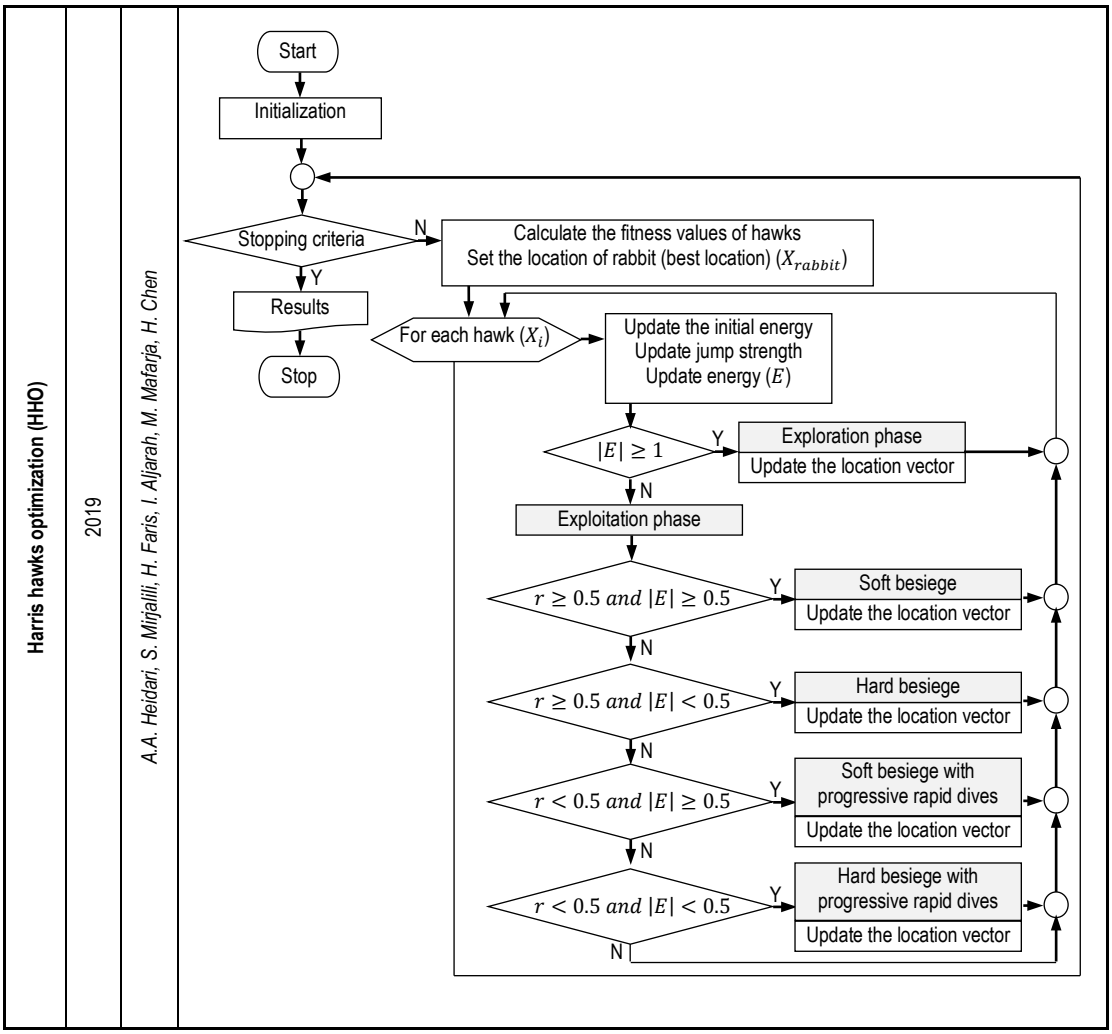
Definition of the harmonics (m chops per quarter-wave, $n = 1, 3, 5, 7, ...$)	
Single-phase half-bridge inverter	***Single-phase full-bridge inverter***
	
$B_n = \frac{4V_s}{n\pi}\left\{1 + 2\sum_{k=1}^{m}(-1)^k Cos(n\alpha_k)\right\}$	$B_n = \frac{4V_s}{n\pi}\left\{\sum_{k=1}^{m}(-1)^{k+1} Cos(n\alpha_k)\right\}$
$0 < \alpha_1 < \alpha_2 < \alpha_3 < \cdots < \alpha_m < \pi/2$	

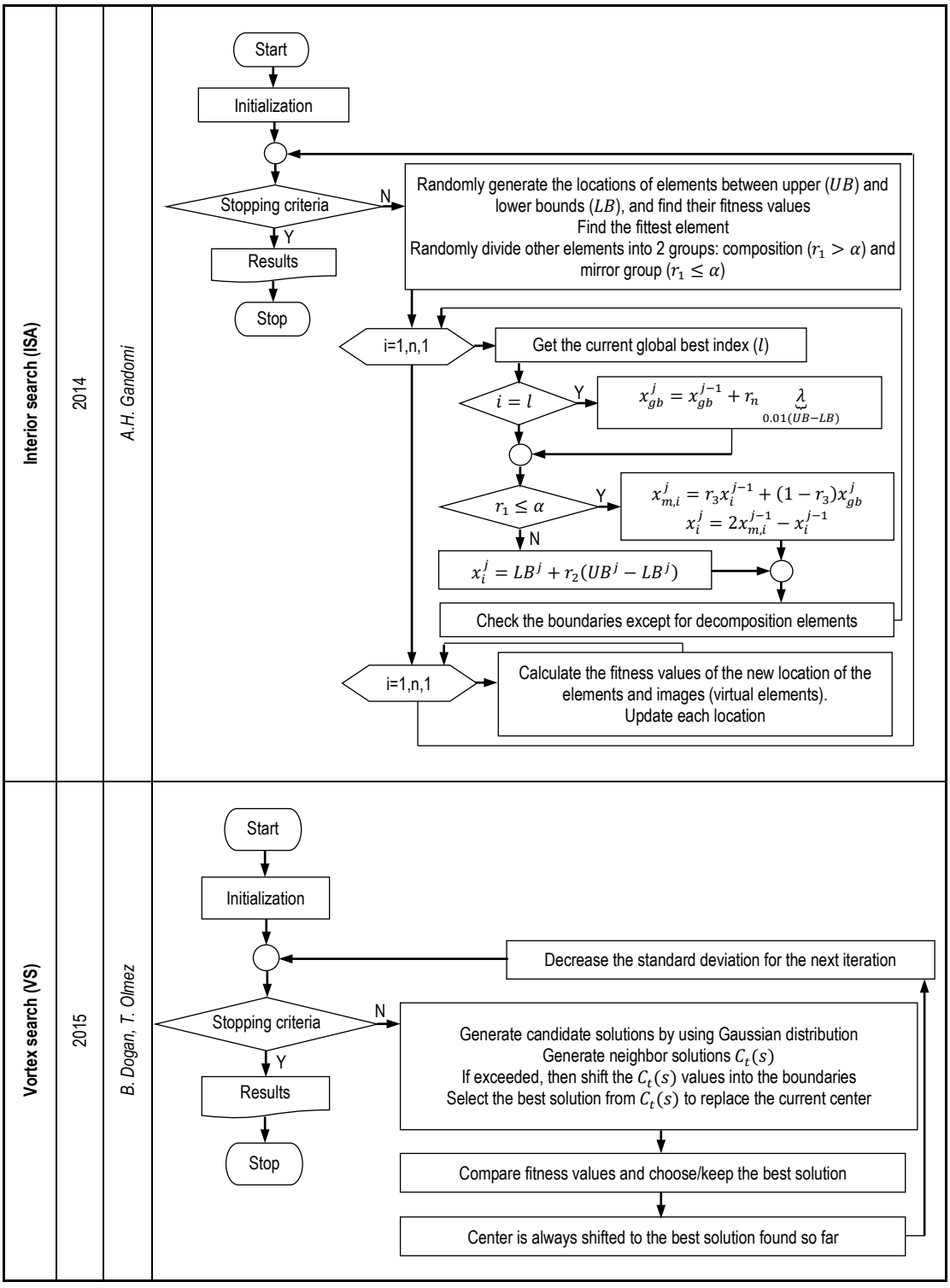
Table 2. The flowcharts of the used algorithms

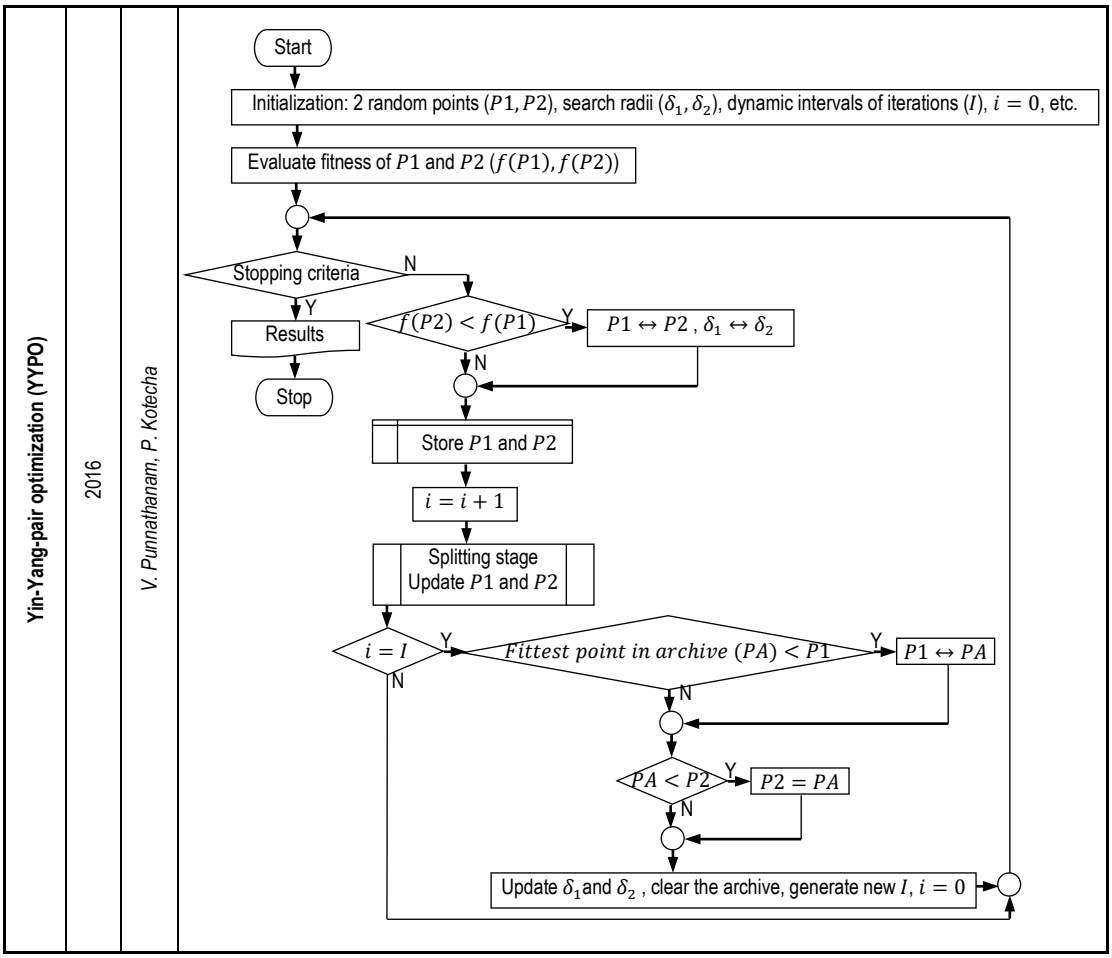
Alg.	Y.	D.	Flowchart
Backtracking search (BS)	2013	*P. Civicioglu*	
Cuckoo search (CS)	2009	*X-S. Yang, S. Deb*	

Electromagnetic field optimization (EFO)	2016	*H. Abedinpourshotorban, S.M. Shamsuddin, Z. Beheshti, D.N.A. Jawawi*
Harmony search (HS)	2001	*Z.W. Geem, J.H. Kim, G.V. Loganathan*




Harris hawks optimization (HHO)
2019
A.A. Heidari, S. Mirjalili, H. Faris, I. Aljarah, M. Mafarja, H. Chen
Start
Initialization
Stopping criteria
N
Calculate the fitness values of hawks
Set the location of rabbit (best location) (X_{rabbit})
Y
Results
Stop
For each hawk (X_i)
Update the initial energy
Update jump strength
Update energy (E)
$|E| \geq 1$
Y
Exploration phase
Update the location vector
N
Exploitation phase
$r \geq 0.5$ and $|E| \geq 0.5$
Y
Soft besiege
Update the location vector
N
$r \geq 0.5$ and $|E| < 0.5$
Y
Hard besiege
Update the location vector
N
$r < 0.5$ and $|E| \geq 0.5$
Y
Soft besiege with progressive rapid dives
Update the location vector
N
$r < 0.5$ and $|E| < 0.5$
Y
Hard besiege with progressive rapid dives
Update the location vector
N


Interior search (ISA)
2014
A.H. Gandomi
Start
Initialization
Stopping criteria
N
Y
Results
Stop
Randomly generate the locations of elements between upper (UB) and lower bounds (LB), and find their fitness values
Find the fittest element
Randomly divide other elements into 2 groups: composition ($r_1 > \alpha$) and mirror group ($r_1 \leq \alpha$)
i=1,n,1
Get the current global best index (l)
$i = l$
Y
$x_{gb}^j = x_{gb}^{j-1} + r_n \underbrace{\lambda}_{0.01(UB-LB)}$
$r_1 \leq \alpha$
Y
N
$x_{m,i}^j = r_3 x_i^{j-1} + (1 - r_3) x_{gb}^j$
$x_i^j = 2x_{m,i}^{j-1} - x_i^{j-1}$
$x_i^j = LB^j + r_2(UB^j - LB^j)$
Check the boundaries except for decomposition elements
i=1,n,1
Calculate the fitness values of the new location of the elements and images (virtual elements).
Update each location
Vortex search (VS)
2015
B. Dogan, T. Olmez
Start
Initialization
Decrease the standard deviation for the next iteration
Stopping criteria
N
Y
Results
Stop
Generate candidate solutions by using Gaussian distribution
Generate neighbor solutions $C_t(s)$
If exceeded, then shift the $C_t(s)$ values into the boundaries
Select the best solution from $C_t(s)$ to replace the current center
Compare fitness values and choose/keep the best solution
Center is always shifted to the best solution found so far

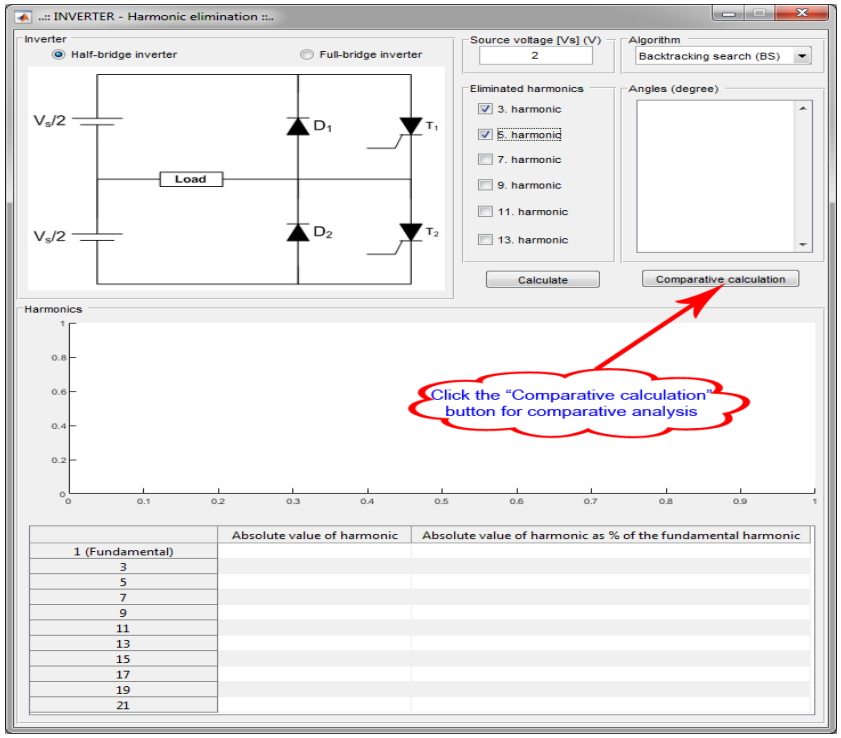


4. APPLICATIONS

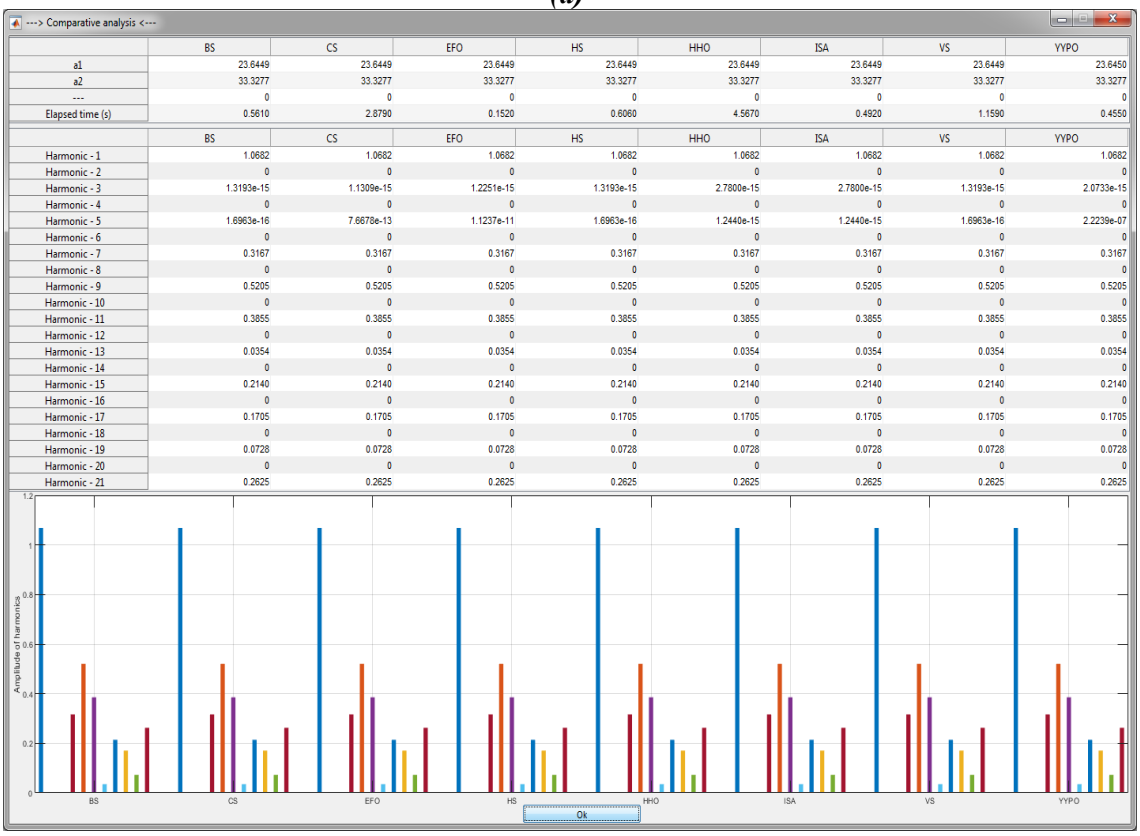
In this work, MATLAB (MathWorks, 2019) is used as a graphical user interface to perform the applications. Using the metaheuristic algorithms, single or comparative analysis can be carried out to determine the optimal angles through the software developed in order to eliminate harmonics. The software is also able to show the results graphically and numerically. In the first application, the purpose is to eliminate third and fifth harmonics in the half-bridge inverter and the related equations are given in Eq. 1 (Rashid, 2013). The comparative results related to the solution of Eq. 1 can be shown in Figure 2 and Table 3.

$$\left.\begin{aligned} 1 - 2Cos(3\alpha_1) + 2Cos(3\alpha_2) = 0 \\ 1 - 2Cos(5\alpha_1) + 2Cos(5\alpha_2) = 0 \end{aligned}\right\} \quad (1)$$

It can be seen that in Table 3, there are no big differences (less than %0.001) in terms of the values of both angles $\alpha_1$and α_2 for all the algorithms. However, considering run-times given in the last column of Table 3, all the algorithms solve the harmonic elimination problem with different speeds. The table indicates that EFO achieves the results with the lowest run-time of $0.152\ s$. ISA and YYPO stay behind EFO with a difference of around $0.3\ s$. In addition to this, HHO, which is the more current algorithm than the others, but the run-time of this algorithm is considerably low as compared to the rest of the algorithms for the first application. HS and BS have also the similar run-time with the identical angle values, showing that one of them can be chosen in solving this problem.



(a)



(b)

Figure 2:
The screenshot of the first application

Table 3. The results of the first application

Algorithm	α_1	α_2	Time (s)
BS	23.6449441898361	33.3276795599481	0.561
CS	23.6449441898099	33.3276795599229	2.879
EFO	23.6449441894526	33.3276795595800	0.152
HS	23.6449441898361	33.3276795599481	0.606
HHO	23.6449441898361	33.3276795599480	4.567
ISA	23.6449441898361	33.3276795599480	0.492
VS	23.6449441898361	33.3276795599481	1.159
YYPO	23.6449517792410	33.3276868433341	0.455

In the second applications, the half-bridge inverter is used for elimination of fifth and seventh harmonics (Patel and Hoft, 1973). The singular and comparative results of second application are given in Figure 3 and Table 4, respectively. When regarding the outcomes of the switching angles given in Table 4, all the algorithms achieve similar results, which are almost the degrees of 16 and 22 for $\alpha_1$and α_2, respectivelly. When comparing the first application with the second one in terms of run-time, EFO remains stable at almost the run-time of $0.15\ s$ while a sharp increase occurs in HS, rising up from $0.606\ s$ in the first application to $1.524\ s$ in the second application. In contrast, YYPO, which is in the second place with respect to the run-time, can reach similar results without any clear differences. These show that EFO and YYPO are performing well for both the applications. Moreover, the highest run-time belongs to HHO as similar to the first application. This indicates that HHO is not suitable in the applications which require high speed.

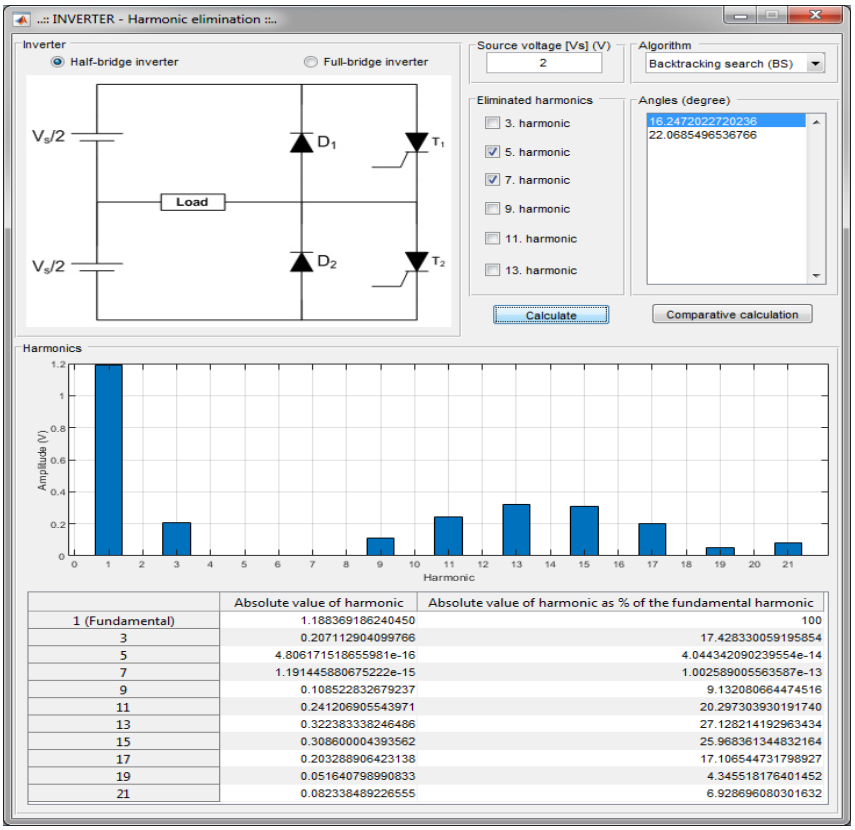
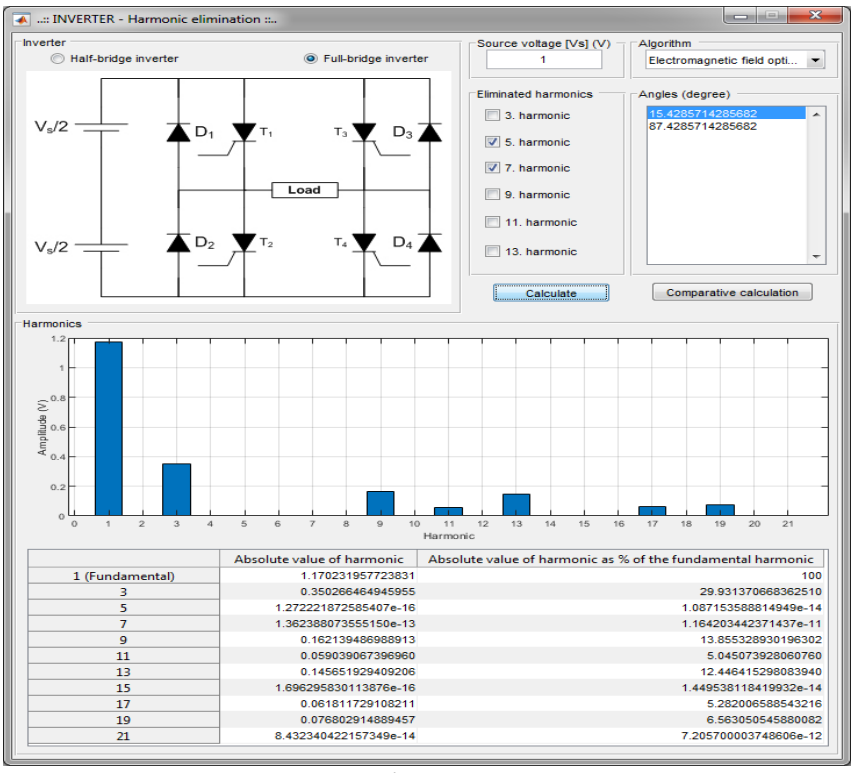


Figure 3:
The screenshot of the second application

Table 4. The results of the second application

Algorithm	α_1	α_2	Time (s)
BS	16.2472022720236	22.0685496536766	0.448
CS	16.2472022730367	22.0685496547445	3.572
EFO	16.2472021397706	22.0685495142732	0.159
HS	16.2472022720236	22.0685496536766	1.524
HHO	16.2472022720200	22.0685496536700	5.990
ISA	16.2472022720236	22.0685496536766	0.509
VS	16.2472022720236	22.0685496536766	1.132
YYPO	16.2470447379089	22.0683836028402	0.448

In the third application, the full-bridge is used for the elimination of fifth and seventh harmonics (Patel and Hoft, 1973). The singular and comparative results of third application are given in Figure 4 and Table 5, respectively. As shown from Table 5, as similar to the first and second applications, no significant differences exist between the algorithms in terms of the values of angles $\alpha_1$and α_2. The differences become when considering the run-time of the algorithms, demonstrating that EFO is still in the first place with $0.162\ s$. as compared to the other algorithms. HHO and CS achieve the worst run-times, meaning that these algorithms should not be in the first choice if run-time is substantially important. On the other hand, BS and ISA have very close run-times and outperform the other algorithms, except for EFO and YYPO, showing the capabilities of them in finding the switching angles within reasonable run-times. It can be observed from the outcomes of all the applications that the problems can be solved with these eight algorithms, but if the run-times of the algorithms are taken into account, EFO is the best option as compared with the other algorithms for all the applications.



	Absolute value of harmonic	Absolute value of harmonic as % of the fundamental harmonic
1 (Fundamental)	1.170231957723831	100
3	0.350266464945955	29.931370668362510
5	1.272221872585407e-16	1.087153588814949e-14
7	1.362388073555150e-13	1.164203442371437e-11
9	0.162139486988913	13.855328930196302
11	0.059039067396960	5.045073928060760
13	0.145651929409206	12.446415298083940
15	1.696295830113876e-16	1.449538118419932e-14
17	0.061811729108211	5.282006588543216
19	0.076802914889457	6.563050545880082
21	8.432340422157349e-14	7.205700003748606e-12

Figure 4:
The screenshot of the third application

Table 5. The results of the third application

Algorithm	α_1	α_2	Time (s)
BS	15.4285714285714	87.4285714285714	0.472
CS	15.4285714285714	87.4285714285714	3.452
EFO	15.4285714285682	87.4285714285682	0.162
HS	15.4285856118238	87.4285856118238	0.782
HHO	15.4285714285714	87.4285714285714	4.768
ISA	15.4285714285714	87.4285714285714	0.428
VS	15.4285714285714	87.4285714285714	1.110
YYPO	15.4286030173399	87.4286030173399	0.366

5. CONCLUSION

The inverters are used for a wide variety of applications due to its flexibility and ease of use in the field of power electronics. In this work, eight metaheuristic algorithms called BS, CS, HS, VS, EFO, ISA, YYPO and HHO are used to eliminate harmonics and three applications are implemented. To do this, the software having the ability to effectively handle harmonic elimination problems is designed, showing the related results numerically and graphically to the users. According to the results, EFO is the fastest algorithm for all the applications, proving itself to be the best option in terms of run-time. YYPO and ISA also stay in second and third places, respectively. If small differences of run-times between these algorithms are not taken into account, all the applications can be performed successfully with them. The results show that the algorithms used can eliminate harmonics fast and easily, and have sufficient capacity in finding optimal switching angles for all the applications, but with different speeds. Further works should be extended to multilevel inverters to compare the performances of the algorithms.

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