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Genetic Algorithm Application in Asymmetrical 9-Level Inverter

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ABSTRACT

Selective harmonic elimination (SHE) has been a widely researched alternative to traditional PWM techniques. This paper presents the selective harmonic elimination of a uniform step asymmetrical multilevel inverter (USAMI) using genetic algorithm (GA) which eliminates specified higher order harmonics while maintaining the required fundamental voltage. This technique can be applied to USAMI with any number of levels. As an example, in this paper a 9-level USAMI is considered and the optimum switching angles are calculated to eliminate the 5th, 7th and 11th harmonics.

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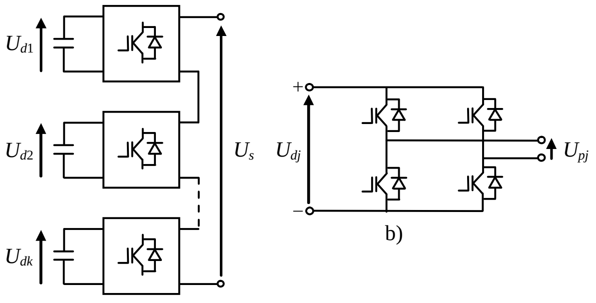
1. INTRODUCTION

Multilevel inverters have been widely used in last years for high-power applications [1]. Variable-speed drives have reached a wide range of standard applications such as pumps, fans and others. Many of these applications use medium-voltage motors (2300, 3300, 4160 or 6600V), due to their lower current ratings in higher power levels [2]. Static Var compensators and active filters are other applications that use multilevel converters [3].

Several topologies of multilevel inverters have been studied and presented. Among them, neutral point clamped inverters [4], flying capacitors inverters also called imbricated cells [5], and series connected cells inverters also called cascaded inverters [6]. The industry often has used the neutral-point-clamped inverter [7]. However, the topology that uses series connected cells inverters presents some advantages, as smaller voltage rate (dU/dt) due to existence of higher number levels, producing less common-mode voltage across motor windings [8]. Furthermore, this topology is simple and its modular configuration makes it easily extensible for any number of desired output voltage levels. Figure 1a shows the basic diagram of this topology with k partial cells represented by Figure 1b. The j^{th} single-phase inverter is supplied by a dc-voltage source U_{dj} ($j = 1 \ldots k$). The relationship between the number of series-connected single-phase inverters in each phase and the number of output voltage levels generated by this topology, respectively k and N, is given by: $N = 2k + 1$, in the case where there are equal voltages in all partial inverters.

In all the well-known multilevel converter topologies, the number of power devices required depends on the output voltage level needed [9]. However, increasing the number of power semiconductor switches also increases the converter circuit and control complexity and the costs. To provide a large number of output levels without increasing the number of converters, a uniform step asymmetrical multilevel inverters (USAMI) can be used [10].



a) b)

Figure 1. a) A series-connected multilevel inverter topology with *k* partial cells, b) Partial cell configuration

The key issue in designing an effective multilevel inverter is to ensure that the Total Harmonic Distortion (THD) of the output voltage waveform is within acceptable limits. Selective harmonic elimination (SHE) has been intensively studied in order to achieve low THD [11, 12]. The output voltage waveform analysis using Fourier theory produces a set of non-linear transcendental equations. The solution of these equations, if exists, gives the switching angles required for certain fundamental component and selected harmonic profile. Iterative procedures such as Newton-Raphson method has been used to solve these sets of equations [13]. This method is derivative-dependent and may end in local optima, and a judicious choice of the initial values alone guarantees conversion [14]. Another approach based on converting the transcendental equation into polynomial equations is presented in [15], where resultant theory is applied to determine the switching angles to eliminate specific harmonics. That approach, however, appears to be unattractive because as the number of inverter levels increases, so does the degree of the polynomials of the mathematical model. This is likely to lead to numerical difficulty and substantial computational burden as well.

In this paper, a general genetic algorithm approach will be presented, which solves the same problem with a simpler formulation and with any number of levels without extensive derivation of analytical expressions. GA is a search method to find the maximum of functions by mimicking the biological evolutionary processes. There are only a few examples of GA applications for power electronics in the literature [16-19], but none on GA applied to USAMI. This approach is compared to the conventional Newton-Raphson method, where the superiority of the presented algorithm is reported.

2. UNIFORM STEP ASYMMETRICAL MULTILEVEL INVERTER

Multilevel inverters generate at the ac-terminal several voltage levels as close as possible to the input signal. Figure 2 for example illustrates the *N* voltage levels U_{s1}, U_{s2}, ... U_{sN} composing a typical sinusoidal output voltage waveform. The output voltage step is defined by the difference between two consecutive voltages. A multilevel converter has a uniform or regular voltage step, if the steps ΔU between all voltage levels are equal. In this case the step is equal to the smallest dc-voltage, U_{d1} [10]. This can be expressed by

$$\left|U_{sl} - U_{s(l-1)}\right| = \Delta U = U_{d1},\ l = 2 \ldots N \qquad (1)$$

If this is not the case, the converter is called a non uniform step AMI or irregular AMI. An USAMI is based on dc-voltage sources to supply the partial cells (inverters) composing its topology which respects to the following conditions:

$$\begin{cases} U_{d1} \le U_{d2} \le \ldots \le U_{dk} \\ U_{dj} \le 1 + 2\sum\limits_{l=1}^{j-1} U_{dl} \end{cases} \qquad (2)$$

where k represents the number of partial cells per phase and $j = 1 \ldots k$. The number of levels of the output voltage can be deduced from

$$N = 1 + 2\sum_{j=1}^{k} \frac{U_{dj}}{U_{d1}} \tag{3}$$

This relationship fundamentally modifies the number of levels generated by the multilevel topology. Indeed, the value of N depends on the number of cells per phase and the corresponding supplying dc-voltages.

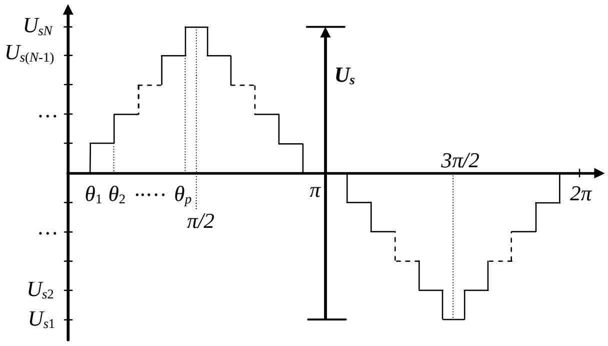


Figure 2. Typical output voltage waveform of a multilevel inverter

Equation (3) accepts different solutions. With $k = 3$ for example, there are two possible combinations of supply voltages for the partial inverters in order to generate a 13-level global output, i.e., $(U_{d1}, U_{d2}, U_{d3}) \in \{(1, 1, 4), (1, 2, 3)\}$, and there are three possible combinations to generate a 15-level global output, i.e., $(U_{d1}, U_{d2}, U_{d3}) \in \{(1, 1, 5), (1, 2, 4), (1, 3, 3)\}$. Figure 3 shows the possible output voltages of the three partial cells of the 9-level inverter with $k = 3$. The dc-voltages of the three cells are $U_{d1} = 1p.u.$, $U_{d2} = 1p.u.$ and $U_{d3} = 2p.u.$. The output voltages of each partial inverter are noted U_{p1}, U_{p2} and U_{p3} and can take three different values: $U_{p1} \in \{-1, 0, 1\}$, $U_{p2} \in \{-1, 0, 1\}$ and $U_{p3} \in \{-2, 0, 2\}$. The result is a generated output voltage with 9-levels: $U_s \in \{-4, -3, -2, -1, 0, 1, 2, 3, 4\}$. Some levels of the output voltage can be generated by different commutation sequences. For example, there are four possible commutation sequences resulting in $U_s = 2p.u.$: $(U_{p1}, U_{p2}, U_{p3}) \in \{(-1, 1, 2), (0, 0, 2), (1, -1, 2), (1, 1, 0)\}$. These redundant combinations can be selected in order to optimize the switching process of the inverter [20].

These different possibilities offered by the output voltage of the partial inverters, and the redundancies among them to deliver a same output voltage level, can be considered as degrees of freedom which can be exploited in order to optimize the use of a USAMI.

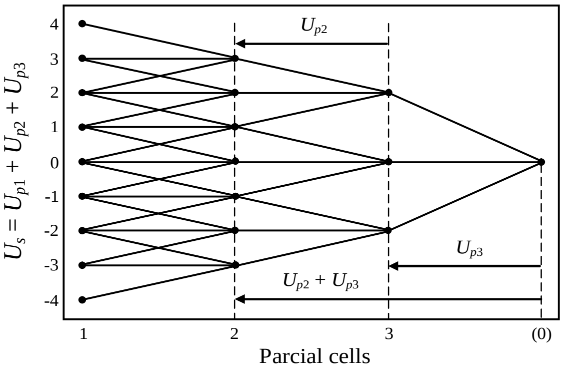


Figure 3. Possible output voltages of each partial inverter to generate $N = 9$ levels with $k = 3$ cells per phase ($U_{d1} = 1p.u.$, $U_{d2} = 1p.u.$ and $U_{d3} = 2p.u.$)

3. MODULATION CONTROL

Generally, traditional PWM control methods and space vector PWM methods are applied to symmetrical multilevel inverter modulation control [21-24], and can also be used to control asymmetrical multilevel inverter. These methods will cause extra losses due to high switching frequencies. For this reason, low-switching frequency control methods, such as selective harmonic elimination, represent interesting and alternative solutions [15, 25].

The SHE is based on the Fourier analysis of the generated voltage U_s at the output of the USAMI (Figure 2). This voltage is symmetric in a half and a quarter of a period. As a result, the even harmonic components are null. The Fourier series expansion for the U_s voltage is thus:

$$U_s = \sum_{n=1}^{\infty} U_n \sin(n\omega t), \text{ with } U_n = \frac{4U_{d1}}{n\pi}\sum_{i=1}^{p}\cos(n\theta_i) \tag{4}$$

where U_n is the amplitude of the harmonic term of rank n, $p = (N - 1)/2$ is the number of switching angles per quarter waveform, and θ_i is the i^{th} switching angle.

The p switching angles in (4) are calculated by fixing the amplitude of the fundamental term and by canceling the $p - 1$ other harmonic terms. Practically, four switching angles (θ_1, θ_2, θ_3, θ_4) are necessary for canceling the three first harmonics terms (i.e., harmonics with a odd rank and non multiple of 3, therefore 5, 7 and 11) in the case of a three phase 9-level USAMI composed of $k = 3$ partial inverters per phase supplied by the dc-voltages $U_{d1} = 1p.u.$, $U_{d2} = 1p.u.$ and $U_{d3} = 2p.u.$. These switching angles can be determined by solving the following system of non linear equations:

$$\begin{cases} \sum_{i=1}^{p=4}\cos(\theta_i) = \pi r \\ \sum_{i=1}^{p=4}\cos(n\theta_i) = 0 \text{ for } n \in \{5, 7, 11\} \end{cases} \tag{5}$$

where $r = U_1/4U_{d1}$ is the modulation rate. The solution of (5) must also satisfy

$$0 < \theta_1 < \theta_2 < \theta_3 < \theta_4 < \frac{\pi}{2} \tag{6}$$

An objective function is then needed for the optimization procedure, which is selected as a measure of effectiveness of eliminating selected order of harmonics while maintaining the fundamental component at a pre-specified value. Therefore, this objective function is defined as:

$$F(\theta) = F(\theta_1, \theta_2, \theta_3, \theta_4) = \left(\sum_{i=1}^{p=4}\cos(\theta_i) - \pi r\right)^2 + \sum_{i=5,7,11} U_i^2 \tag{7}$$

The optimal switching angles are obtained by minimizing equation (7) subject to the constraint (6), and consequently the required harmonic profile is achieved. The main challenge is the non-linearity of the transcendental set of equation (5), as most iterative techniques suffer from convergence problems and other techniques such as elimination using resultant theory [15] and Walsh function [26] are complicated. It is, therefore, worth considering more techniques and simple techniques such as GA.

4. SOLUTION USING GA

GA is a search mechanism imitates the natural selection and the genetics of living organisms. A typical GA consists of three operators, i.e., reproduction, crossover, and mutation [27]. A flowchart of the GA algorithm is shown in Figure 4.

The process of a GA usually begins with a randomly selected population of chromosomes. These chromosomes are representations of the problem to be solved, in this case switching angles θ_1, θ_2, θ_3 and θ_4 of a 9-level USAMI. Then to start the search procedure, the switching angles are randomly generated. These values must be satisfied the conditions of (6) for the chosen number of population. According to the attributes of the problem, different positions of each chromosome are encoded as bits, characters, or numbers. These positions are sometimes referred to as genes and are changed randomly within a range during evolution. An evaluation function *F*(¯) is used to calculate the "goodness" of each chromosome.

During evaluation, two basic operators, crossover and mutation, are used to simulate the natural reproduction and mutation of species. In crossover, randomly selected subsections of two individual chromosomes are swapped to produce the offspring. In mutation, randomly selected genes in chromosomes are altered by a probability equal to the specified mutation rate. These operators are applied to offspring to generate next generations during optimization process. When the convergence is achieved, the repeat of this process is stopped. With a considerable number of generations and large number of population in each generation, the algorithm searches for all probable set of solutions and finally compute the angles ¯$_1$, ¯$_2$, ¯$_3$ and ¯$_4$, to contribute the minimum *F*(¯).

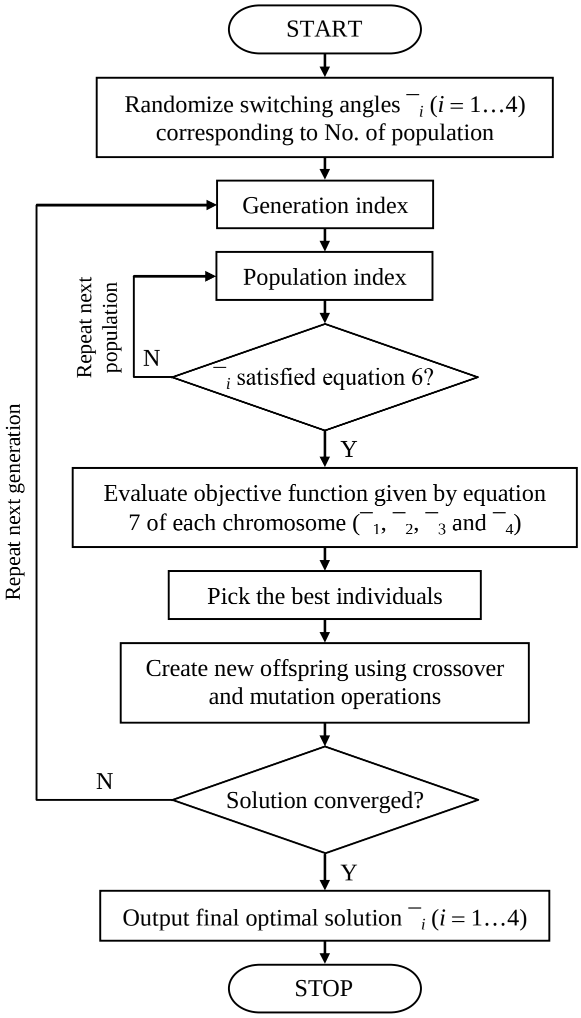


Figure 4. Flowchart of GA for a 9-level USAMI

The program is run for different values of modulation rate and the switching angles corresponding to minimum *F*(¯) are stored as a look-up table. The parameters selected for the implementation of GA are: the population size = 110, the number of generations = 110, the crossover probability = 0.35 and the mutation probability = 0.35. The result is represented by Figure 5 where one can see the presence of two possible solutions of angles for $0.70 \leq r \leq 0.76$. On the other side, the system does not accept any solution for $r < 0.629$, $0.64 < r < 0.7$ and $0.897 < r < 0.921$. The system has an unique solution for all the other values of r.

In the case of two possible solutions of an angle ¯$_i$, one clear way to choose a particular solution is simply to pick the one that results in the lowest THD given by equation 8. The THD corresponding to the solutions given in Figure 5 is represented by Figure 6.

$$\text{THD} = \sqrt{\sum_{n=5,7,\ldots}^{\infty}\left(\frac{1}{n}\sum_{i=1}^{p=4}\cos(n{}^{-}{}_{i})\right)^{2}} \Bigg/ \sum_{i=1}^{p=4}\cos({}^{-}{}_{i}) \qquad (8)$$

As seen on Figure 7, any solution that yields a cost function less than 0.0001 is accepted. We clearly notice that the number of solutions for each *r* increases or decreases in according to precision constraint value by which solutions are calculated.

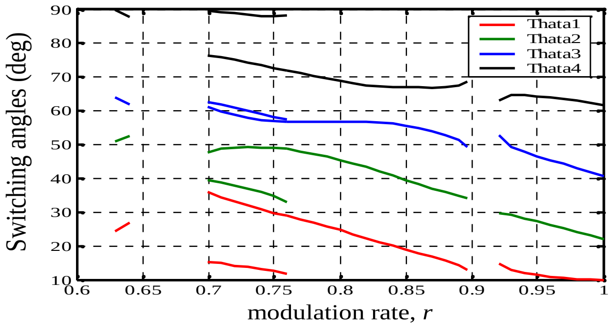


Figure 5. All switching angles versus *r* for a 9-level USAMI

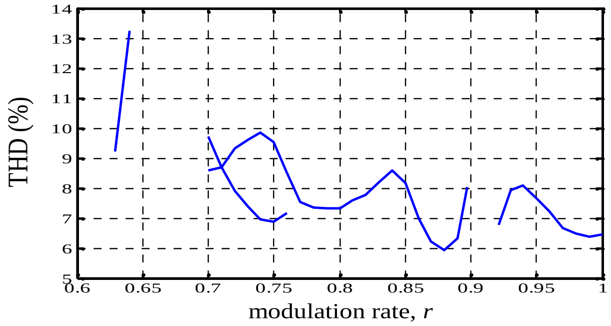


Figure 6. THD versus *r* for all switching angles

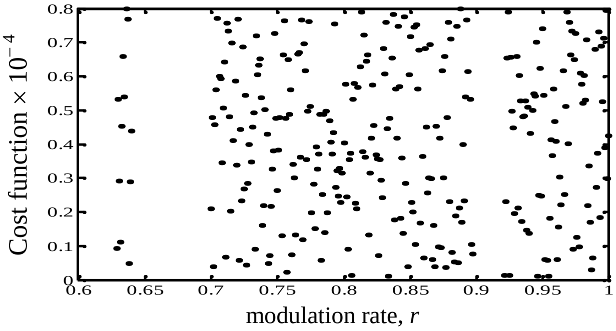


Figure 7. Cost function versus *r*

The comparison between the conventional Newton-Raphson iterative method and the proposed GA technique for the 9-level USAMI, regarding the computational time and corresponding THD are tabulated in Table 1. It is clearly evident that the proposed GA technique is both extremely faster and optimal than the conventional Newton-Raphson method, which reflects the superiority of the introduced technique as far as computational burdens and quality of the output waveform are concerned.

Table 1. Comparison between iterative Newton-Raphson technique and the proposed GA technique

Technique	THD (%)	Computational time (s)
Newton-Raphson	9.92	23.48
Genetic Algorithm	6.89	2.07

5. TEST RESULTS

In this Section, simulations were performed to validate the genetic algorithm approach presented in Section 4. The simulations have been achieved using Matlab-Simulink. The 9-level USAMI composed of k = 3 partial inverters per phase supplied by the dc-voltage sources $U_{d1} = 1p.u.$, $U_{d2} = 1p.u.$ and $U_{d3} = 2p.$u. (U_{d1} = 250V, U_{d2} = 250V and U_{d3} = 500V with IS Units) was attached to a three-phase induction motor with the following data: rated power P_n = 1MW, stator resistance $R_s = 0.228\Omega$, rotor resistance $R_r = 0.332\Omega$, stator inductance L_s = 0.0084H, rotor inductance L_r = 0.0082H, mutual inductance L_m = 0.0078H, number of pole pairs P = 3, rotor inertia J = 20kg.m^2, viscous friction coefficient K_f = 0.008 Nm.s.rad^{-1}.

In the test, the value of r was chosen to 0.75 in order to produce a fundamental voltage of $U_1 = 4rU_{d1} = 3p.u.$ (i.e., U_1 = 750V) along with f = 50Hz. As can be seen in Figure 5, there are two different solution sets for r = 0.75. The solution set that gave the lowest THD, i.e., 6.89% as indicated by Figure 6, was used. The output voltages U_{p1}, U_{p2} and U_{p3} of each partial inverter and U_a, the phase a voltage, are represented by Figure 8. The harmonic content of U_a is calculated using the Fast Fourier Transform (FFT) and it is represented by Figure 9. This figure shows that the 5th, 7th and 11th harmonics are absent from the waveform as predicted. The triple harmonics (3rd, 6th, 9th, etc.) in each phase do not need be canceled as they are automatically cancelled in the line-line voltages. The THD of the line-line voltage was computed and was found to be 6.91% which compares favourably with the value of 6.89% predicted with Figure 6.

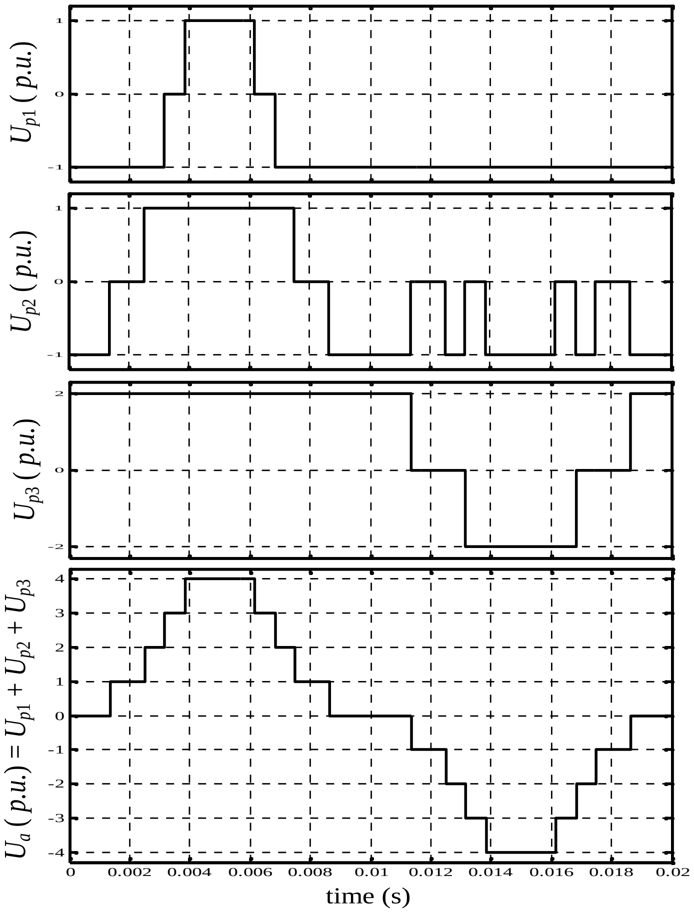


Figure 8. Output voltages of each partial inverter and phase a voltage using the solution set with the lowest THD (with r = 0.75)

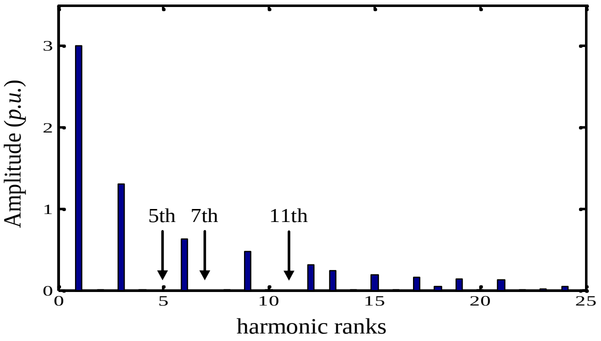


Figure 9. Harmonic content of U_a

Figure 10 shows the phase *a* current i_a corresponding to U_a. The harmonic content of this current is given by Figure 11. One can notice that the harmonic content of i_a is lower than the one of U_a. This is due to the filtering effect introduced by the motor’s inductance. The THD of this current amounts to 2.08%.

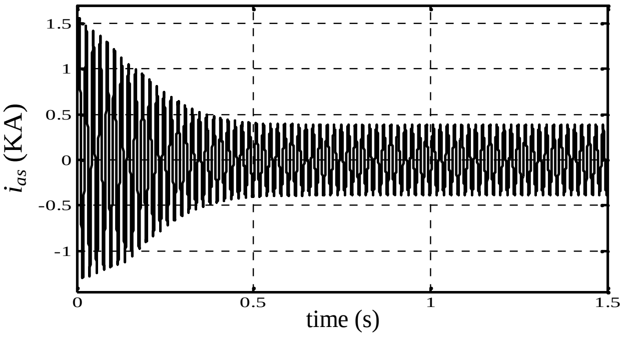


Figure 10. Phase *a* current corresponding to U_a

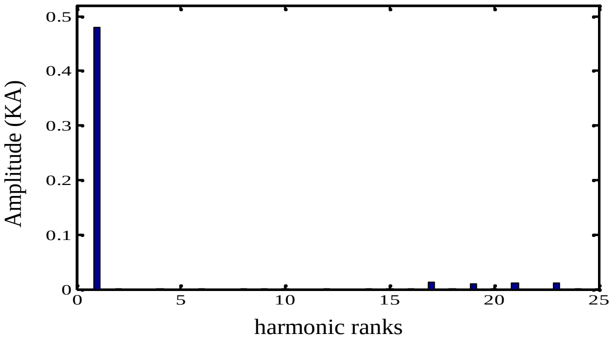


Figure 11. Harmonic content of the phase *a* current i_a

6. CONCLUSION

A GA method to generate optimal switching angles in order to eliminate a certain order of harmonics in a USAMI is introduced in this paper. The results obtained show that 5th, 7th and 11th order harmonics are eliminated effectively in a 9-level USAMI. A comparison between the proposed technique and the conventional Newton-Raphson method in terms of computational times and resulted THD is reported, where it reveals that the algorithm can be effectively used for selective harmonic elimination of USAMI and results in a dramatic decrease in both the computational times and the output voltage THD. As in this approach, GA is applied to any problem where optimization is required. Therefore, it can be used in many applications in power electronics.

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