THE REDUCTION OF TOTAL HARMONIC DISTORTION FOR THE MULTILEVEL CONVERTER USING GENETIC ALGORITHMS OPTIMIZATION METHOD

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Abstract*: Electricity, DC voltage - AC voltage, conversion generated from certain renewable energy sources such as photovoltaic panels should be made with quality factors imposed by the present standards. In the case of multilevel converters the achievement of reasonable distortion factor is realized by optimizing the targeted waveform using Newton Raphson method. This paper presents an optimization solution based on genetic algorithm. Voltage waveforms obtained by this technique and the total harmonic distortion degree of reduction are presented by comparing the results obtained from supplying a consumer with a voltage generated in classical way through DC-AC conversion, using multilevel converter.*

I. INTRODUCTION

In the last decades, the demand of energy produced from renewable sources has increased due to environmental issues and decrease of classics fuel sources: oil, coal and natural gas. Among renewable energy sources the most commonly used for grid connection [1] are photovoltaic panels and wind turbines. The control of the output voltage and frequency are the main problems in the connection of these renewable sources to the grid and therefore for connection, special converters are used in order to make frequency and voltage regulation.

In the case when renewable source produce DC voltage, such as photovoltaic panels or fuel cells the DC-DC converters are used in order to change the level of DC voltage to the required value demanded by application. The converters are also used to improve the voltage quality provided by energy sources. DC-AC converters are used to convert the DC voltage to

AC voltage, at the level of voltage and frequency from the grid. The development of medium and high power renewable sources applications have determined a series of researches in the field of multilevel converters, especially for wind turbine applications, which have as disadvantage the speed variation.

Since the 80s, many power electronics researches have focused on improving the efficiency of current and voltage parameters from semiconductor devices. In order to obtain higher voltage levels electronic converters have been developed. In 1981, converter schematics proposed neutral point-clamped PWM inverter PWM NPC, as well as improved version of multilevel converter with two levels and which today is known as the “diode-clamped multilevel inverter”.

Multilevel converter topologies can be divided into three major groups:

- Cascaded multilevel inverters;
- Diode-clamped multilevel inverters;
- Flying-capacitor multilevel inverter.

Along with the converter topology [5], the current researches in the field of multilevel converters are oriented towards finding the optimal solution for commutation. Control strategy aims the minimization of harmonic spectrum for the output sizes and switching losses reduction as low as possible. There are three commutation methods, specifics to multilevel converters such as:

Selective Harmonic Elimination. At this method, each switching device is switched on and off once in one cycle of the connection-disconnection, and the control angles are chosen according to the harmonics that needs to be eliminated in order to minimize the total harmonic distortion factor (THD) for the output voltage.

Carrier-Based PWM. At this method, the switches command signals results from the comparison of reference signal with the signal measured on the AC grid.

Space-Vector PWM. The method is based on command reconfiguration by sampling the command signal according to the inverter output voltage vector.

Multilevel converters allows the growth of output voltage without increasing nominal voltage on the components used by static switches in order to provide direct connection of renewable energy to the grid. In addition it is to be notice that multilevel inverters synthesize sinusoidal waveform with a distortion factor smaller than in the case of two-level inverters.

The technique by which the multilevel inverters synthesizes the waveform, permits the reduction of voltage and current waveforms harmonic content using dimensional reduced filters mounted at the inverter output.

Among the various types of the multilevel converters, cascaded converters are usually used for photovoltaic sources, due to the modular structure, but the number of commutations is higher than in the case of other types of multilevel converters and it is required to have independent voltage sources. The converter with clamped diode is another type of multilevel convertor, widely used in conversion systems for grid connection, due to the minimum number of active components and the use of common DC sources [2]. The clamped diode converter structure has as disadvantage the imbalance of neutral point, and so equilibrations solutions need to be used for the neutral point potential [3] using capacitors. This method leads to a more complex control system. Also, the existing methods are not applicable to all voltage levels from the system. The utilization of auxiliary devices needed for equilibration or active rectifier leads to increased complexity and value of the equipment [3, 4].

II. MULTILEVEL CONVERTERS IN THE SYSTEMS USING ENERGY CONVERSION

As it is known, the application of DC voltage-AC voltage conversion at fixed frequency and amplitude are: the injection into the system of energy provided by renewable energy sources; energy supplying by interruptible power sources; DC power transmission at high voltage.

The most important problem of the conversion is the fact that the alternative voltage injected need to have a minimal distortion factor and so the harmonics injected are decreased to minimum values. AC-DC voltage conversion is achieved through inverters. Inverter topologies research was influenced by the development of "off-shore" renewable energy sources. The energy transport and energy injection into the power system was another problem studied by the researchers. The energy produced from renewable sources "off-shore" is converted to DC, transported to the mainland, where it is converted into AC voltage and delivered to power system. At the conversion elements, the most important issue is the commutation. The commutation can be "soft" when the waveform is synthesized by the control circuits through pulse width modulation (PWM) or "hard" when the waveform is synthesized [5] by the command of static commutation devices through diagram topology used in the inverter power circuit.

In general is desired to avoid commutation on the inverter force side, but for mentioned applications, this cannot be prevented. Semiconductor devices are usually limited by the reverse voltage at values lower than 10 kV, but on the transport of DC high voltage (HVDC) the 100 kV switching voltage is exceeded and the commutation is achieved by connecting a series of semiconductor devices or using multilevel converters. The simplest topology that can be used for this conversion is the two-level inverter which is made of four switches. Each switch consists of an antiparallel diode, since the configuration needs reverse current diode.

A multilevel inverter is a power electronic system that synthesizes a sinusoidal output voltage from several DC sources. DC sources can be batteries, solar cells or capacitors. Multilevel inverter operation is based on a number of switches connected in series in order to obtain on the output voltage and sinusoidal current. Since multiple switches are connected in series, the angle of commutation is important for multilevel inverters, because all switches would be operated in such a way that the output voltage and current to have minimum harmonic distortion.

Total harmonic distortion-THD is reduced by increasing the number of levels. It is obvious that an output voltage with a minimum of total harmonic distortion is desirable, but increasing the number of levels requires more commutation devices and so complicates the command and control circuits. The compromise necessity appears for price-weight-complexity for an output voltage with minimum of total harmonic distortion. Previous work in the area of multilevel inverters focused more on total harmonic distortion and on inverters commutation model. The majority were focused in order to obtain at the output a sinusoidal voltage and a current with minimum total harmonic distortion using different commutation models. The commutation angles in multilevel inverters are so important because it can affect the shape of the output voltage and the total harmonic distortion of current. There are several studies on different methods of harmonics elimination which are related to commutation angle calculation [6]. The newest method used to eliminate harmonics is the resultant theory. The harmonics elimination in a multilevel converter using this method focuses on the resultant theory in order to calculate the commutation angles. Some papers have focused on different uses of multilevel inverters, while others relate to different topologies depending on the electricity application for which are used. The paper [6] compares the H-bridge multilevel inverters in the case of high power electric motors. The most common multilevel inverter topologies are: diode-clamped multilevel inverter (DC-MLI); flying capacitor multilevel inverter (FC-MLI); cascaded H-Bridge Multilevel Inverters (CHB MLI).

When the number of levels is larger than three, at DC MLI inverters, the number of clamped diodes and the complexity of the scheme are increased. FC-MLI inverters are based on voltage balancing and can generate different waveforms at the output. It also requires a phase balancing capacitors and leads to increased complexity by increasing the number of capacitors. They are defined as different combinations of capacitors allowing the charging or discharging of the individual flying capacitors in order to produce the same phase leg voltage.

Between these three types of usual multilevel inverters topologies; cascade inverter has the smallest number of components for a given number of levels. Cascade multilevel inverters is made up of a number of cells of H-bridge type in order to synthesize the required voltage from several separated direct voltage sources (SDCS), which may be batteries or fuel cells. All these properties of cascade inverters allow the using of various control strategies using pulse width modulation (PWM) for a more accurate control. In addition for the previously mentioned technologies specific control techniques have been developed for multilevel inverters such as selective harmonic elimination PWM (SHE-PWM), sinusoidal PWM (SPWM), space-vector PWM (SVM) and modulation techniques derived thereof. The modulation methods used for the multi-level inverters can be classified according to the commutation frequency.

III. TOTAL HARMONIC DISTORTION REDUCTION USING GENETIC ALGORITHMS

The genetic algorithms are generally used to solve optimization problems, planning or linear search, multi-criteria. These represent a set of adaptive procedures that finds a solution for a problem investigated by a mechanism of natural selection and genetic evolution. The mechanism was introduced and analyzed by J. Holland, being characterized by the fact that only species (solutions) that are better suited to the environment are able to survive and evolve over generations while those less adapted disappear. The probability of a species to survive and evolve over generations becomes greater while the degree of adaptation increases, which in terms of optimization means that the solution approaches to optimal. To implement the proposed genetic algorithm for optimizing the operation of a multilevel converter in order to reduce the harmonic distortion we use Matlab. The work presented is based on developing a function to perform the optimization based on genetic algorithms:

$$[Param, THD] = f\_GAImplem(ConvLvl, IterNo) \tag{1}$$

The implemented function f_GAImplem receives as input ConvLvl, the level of multilevel converter, whose function is to be optimized and the IterNo represents the number of iterations of the optimization process. The output data provided are: Param, the list of optimization operating parameters for the studied multilevel converter (wave amplitude and pulse width used for the reconstruction of sine wave waveform) and the harmonic distortion THD provided by the converter. The genetic algorithm implemented in the developed Matlab function is based on a population of one hundred individuals, randomly generated, each representing a possible set of operating parameters for the studied multilevel converter. In order to determine the optimal solution for the genetic algorithm implemented for each individual (set of possible operating parameters) it is needed to find the mean square error of the waveform provided by the converter and sinusoidal waveform that is intended to be achieved:

$$MSQ_{err} = \frac{1}{N}\sum_{i=1}^{N}\left[Conv(\omega \cdot t_i) - Sin(\omega \cdot t_i)\right]^2 \tag{2}$$

where: MSQ_{err} is the reconstruction mean square error of the sine wave; N is the number of intermediate points on a period used for the MSQ_{err} evaluation; $Conv\ (\omega \cdot t_i)$ is the effective value at the moment t_i of the waveform signal supplied by the studied converter; N is the pulsation corresponding to the frequency f of the signal provided by the converter.

Also, for each possible converter operating parameters we evaluate the signal harmonic distortion for the given waveform:

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + \cdots + V_n^2}}{V_1} \quad [\%] \tag{3}$$

where: *THD* is the percentage of harmonic distortion for the signal supplied by the converter; V_k is the amplitude of the k voltage harmonic obtained from the Fourier decomposition, $k = 1,n$ (where n is the number of harmonics under investigation).

In order to achieve the Fourier decomposition of the signal supplied from a possible configuration of multilevel converter investigated on the basis of below relations (3) ÷ (5) we have used Matlab. Here we named a function called f_FourierDeComp(Param), which receives as a input data the signal amplitude and the waveform width of pulses used for the reconstruction of the sinusoidal waveform.

$$V_k = \sqrt{A_k^2 + B_k^2}, \qquad \phi_k = \arctan\left(\frac{B_k}{A_k}\right) \tag{4}$$

where:

$$A_k = \frac{2}{T} \cdot \int_0^T Conv(\omega \cdot t) \cdot Sin\left(\frac{2 \cdot \pi \cdot k \cdot t}{T}\right) dt \tag{5}$$

$$B_k = \frac{2}{T} \cdot \int_0^T Conv(\omega \cdot t) \cdot Cos\left(\frac{2 \cdot \pi \cdot k \cdot t}{T}\right) dt \tag{6}$$

Since harmonic distortion factor *THD* does not provide information regarding the harmonic component of the signal studied in order to determine the multilevel converter configurations which produce waveforms with a low-order harmonics 3, 5 and 7, for each possible solution (individual) the weighted harmonic distortion factor is also evaluate:

$$THD_b = \frac{1}{V_1} \cdot \sum_{k=1}^{n} \sqrt{\left(\frac{V_k}{\log(k)}\right)^2} \quad [\%] \tag{7}$$

In order to determine the optimal solution of multilevel converter (best individual), in terms of those presented above, genetic algorithms implemented within the f_GAImplem function, uses a global cost function that takes into account the weighted value of three factors THD, THD_h and MSQ_{err},

$$CostFunc = THD + 1.5 \cdot THD_b + 0.5 \cdot MSQ_{err} \tag{8}$$

Table 1. The Results obtained for the 3 Steps Inverter

Nr. of iterations	Pop	The best values obtained for the THD (%)				
10000	50	27.42	27.42	27.42	27.42	27.42
20000	50	23.59	23.59	23.59	23.59	23.59
1000	500	10.80	10.80	10.80	10.80	10.80

Table 2. The Results obtained for the 4 and 6 Steps Inverter

Nr of steps	The best values obtained for the THD					
4	8.143	18.788	19.623	16.705	19.648	18.408
6	6.347	136.524	45.530	42.171	50.511	56.558
6	5.866	5.881	5.884	50.210	38.126	79.017

Genetic algorithm implemented in Matlab allows through programming mode the selection of the desired number of iterations. Being an iterative process, requires a longer period of running, and in the first phase the program tests the 3 step inverter. At first run for 3 steps we introduce a number of iterations 10000 and then 20000, however, the results do not meet the proposed limits. Therefore, we increase the population of individuals from 100-to 500, 1000 iterations, thus yielding better results, as can be seen from Table 1.

Also, table 1 shows that the solutions obtained are identical. Therefore, a function must be introduced to allow the visualization of intermediate solutions convergence from the algorithm. The graph of convergence is shown in *figure 1*.

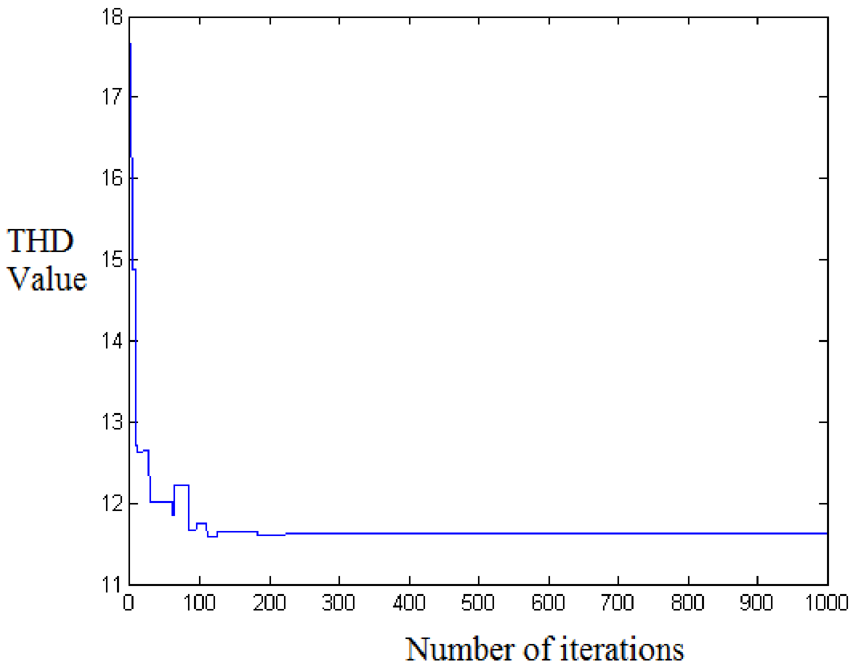

Fig. 1. The solutions convergence graphic for the 3 step inverter.

The results thus obtained were considered superior to those obtained previously. Also should be noted that they within the standard SR EN 50160/2011, which requires the value of THD's to under 8%.

The convergence graphs of THD values for 4 and 6 steps inverter are shown in *figures 2* and *3*.

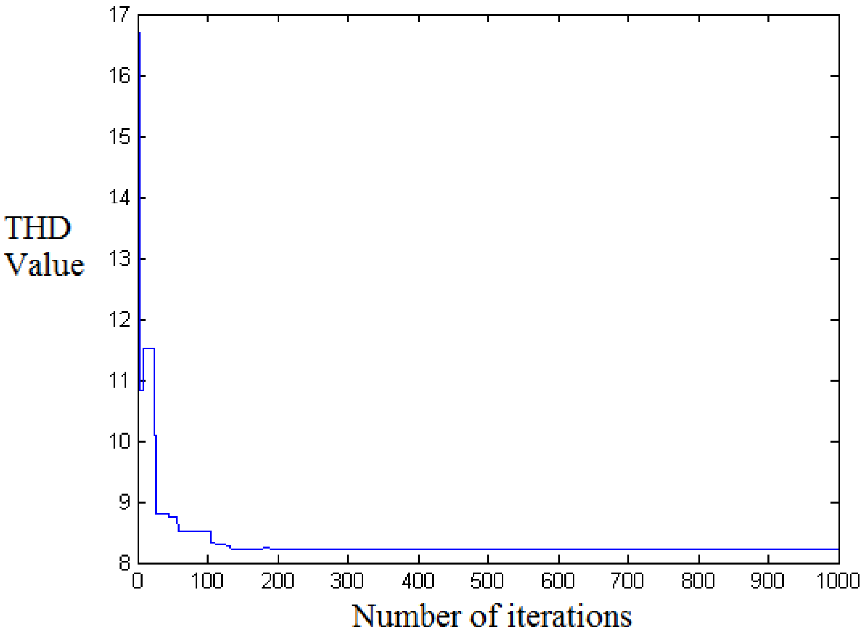

Fig.2. The solutions convergence graphic for the 4 step inverter.

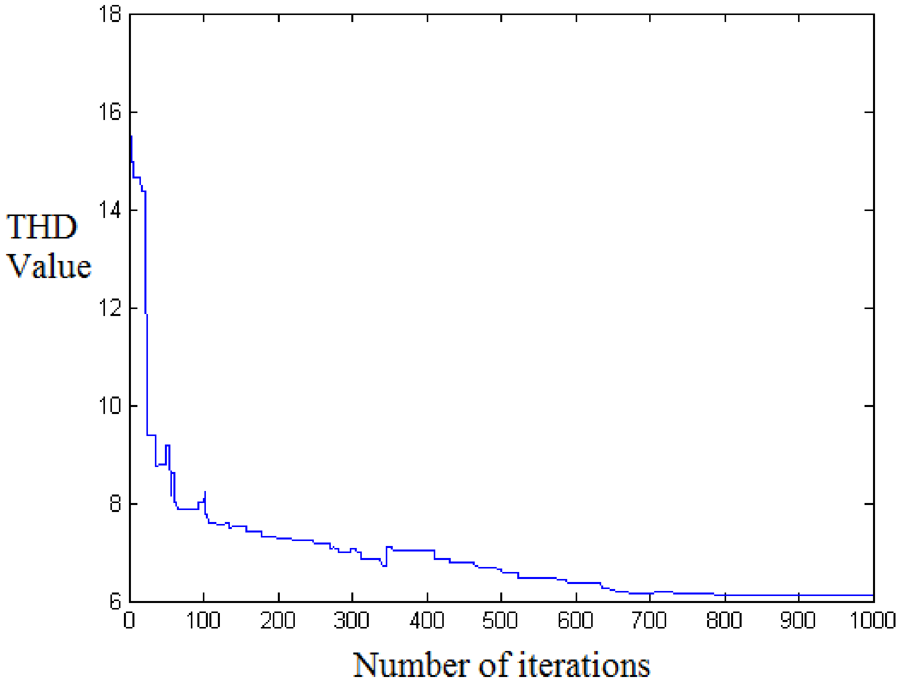

Fig. 3. The solutions convergence graphic for the 6 step inverter.

The goal of the algorithm was to obtain a waveform with the specified number of steps, with a value of THD as low's as possible in order to be inserted into the programmable source. What makes the presented algorithm outperforms other methods is that in the case of three steps, we have six variables, width and height of each step voltage.

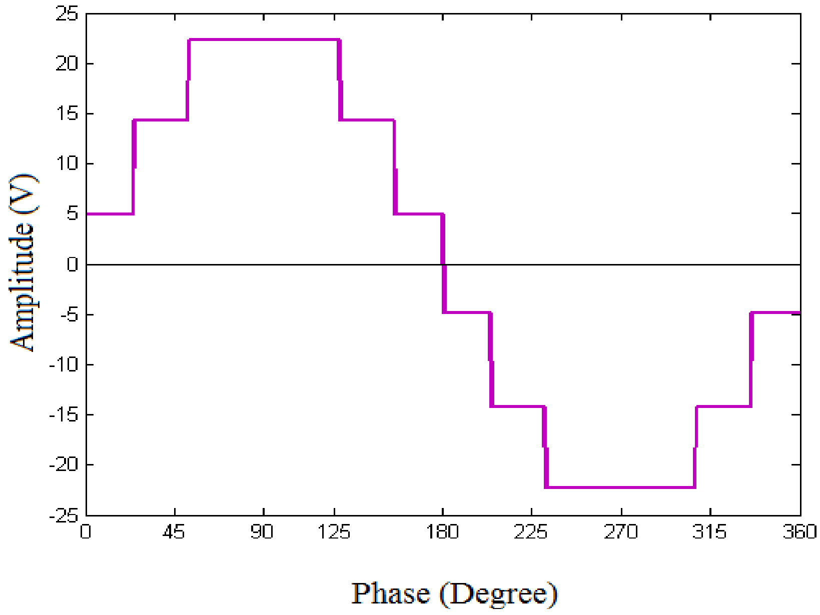

Fig. 4. The waveform shape for 3 steps inverter

Thus, the three waveform width must satisfy the condition that their sum is equal to π/2, and by testing a number of values which satisfy the basic condition to get the best solution with low THD.

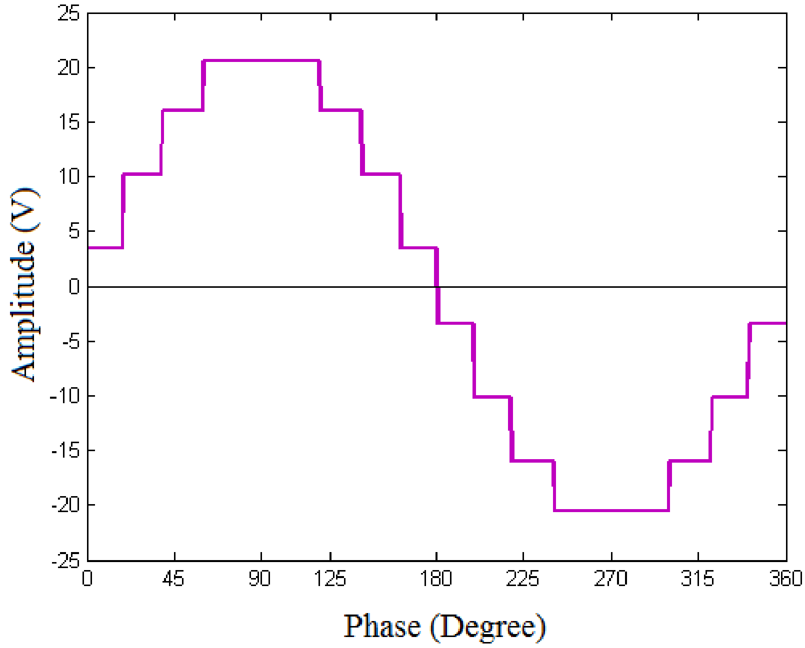

Fig. 5. The waveform shape for the 4 steps inverter

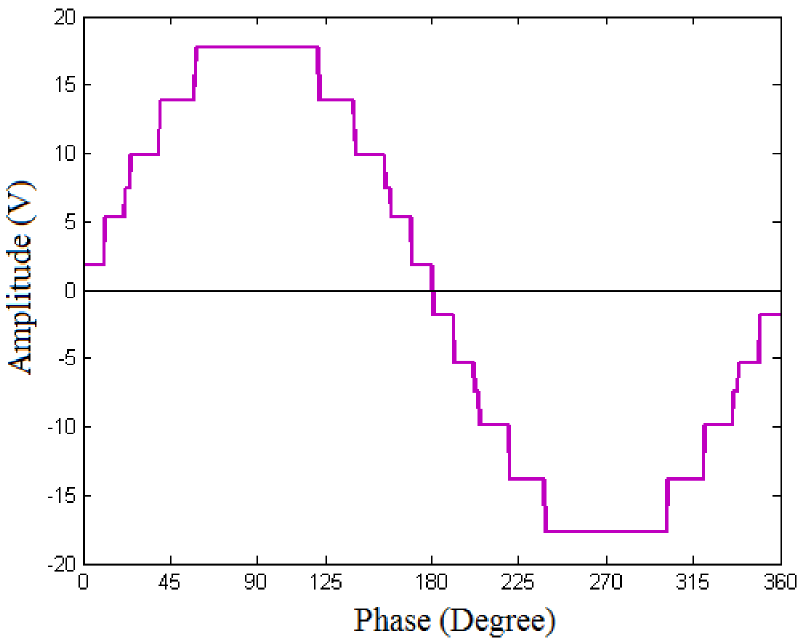

Fig. 6. The waveform shape for 6 steps

IV. EXPERIMENTAL RESULTS

The waveforms thus obtained are plotted in *figures 4, 5* and *6* are there are used for experiments. It must be notice that these waveforms must be processed to be placed in the programmable source [7, 8, 9].

Analyzing the waveforms, it can be seen that what makes them different from most of the literature is the variation of steps not only on the voltage level but also on the value of switching angle. Also, the obtained waveform is not starting from zero like the majority of waveforms in the literature and available in the library of programmable source. THD's values thus obtained are superior to those obtained by other methods.

The programmable source used for testing is an instrument from CTS series produced by California Instruments, which provides an efficient test solution in terms of value for money, which aims to verify the product compliance with a large number of testing standards in ac and dc current. The CTS Series of testing system offers the following advantages: Single-phase and three-phase systems for a wide range of power debited on the load; Data acquisition system with direct access to the PC bus provides high resolution and high sampling rate for accurate measurement and high transfer speeds, even in three phase mode, unlike other IEC test systems that provide a rate transfer limited by the IEEE-488 interface; test software PC-based for harmonics and flicker that offers real-time data color update and continuous monitoring of PASS / FAIL type; Support for European and Japanese standards; Simple utilization under Windows offering IEC test setup, data analysis, display and test reports in MS Word format; High resolution, no gap acquisition data storage to disk in ASCII format for post-acquisition analysis and reporting. Resumption of recorded test data step or fast - Fast Forward.

Single Step and Fast Forward replay of recorded test data.

Available in a choice of power levels ranging from 1250 VA to 30,000 VA, CTS Systems cover the complete range of single and three phase products that need testing to conform with existing and pending IEC standards.

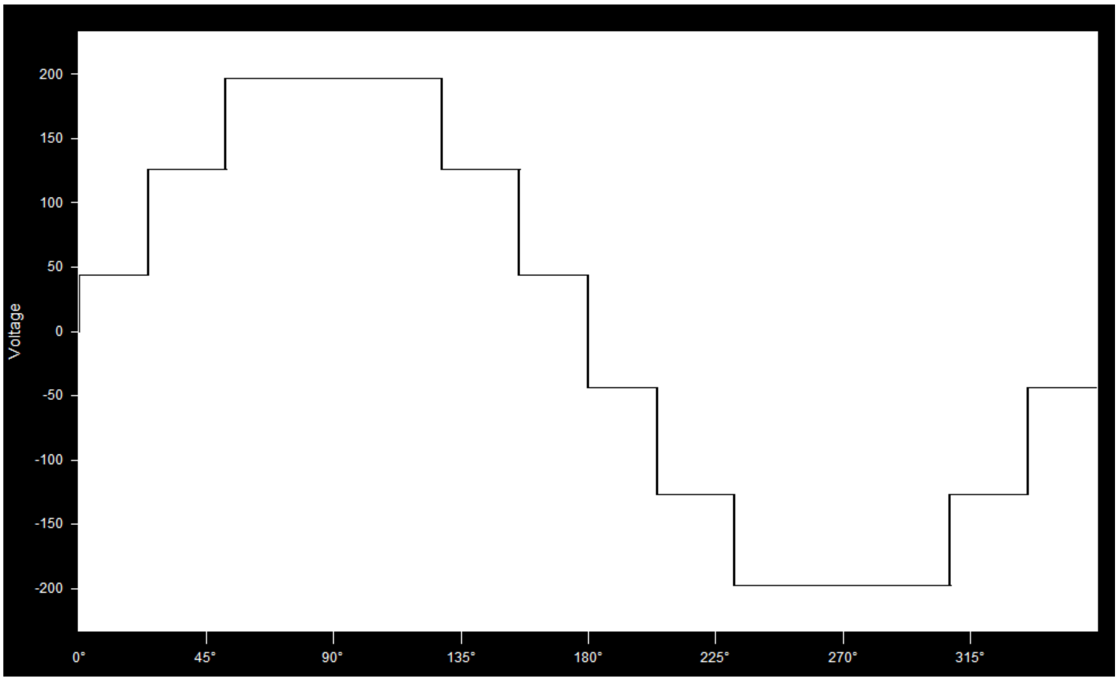

Fig.7. The ideal waveform of three steps inverter functioning with no load

All iX Series AC sources meet IEC requirements for low voltage distortion and offer arbitrary waveform generation, precision measurements, and waveform analysis capabilities for load voltage and current. AC power source real distortion is measured in real time during harmonics testing and any distortion is indicated that could affect the test results. All iX Series based CTS systems support full compliance IEC 61000-4 AC immunity test as well (certain options may be required).

The 1251RP source based on CTS system which can be used for realizing complete harmonics tests and flicker test with low power load and with an peak coefficient of the maximum current.

Source voltage distortion is measured in real-time during the harmonics test and any distortion that could affect the test results is clearly indicated.

A high speed digital signal processor based data acquisition system is used to implement the required IEC compliance measurement system. Direct access to the PC bus ensures a much higher data throughput capability than typically found in single box IEC test systems that use the IEEE-488 instrumentation bus to communicate with the PC.

In harmonics tests, there are available the following determinations: Voltage and Current time domain; Current Harmonics and IEC limits graph; AC Source Voltage Harmonics and IEC; limits graph; Numeric display of F, VRMS, IRMS, IFUND, IPEAK, PF, W, VA, THD.

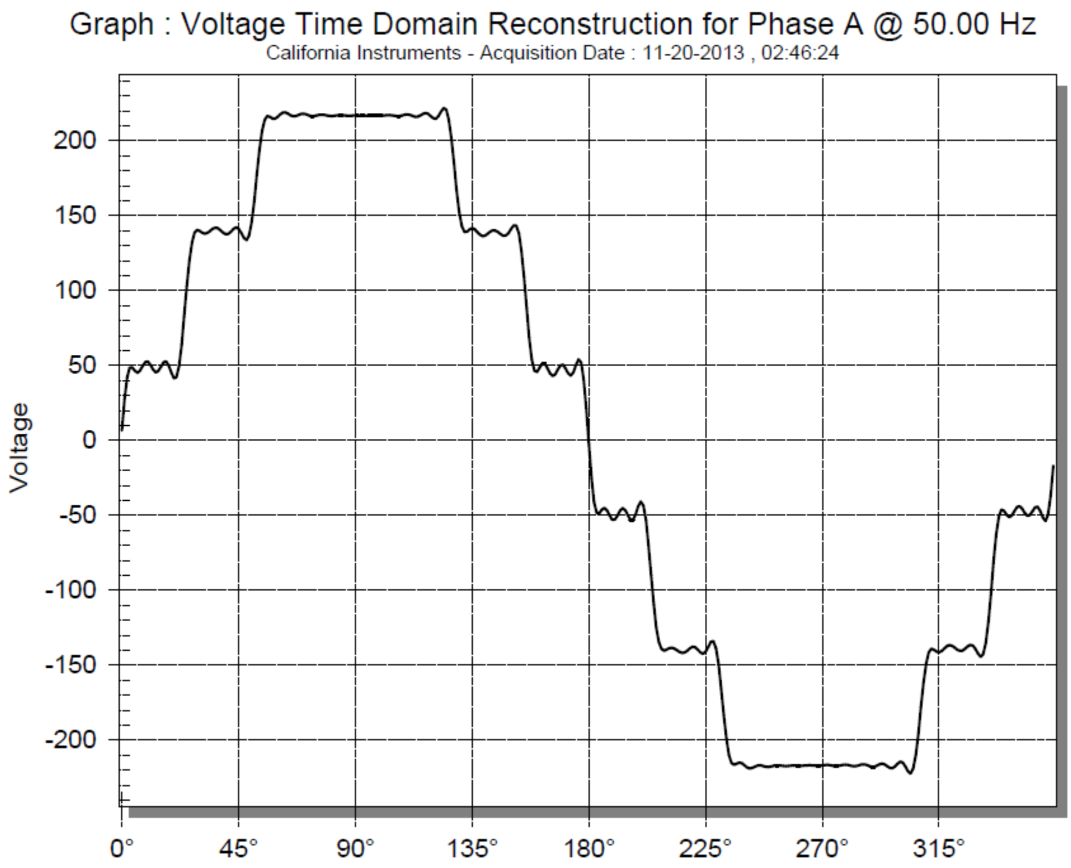

Fig. 8. The waveform obtained through the genetic algorithm, with the 3 steps inverter functioning on load

As load was used an induction motor (asynchronous) single-phase squirrel cage, with the following characteristics: Un=230 Vac; P=460 W; cosφ= 0.8; η=0.8. The load has been provided from the programmable source presented above, with the waveforms generated through the genetic algorithm presented in *figures 3, 4* and *5*. The waveforms used for controlling the multilevel inverters are also generated from the programmable source library. Using the developed software tool we performed the conversion of voltage levels and the waveforms format obtained from genetic algorithm at the levels and format required for supplying the load. In *figure 7*, the waveform thus obtained and placed into the programmable source. In load operation the waveform deviates from the ideal form presented above, as shown in *figure 8*. The same allure waveform can be noticed, less the existence of a ripple caused by the nonlinearity of the motor.

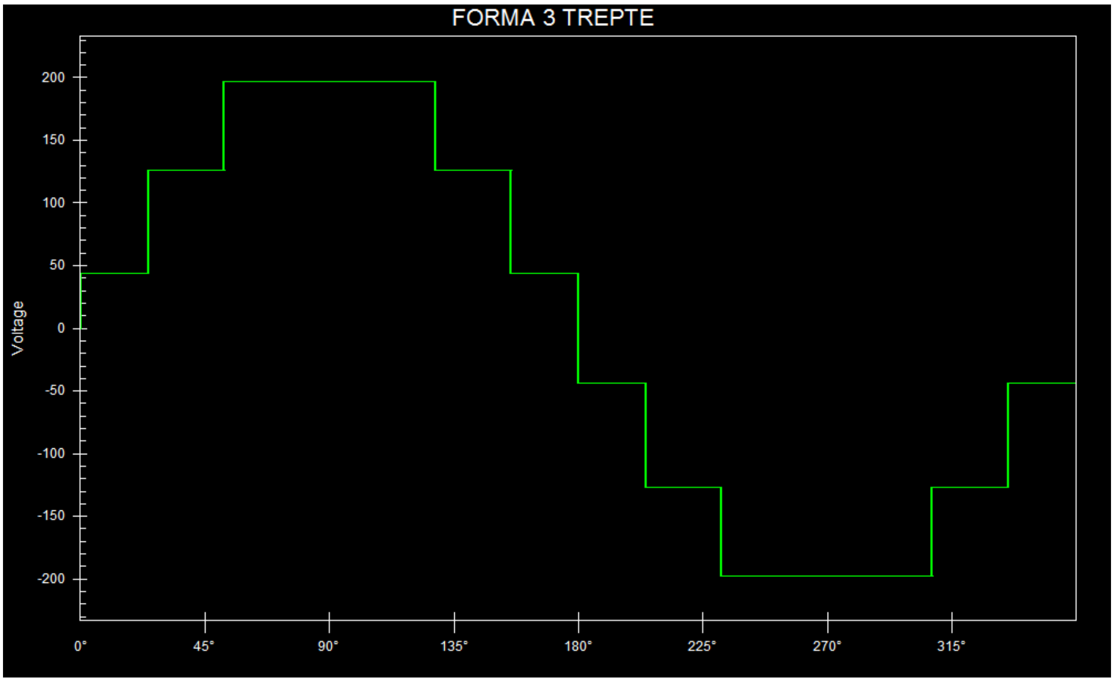

Fig.9. The waveform generated from the programmable source library of the 3 steps inverter operating at no load

In *figure 9* is shown the waveform generated by the programmable source library for the same type of inverter. In *figure 10* the experimental results are presented supplying the motor with the waveform from *figure 9*.

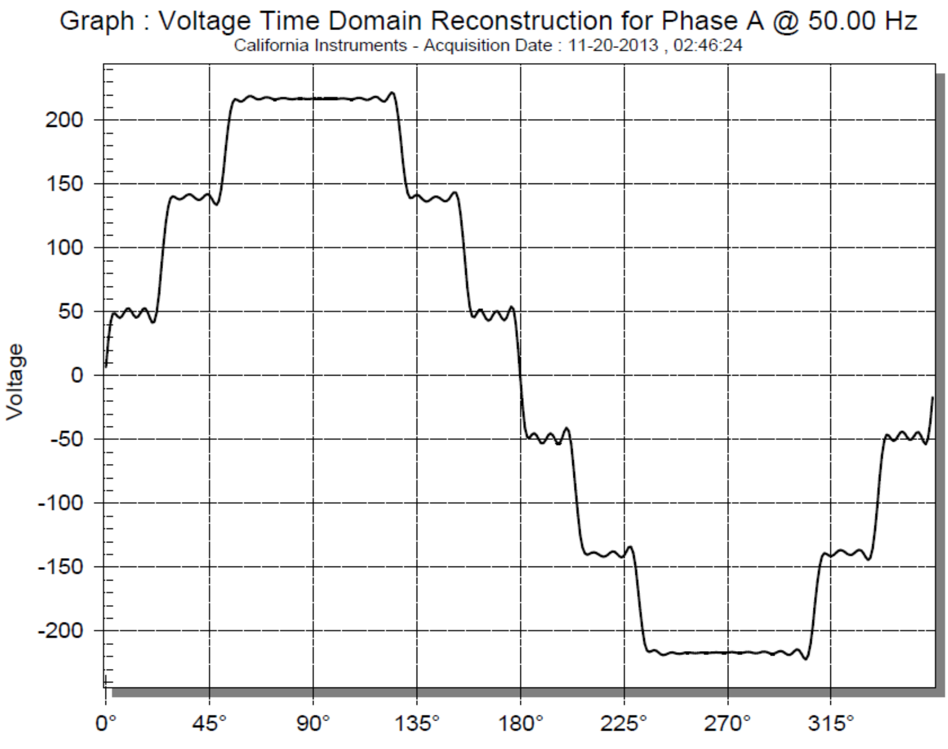

Fig. 10. The waveform generated from the programmable source library of the 3 steps inverter operating in load

V. CONCLUSIONS

In Table 3 the levels of harmonics up to order 49 for supplying the two waveforms are presented [10, 11].

Table 3. The Harmonics Levels

Acquisition Date : 11-20-2013 , 02:46:24
California Instruments
THD Voltage = 11.45 % THD Current = 0.00 %

	rms.	rel. (%)	Phase
Fund	227.890	100.00	0.00
3	1.560	0.68	17.80
5	3.820	1.68	176.00
7	6.450	2.83	358.40
9	6.160	2.70	176.30
11	2.270	1.00	170.00
13	15.930	6.99	358.00
15	14.360	6.30	358.10
17	1.920	0.84	5.40
19	1.170	0.51	4.60
21	2.240	0.98	359.40
23	3.090	1.36	177.10
25	1.810	0.79	175.70
27	5.830	2.56	2.10
29	5.980	2.62	3.60
31	1.460	0.64	9.70
33	1.610	0.71	8.80
35	1.550	0.68	9.30
37	2.000	0.88	185.90
39	1.510	0.66	187.40
41	2.860	1.25	12.90
43	3.180	1.40	15.10
45	1.080	0.47	21.20
47	1.640	0.72	20.60
49	1.390	0.61	22.50

Acquisition Date : 11-20-2013 , 02:54:44
California Instruments
THD Voltage = 16.85 % THD Current = 0.00 %

	rms.	rel. (%)	Phase
Fund	225.840	100.00	0.00
3	11.170	4.95	175.70
5	0.290	0.13	97.30
7	4.410	1.95	169.40
9	24.900	11.03	358.60
11	20.040	8.87	358.10
13	2.550	1.13	164.20
15	0.290	0.13	94.20
17	1.530	0.68	158.10
19	10.590	4.69	358.70
21	9.300	4.12	359.30
23	1.390	0.62	159.80
25	0.260	0.12	95.60
27	0.820	0.36	154.00
29	6.090	2.70	3.40
31	5.530	2.45	5.10
33	0.960	0.43	161.20
35	0.240	0.11	100.10
37	0.550	0.24	156.20
39	4.040	1.79	11.20
41	3.780	1.67	13.60
43	0.760	0.34	165.70
45	0.210	0.09	106.00
47	0.450	0.20	162.40
49	2.950	1.31	20.80

It can be seen that through the developed genetic algorithm, the third harmonic is reduced from 4.95% to 0.68%, which significantly increases the motor operation efficiency (decreasing its operating temperature). On the other hand, there is an increase in the level of the fifth-order and the seventh voltage harmonics. Fifth order harmonic increases to 1.68%, while the seventh order increases to 2.83%. In view of the fact that the two harmonic components determines the negative sequence and may result in oscillation operation, it is important that the harmonic components to be filtered by means of harmonic filters.

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