Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 11 Issue 1, January - 2024

Integrated Test Platform for Multi-Level Modular DC-AC Converters (MMC) for Total Harmonic Distortion Reduction (THD)

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***Abstract*— This paper focuses on the issues arising from the use of multi-level converters connected to renewable energy sources in traditional electric grids. The main element of interest in this application, the total harmonic distortion factor is analyzed, from various points of view: mathematical, Labview simulations and experimental laboratory determinations. The integrated test platform for Modular Multilevel Converter (MMC) designed to reduce total harmonic distortion (THD) injected into the power system, aims to develop a test system for MMC converters optimized by genetic algorithms, in order to reduce harmonic distortions of multilevel converters thereto connected. The paper analyzes the decision makers behind the choice of a certain type of multilevel converter for various applications, highlighting the elements that must be considered when connecting renewable energy sources to electricity networks. For a certain voltage level, the software genetic algorithm implemented in the test platform transmits the hardware disconnection command, so that the connection time of the conversion module will ensure a minimum THD.**

Keywords—power grid; power electronics; multilevel converter; harmonic distortion factor.

I. Introduction

In the last decades, the demand for energy generated by renewable sources has increased due to environmental problems and declining conventional fuel sources. Among the most frequently used renewable energy sources connected to the interconnected power system are the photovoltaic parks and wind farms. The regulation of the output voltage and frequency are the main problems in connecting these renewable sources to the system. Since the renewable sources produce DC voltage, respectively photovoltaic panels or fuel cells, DC to AC voltage inverters is used.

To reduce losses, the most important conversion problem to be solved is that the AC voltage injected into the system must have a minimum distortion factor. This requirement is achieved by minimizing the harmonic content injected into the system. The DC to AC voltage conversion is done with the help of inverters [1,2,3]. The diversification of inverter topologies was influenced by the development of offshore renewable energy sources, the issue of high voltage direct current transport and the synchronized voltage injection into the power system. In DC-AC conversion equipment, the important issue is the switching process which can be "soft" when the waveform is synthesized in the control circuits by pulse width modulation or "hard" when the synthesis is performed by controlling the static devices and the topology of the scheme used in the power circuit of the inverter. Currently, modular multilevel converters (MMCs) are developing rapidly and are widely used for emerging applications, such as medium or high voltage DC to AC conversion. The operation of MMC inverters is based on modules series connected on which the voltage drop is constant at the value determined by the number of modules used. Therefore, the connection time of each module must be determined so that the output voltage and current to have a minimum harmonic distortion. Total harmonic distortion (THD) is reduced by increasing the number of switched voltage levels. It is obvious that an output voltage with a minimum total harmonic distortion is desirable but increasing the number of voltage levels requires more switching devices and complicates control circuits [4,5,6].

The paper proposal presents an integrated test platform for multilevel modular DC-AC (MMC) converters designed to reduce the total harmonic distortion (THD) injected into the interconnected system. The aim is to develop a test system for MMC converters optimized by genetic algorithms, designed to reduce the harmonic distortions of multilevel converters connected to an interconnected power system. It is necessary that the converters optimized by genetic algorithms be tested on the platform, starting from a predetermined population of individuals, randomly generated, each of them. representing a possible set of operating parameters of the analyzed converter [7, 8].

To determine the optimal solution of the implemented genetic algorithm, the test platform must be able to determine the mean square error between the waveform provided by the converter and the sine waveform to be obtained. It is necessary that the test platform be capable through the equipment provided, to determine the performance of all types of converters and to optimize the waveform generated by the converter by implementing filters that reduce harmonics of different frequency from the interconnected network harmonics. This can reduce the losses in the transmission and distribution system. Last but not least, it is necessary that the platform be able to determine the harmonic distortion generated by a software-generated waveform. On the platform it is also necessary to be possible to improve the performance of MMC type DC-AC converters used in the energy system. Usually for existing or newly designed and manufactured converters on the market, the most used solution for limiting voltage harmonics is the use of passive filters, and the system must be designed so as to allow the choice of the solution that minimizes the distortion factor.

II. Theoretical Considerations

Unlike other applications of multilevel converters, the use in DC-AC conversion of the voltage provided by photovoltaic facilities has an important advantage, namely that the injected voltage has a fixed frequency. The drawbacks are related to the high voltage and power to be injected into the system, as well as power quality issues. One must keep in mind that the network in which the voltage is injected is of infinite power and has a very different behavior from consumers who fall into the category of nonlinear loads. Therefore, any DC-AC converter solution must consider two aspects:

• choosing the static switching device depending on the converter MMC type.

• the control principle used to obtain a sinusoidal voltage having the same frequency as the mains frequency.

The most common multilevel inverters topologies through which the division of the direct voltage provided by the renewable PV source is performed at the input are the multilevel inverters with diodes DC-MLI (Fig. 1.), the multilevel inverters with flying capacitor FC-MLI (Fig. 2) and the multi-level inverters with H-bridge in cascade CHB-MLI (Fig. 3).

Together with the converter topologies, current research in the field of multilevel converters is focused towards finding the optimal switching solution [9]. The control strategy aims to minimize the harmonic spectrum of the output values and to minimize switching losses [10, 11].

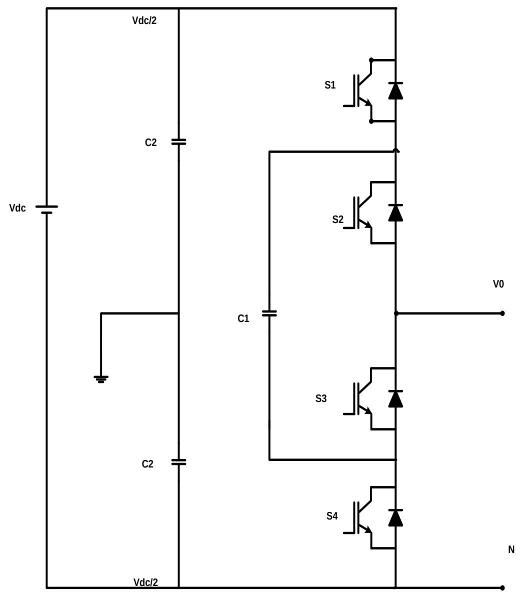

Fig. 1. *Three-level DC-MLI*

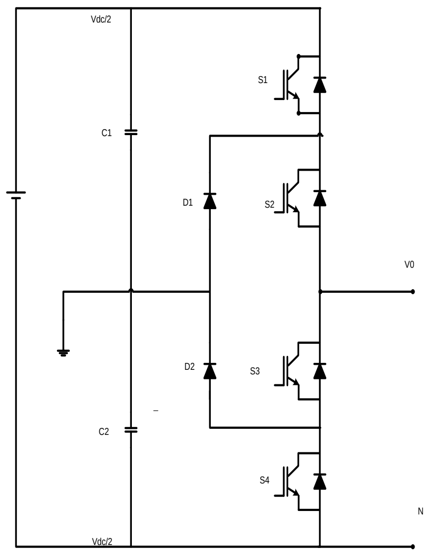

Fig. 2.*Three-level FC-MLI*

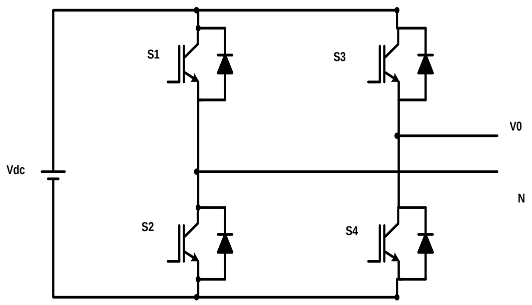

Fig. 3.*Three-level CHB-MLI*

By series connecting n switching circuits, connected to DC voltage sources, it is possible to sum the output voltages that can be of the same or of a different value. The optimization of the waveform can also consider another variable parameter, namely the switching angles. There are three possibilities to optimize the waveform of multilevel inverters, depending on the following variable parameters:

• Constant voltage steps and variable switching angle.

• Variable voltage steps and constant switching angle.

• Variable voltage steps and variable switching angle.

An element that must be taken into account in the synthesis of the waveform is related to the slope of a sinusoidal function in the origin, a function which can be synthesized with n switching circuits series connected, output voltages with 2n levels, in the situation where the voltage at the output of the inverter does not contain step voltage 0 volts and output voltage with (2n + 1) levels, in case the output voltage contains the zero voltage step.

The multilevel synthesis of the waveform has been approached by various mathematical procedures. They allow steps waveform synthesis as the best approximation of the sinusoidal output waveform and are based on the Fourier series and the Wavelet transform.

Waveform synthesis is based on the Fourier Series expansions, in which case the scaling function $\varphi_n(x)$ is defined as follows for n =…-2, -1, 0, 1, 2, …:

$$\varphi_n(x) = \varphi(x - n\alpha) \tag{1}$$

The equation defines a set of rectangular pulses of unitary amplitude and an angle of α. The position of the pulse on the x-axis depends on the parameter n.

If the variable x belongs to an interval [a, b], with the length $k\alpha$ ($k \geq 1$), the functions $\varphi_n(x)$ satisfy to the following two conditions:

$$\left|\varphi_n\right|^2 = \int_a^b \varphi_n^{\;2}(x)dx = \alpha\,, \tag{2}$$

respectively:

$$\int_a^b \varphi_k(x)\cdot\varphi_m(x)dx = 0, k \neq m \tag{3}$$

Development (1) defines a set of orthogonal functions called an orthogonal base. Since all functions $\varphi_n(x)$ have their norm equal to α, this base is called an orthonormal base.

The development of the function *f(x)* in a generalized Fourier series is related to a set of scaling functions as follows:

$$f(x) = \sum_{n=0}^{n} c_n \varphi_n(x) \tag{4}$$

where:

$$c_n = \frac{(f, \varphi_n(x))}{\left|\varphi_n\right|^2} = \frac{\int_a^b f(x)\cdot\varphi_n(x)\cdot dx}{\alpha} \tag{5}$$

The development (3) is valid for any function $f(x)$. The Fourier series contains an infinite number of elements and allow to approximate a function $f(x)$ by an infinite set (a sum) of adequately scaled functions $\varphi_n(x)$. Particularly, it is possible to expand a function $f(x) = \sin(x)$ by summing an infinite set of rectangular pulses. It is in opposition to a typical application of the Fourier series where any function *f(x)* is developed as a set of harmonics. According to (3) and (4) the expansion of sin(x) in the given interval is:

$$\sin(x) = \sum_{n=0}^{\infty}\left\{\frac{\int_a^b \sin(x)\cdot\varphi_n(x)\cdot dx}{\alpha}\varphi_n(x)\right\}, x \in \langle a, b \rangle \tag{6}$$

Equation (6) defines a series of consecutive rectangular pulses represented by functions $\varphi_n(x)$. The value for each pulse amplitude is different and is determined by calculating its integral. Rectangular pulses are one of the most important waveforms of the output voltage of an inverter. Thus, the composition of stepped waveforms using rectangular pulses is not a novel approach, but it is used mostly in the addition of the waveforms along the vertical axis. The resulting phase voltage was synthesized by adding the voltages generated by the different modules of a cascaded inverter. The presented proposal relates on the addition of pulses "along x axis" or in a time scale. Consecutive pulses form the resulting voltage or current of the converter.

III. Simulation

The analysis of the MMC solutions currently used for DC-AC conversion highlights the advantages and drawbacks but indicates the research areas that need to be further developed. The two-level inverter has the lowest cost and weight compared to the other topologies, but has a large total harmonic distortion THD value, approximately 40% when the commutation is on the fundamental harmonic. To the weight and cost calculation, the cost and weight of the needed filter must be added since a 40% harmonic distortion on the output voltage exceeds the limit.

The cost and weight of the five-level inverter seems to be better than the cost and weight of the nine-level inverter. By increasing the number of levels in the inverter a increase in cost and weight appears. The advantage of the nine-level inverter is in the THD value, which is smaller, the total THD for a nine-level inverter is 7% and for a five-level inverter is 17%. Nonetheless a filter is required in both cases, so a five-level inverter and a filter seem to be the better solution [12].

The flying capacitor multilevel inverter has the smallest power loss of all types since there are no diodes in this configuration. For instance, the power loss in a five-level flying capacitor multilevel inverter with maximum load is 625W [12]. First, this configuration has the highest weight of all which makes it impractical in applications embedded later in another configurations. Secondly, the cost of this inverter is the highest of them all. The flying capacitor multilevel inverter can be used in circumstances where the loss of power takes precedence overweight and cost.

The cascaded H-bridge multilevel inverter has the smallest weight and cost among the multi-level inverters but also the highest losses. This invertor can be used in applications where cost and weight are more important than the power loss.

This analysis of the multi-level inverters highlights the set of problems that arise in connecting the renewable energy sources to the power grid [13]. The main factor that must be considered is the harmonic distortion, which should be minimal, at the power grids designated frequency and the fact that the grid's frequency is fixed, which constitutes an advantage when choosing the type of converter needed.

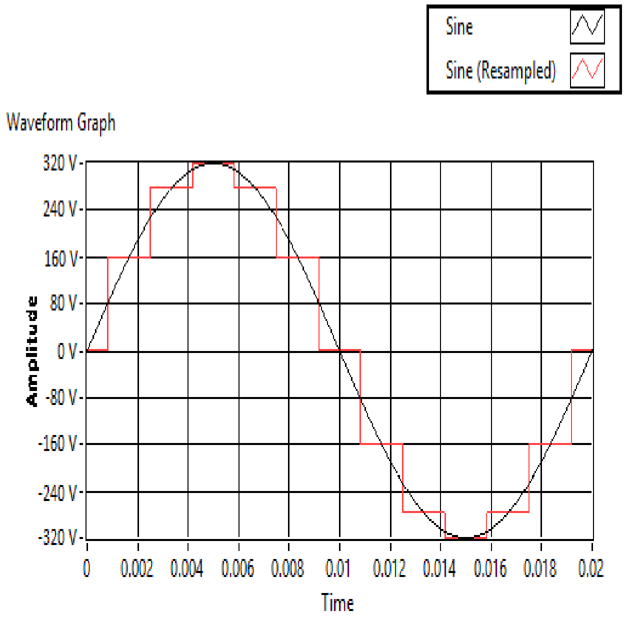

Fig.4. *The approximation of the function f(x) = sin x for N = 24 (α = π/12).*

Practically, in power electronics applications, the approximation of a sinusoidal waveform is achieved using a finite number N of the series members. The accuracy of approximation increases with N. Also, the most important criterion of the accuracy or rather the quality of approximated waveforms is the THD, namely the total harmonic distortion. [14, 15]. A very simple example of a percentage approximation is shown in Fig. 4. The stepped waveform was obtained after approximations based on the set defined according to (1) and (2). The simulations have used the Labview Software from National Instruments, which allows a simple implementation and an ease of use. The implemented virtual instrument allows for choosing the number of steps. Thus, we can see various values of THD in relation to the number of steps. It is easy to observe that with the number of steps, the THD value decreases. The virtual instrument can also display the waveforms, which was the goal of this simulation all along. By comparing the simulation results with the experimental results, one can have a better picture of the practical problems that arise when connecting a load and of the difficulty to obtain a better THD value.

The results of the Fourier approximation for various values of *N* are presented in Table 1. F_N designates the number of steps from the given interval – in this case [0,2*π*]. The N_{FN} parameter designates the necessary number of voltage sources and THD is the total harmonic distortion. Of course, the end goal is the THD value, but as discussed before, one must not forget the importance of *N*. This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

TABLE I. THD VALUES RESULTED FROM THE SIMULATION

F_N	α	N_{FN}	THD (%)
F_N=2	π	1	46.58
F_N=6	π/3	2	29.22
F_N=12	π/6	3	13.52
F_N=16	π/8	4	8.89
F_N=24	π/12	6	5.9

IV. EXPERIMENTAL RESULTS

Simulated waveforms should be used for experimental validation, demonstrating the concept of emulator for optimizing frequency converters. Integrated test platform for multi-level modular DC-AC converters (MMCs) designed to reduce total harmonic distortion, is based on the 15003iX-CTS 400 [16] programmable source, and features waveforms in the CiGui iX software library generated by unoptimized multilevel converters. It also accepts software stored in digital oscilloscopes compatible with the 15003iX-CTS 400 programmable source.

In the case of multilevel converters, obtaining a reasonable distortion factor was achieved by optimizing the target waveform using the Newton Raphson method. One solution for reducing the distortion factor of existing waveforms in the programmable source database is to use other optimization algorithms.

Genetic algorithms are generally used to solve problems of optimization, planning or non-linear, multi-criteria check. These are a set of adaptive procedures that find the solution to a problem investigated through a mechanism of natural selection and genetic evolution.

The voltage waveforms obtained by this technique and the degree of reduction of the total harmonic distortion can be compared by analyzing the results obtained from the supply of a consumer with a voltage classically generated by DC-AC conversion, using a multilevel converter.

The advantages of using the test platform in analyzing the performance of MMC inverters can be highlighted by comparing the results obtained by feeding the load with a non-optimized voltage, generated from the library of the programmable source and with an optimized voltage, generated by genetic algorithm [17].

To evaluate the THD factor values a three-phase squirrel cage induction motor phase having the following characteristics: *Un*= 230 Vac, *P* = 460 W, cos φ = 0.8, η = 0.8 was used. The motor was supplied through by the programmable source, successively with the waveforms generated by a genetic algorithm for inverters having different levels of pulses and with similar waveforms generated by the programmable source.

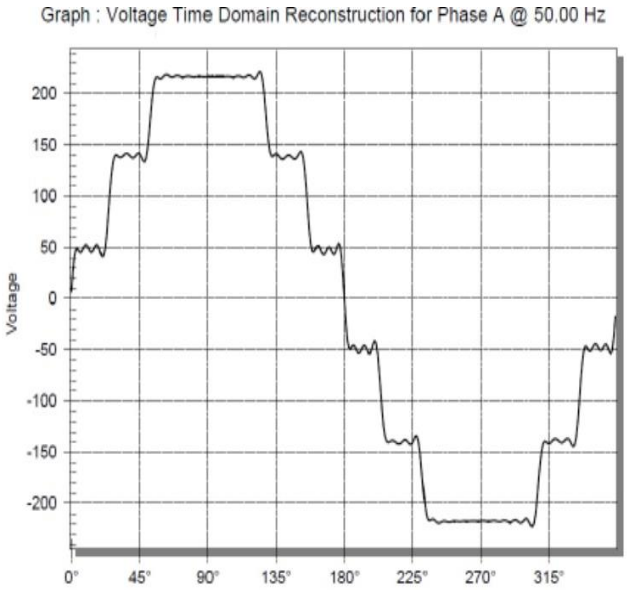

Fig.5 *Voltage generated by the programmable source database*

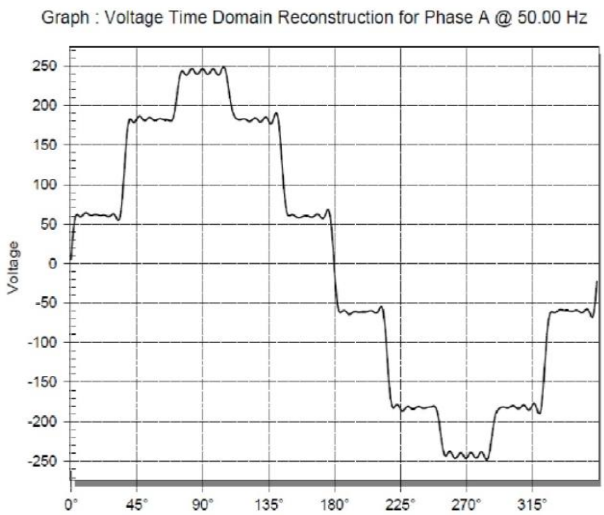

Fig 6. *Voltage generated by genetic algorithm*

One may observe almost the same aspect of the two voltage waveforms. The ripple is inherently caused by the nonlinearity of the load.

TABLE II. THD VALUES RESULTED FIG. 5.

California Instruments THD Voltage = 16.85 %			
	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

TABLE III. THD VALUES RESULTED FIG. 6

California Instruments THD Voltage = 11.45 %			
	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

One may see that the third harmonic is reduced from 4.95% to 0.68%, which contributes significantly to an increased efficiency of the motor (the case temperature also lowered).

On the other hand, the level of the fifth order and the seventh order harmonics increased. Fifth order harmonic increased to 1.68% and the seventh order increased to 2.83%. The presence of these harmonics may cause oscillations at the motor shaft. Thus, it is important that these harmonic components to be filtered with harmonic filters.

Regarding the MMC converter test system (Fig. 7), it should be noted that the important part of the system is the power analyzer. It must be carried out in accordance with IEC standards, which provide detailed information on voltage and current.

The measurement of harmonics and inter-harmonics is performed in real time, without lag, in order to be in full accordance with the latest modification of the IEC 61000-4-7 standard [18].

The voltage at the DC source and the power injected into the tested converter must be monitored continuously throughout the test. It is necessary to compare the voltage distortions and the characteristics of the current harmonics with the class limits imposed by the IEC standards to determine whether or not the equipment under test passes the test.

The test limits are stored in a database, which can be updated without the need to modify the software.

Other software changes that may occur as a result of changing IEC standards are updated by installing the latest software version.

All IEC harmonic tests must be accessible via a control window displayed on the PC monitor.

During the test it is necessary to update in real time the display of the voltage waveforms, in the time domain and of the parameters of the tested converter, such as V_{RMS}, I_{RMS}, I_{FUND} I_{PEAK}, the active and apparent power and the power factor.

The current harmonic window will display the instantaneous harmonics. During the entire test, it must be possible to indicate that it is in the PASS test curve or in the FAIL rejection curve if the limits has been exceeded.

Fig. 7. *Integrated test platform for modular multi-level DC-AC converters (MMCs)*

It must be possible to monitor the output voltage distortion of the DC-AC converter during the entire test. The following characteristics of the analyzed MMC converter must be graphically available in the harmonic tests:

• voltage ranges and updated values at the time of testing.

• current harmonics and limit values imposed by the IEC standard.

• voltage source distortion and IEC limit values.

• alternating current source voltage harmonics and IEC limit values.

From an experimental point of view, the two control variants of the multilevel inverters - with 12 and 24 voltage steps have been tested.

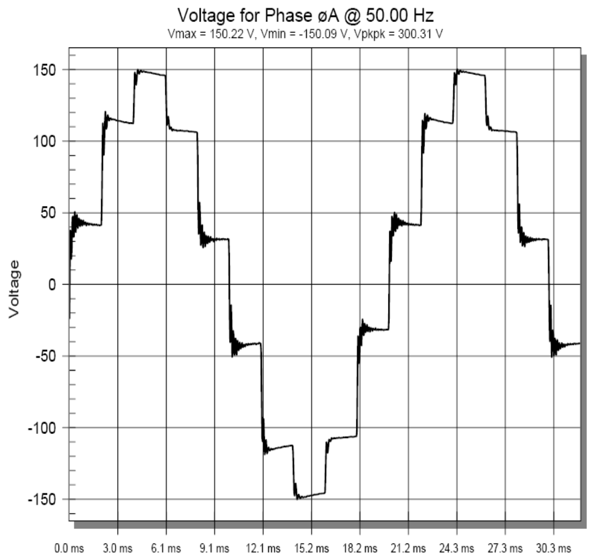

Fig. 8. *12 pulses voltage*

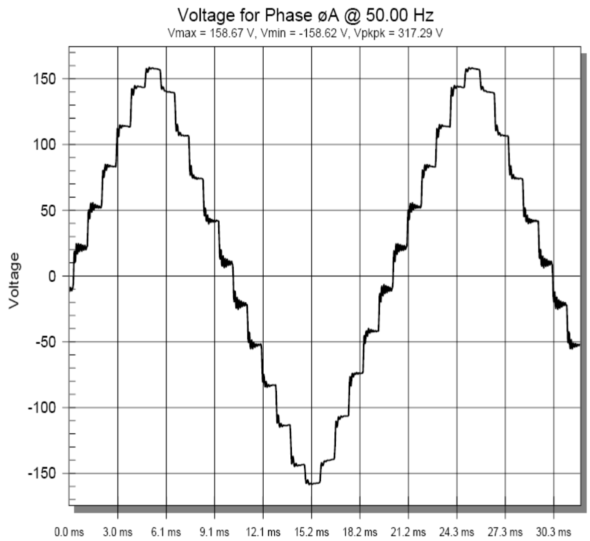

Fig. 9. *24 pulses voltage*

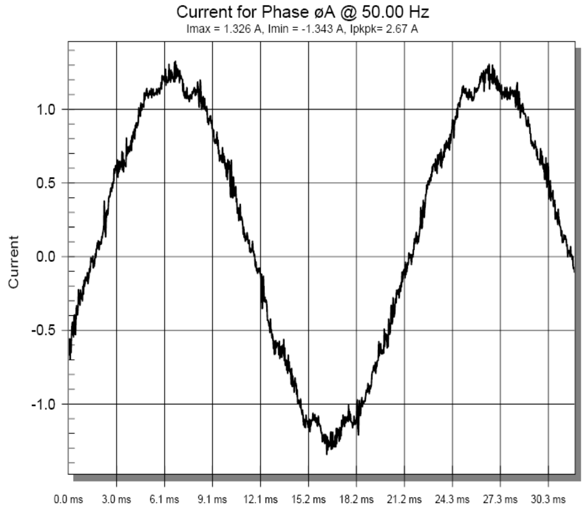

Fig. 10. *12 pulses load current*

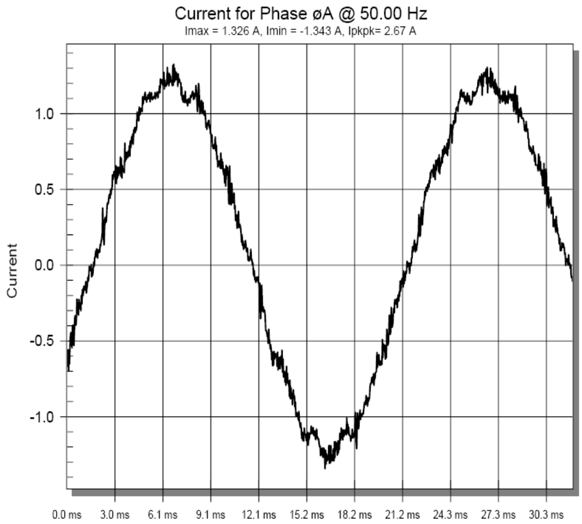

Fig. 11. *24 pulses load current*

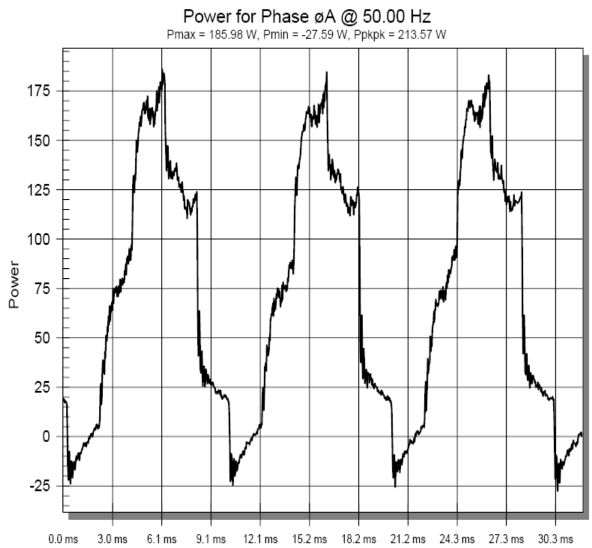

Fig. 12. *12 pulses active power*

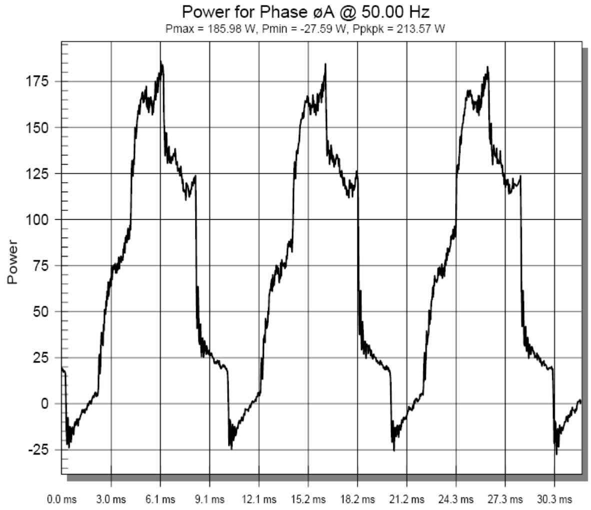

Fig. 13. *24 pulses active power*

The tests were made having as charge a 4F130-4A type squirrel cage induction motor having the following parameters: rated power P=0.37 kW, speed n=1350 rpm, power factor $\cos\varphi$=0.71, rated voltage U_n=220 V, degree of protection IP44.

The measured values for the winding resistance are 27.27 Ω and 64.57 mH for the inductance [19, 20, 21]. With the aid of the oscilloscope, the waveforms for the phase voltage (Fig. 8., Fig.9.), the absorbed phase current (Fig. 10., Fig. 11) and active power were obtained. (Fig. 12., Fig. 13.).

V. Conclusions

The choice of the inverter topology should be based on the invertor use. Each has advantages and drawbacks. By increasing the number of voltages steps the THD value will drop (as seen in Table IV) on the other hand the cost and weight of the equipment will increase. Also, since the switching angles are not identical, each switch will have a separate control circuit.

To determine the optimal algorithm solution implemented on the integrated test platform for multilevel modular converters (MMC), the mean square error between the waveform provided by the converter and the sine waveform needed to be obtained was determined. The model was tested by simulation, its convergence being experimentally validated.

The synthesized waveform was tested experimentally for two types of multilevel converters, namely with three and six steps (respectively with 12 and 24 pulses) in two different situations. In the first case, the waveform from the developed genetic algorithm was used, and in the second case, the waveform commonly used for these types of inverters from the programmable source library. The results (see Table IV) highlight the performance of the developed algorithm. Thus, for the three-stage and 12-pulse inverter, the total harmonic distortion obtained by the control generated by the developed algorithm is 11.45% compared to the value of 19.85% resulting from the conventional control.

TABLE IV. CHARACTERISTIC SIZES WHEN POWER SUPPLY WITH MULTILEVEL INVERTER

Converter type	12 pulses	24 pulses
Date	15.04.2021	15.04.2021
Time	12:24:30	12:43:54
Fund [Hz]	50	50
V_{RMS} [V]	141.98	142.09
V_{DC} [V]	0.00	0.00
THD_U [%]	11.45	5.85
I_{RMS} [A]	1.205	1.181
I_{CF} [A]	1.552	1.536
THD_I [%]	4.46	2.73
Power [W]	147	146
PF	0.863	0.874

For the six-stage inverter (24 pulses) the total harmonic distortion obtained by the control generated by the genetic algorithm is 5.85% compared to the value of 11.77% [17] from the conventional control. It should be noted that the value of 5.85% of the total harmonic voltage distortion factor is below the 8% limit stipulated in the standards.

This is a remarkable result, as no additional filtering measures are needed in this situation, which obviously generates additional retrofit and implicit maintenance costs. However, if every harmonic generated by the use of the genetic algorithm (as seen in Table V) is analyzed it must be noted the high values of the 3, 9 and 11 order harmonics. However, the test platform has the possibility to correct these issues, by changing the duration of the voltage pulses that generate these harmonics [18, 19].

TABLE V. HARMONICS GENERATED BY MULTILEVEL CONVERTERS

Characteristic size	12 pulses	24 pulses
Voltage distortion factor K_D	16.92	11.8
Current distortion factor K_D	4.27	2.51
Fundamental component	97.24	98.19
3^{rd} harmonic component	4.80	9.5
5^{th} harmonic component	0.13	2.60
7^{th} harmonic component	1.93	0.31
9^{th} harmonic component	10.72	0.26
11^{th} harmoniccomponent	8.68	0.10
13^{th} harmonic component	1.10	0.18
15^{th} harmonic component	0.12	0.62
17^{th} harmonic component	0.68	0.58

The distortion factor in such applications needs to follow specific standards, especially since the harmonic distortions generated by the inverter (Table V) spread from the renewable sources to conventional sources increasing the final CPT (Own Technological Consumption) parameter [20, 21].

References

[1] Yang Wang, Ahmet Aksoz, Thomas Geury, Salih Baris Ozturk, Omer Cihan Kivanc and Omar Hegazy, “A Review of Modular Multilevel Converters for Stationary Applications” Applied Sciences, ISSN 2076-3417, 2020, Vol. 10, Issue 7719, doi:10.3390/app. 10217719.

[2] “Multilevel Inverters, Control Methods and Advanced Power Electronic Applications”, ISBN 978-0-323-90217-5, Published 2021, Imprint Academic Press, Copyright © 2021 Elsevier Inc., DOI: https://doi.org/10.1016/C2020-0-03579-6.

[3] Hanying Gao, Xiangnan Liu, Mingjie Ren, Shuai Feng and Zhiying Li, “A Novel Multilevel Controller”, *Electronics* 2021, *10*(10), 1222, https://doi.org/10.3390/electronics10101222 - 20 May 2021.

[4] Liqaa Alhafadhi, Jiashen Teh, Ching-Ming Lai and Mohamed Salem, “Predictive Adaptive Filter for Reducing Total Harmonics Distortion in PV Systems”, Energies 2020, Vol. 13, Issue 3286; doi:10.3390/en 13123286.

[5] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, “Overview of Control and Grid Synchronization for Distributed Power Generation Systems,” IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[6] F. Blaabjerg, R. Teodorescu, M. Lissere, A. Timbus, Overview of Control and Grid Synchronization for Distributed Power Generation Systems, IEEE Transactions on Industrial Electronics, Vol. 53, No. 5, pp. 1398-1409.

[7] Frede Blaabjerg, Tomislav Dragicevic and Pooya Davari, “Applications of Power Electronics”, *Electronics* 2019, *8*(4), 465; https://doi.org/10.3390/electronics8040465 - 25 Apr 2019.

[8] A. Salami, B. Bayat, „Total Harmonic Distortion Minimization of Multilevel Converters Using Genetic Algorithms”, Applied Mathematics, ISSN Print: 2152-7385, 2013, Vol. 4, pp: 1023-1027, http://dx.doi.org/10.4236/am.2013.47139.

[9] Emmanuel Hernández-Mayoral, Efraín Dueñas-Reyes, Reynaldo Iracheta-Cortez, Eduardo Campos-Mercado Vicente Torres-García and Rafael Uriza-Gosebruch, “Modeling and Validation of the Switching Techniques Applied to Back-to-Back Power Converter Connected to a DFIG-Based Wind Turbine for Harmonic Analysis”, *Electronics* 2021, *10*(23), 3046; https://doi.org/10.3390/electronics10233046 - 06 Dec 2021.

[10] Buzdugan M.I., Balan H., Munteanu, R., Munteanu, R. A., “A Practical Procedure in Assessing Power Quality in Power Converters”, Management of Technological Changes, Book 1, 7th International Conference on Management of Technological Changes Location: Alexandroupolis, Greece, 01-03 Sept. 2011, pp. 481-484, ISBN: 978-960-99486-2-3, Document Type: Proceedings Paper.

[11] Balan, H., Buzdugan, M., Vadan, I., Simion, E., Karaissas, P., Hybrid Commutation Converter in HVDC Systems. Materials Science Forum 670, pg. 415-424, ISBN: 978-087849215-2, ISSN: 0255-5476, CODEN: MSFOE, DOI: 10.4028/www.scientific.net/MSF.670.415, Document Type: Proceedings Paper (Web of Science), Conference Paper (Scopus).

[12] Buzdugan, Mircea; Balan, Horia, "Performances of the Anti-perturbation Filters for Current Distortion Factor Reduction", Applied and Theoretical Electricity (ICATE), 2014 International Conference on, 23-25 Oct. 2014, Craiova, Romania, Pages: 1 – 6, Publisher: IEEE, DOI: 10.1109/ICATE.2014.6972657.

[13] Horia Balan, Radu Tirnovan, Mircea I. Buzdugan, "Commutation Technique in the Supply of Electromagnetic Actuators", IET Power Electronics, Volume 7, Issue 1, January 2014, pp. 132 – 140, DOI:10.1049/iet-pel.2013.0172, ISSN 1755-4535.

[14] Aiello, M.; Cataliotti, A.; Favuzza, S.; Graditi, G. "Theoretical and Experimental Comparison of Total Harmonic Distortion Factors for the Evaluation of Harmonic and Interharmonic Pollution of Grid-Connected Photovoltaic Systems", IEEE Transaction on Power Delivery. July 2006, Volume 21, Issue 3, Pages 1390-1397, DOI:10.1109/TPWRD.2005.860231.

[15] Mustafa Ergin Şahin and Frede Blaabjerg, "A Hybrid PV-Battery/Supercapacitor System and a Basic Active Power Control Proposal in MATLAB/Simulink",*Electronics* 2020, *9*(1), 129; https://doi.org/10.3390/electronics9010129 - 09 Jan 2020.

[16] Compliance Test System - User Manual CTS 3.0, California Instruments.

[17] Laslo Horatiu Dacian; Varodi, Traian, The Reduction of Total Harmonic Distortion for the Multilevel Converter using Genetic Algorithms Optimization Method, Carpathian Journal of Electrical Engineering, ISSN 1843-7583, 2018, Vol. 12, Issue 1, pp 7-21.

[18] IEC 61000-4-7: 2002 Electromagnetic compatibility (EMC) Part 4: Testing and Measurement Techniques Section 7: General Guide on Harmonics and Interharmonics Measurements and Instrumentation for Power Supply Systems and Equipment Connected Thereto. DOI: 10.3403/02743713.

[19] Buzdugan M., Ciugudeanu C., Campianu A., "Power Quality of PV Multilevel Inverters in Residential Environment", Renewable Energy and Power Quality Journal, Vol. No. 18, June 2020.

[20] Balan H., Buzdugan M.I., Karaisas P., "Fault Identification on Electrical Machines Based on Experimental Analysis", Lecture Notes in Mechanical Engineering, ISSN: 2195-4356, Pages: 611-630, 2014, Springer Berlin Heidelberg.

[21] Balan, H., Buzdugan, M.I., Botezan, A., Munteanu, R.A., Karaissas, P., Psomopoulos, C., "Testing Wind Variable Speed Driving Systems for Conducted Interferences", SPEEDAM 2012, Sorrento, Italy, 20-22 June 2012, Code92961, Article number 6264482, Pages 565-570, ISBN: 978-146731299-8,DOI: 10.1109/SPEEDAM.2012. 6264482, Document Type: Conference Paper.