Multilevel Converters use for Connecting Renewable Sources to Power Systems

Claudiu Bâlc, Raluca Oglejan, Horia Bălan, Mircea Buzdugan, Cristina Chiorean

Electrical Engineering Department Technical University of Cluj-Napoca

Abstract—This paper centers around the problems that arise from employing multilevel converters to connect renewable energy sources with the traditional power grid. 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 determinations in a laboratory model. Further, we analyze the decision factors behind choosing a certain type of multilevel converter for various applications, highlighting the elements which have to be taken into account when connecting renewable energy sources to the power grid.

Keywords— inverter, power grid, multilevel conveter, harmonic distortion factor

1. INTRODUCTION

Classical sources of energy are commonly placed in economically convenient places and are producing most of the electrical energy, which is being distributed by aerial or underground transmission lines. Monitoring and controlling the systems for power generation and transport ensures parameters stability and energy quality [1, 2, 3]. Renewable energy sources have the advantage of avoiding generating pollution by emissions and the fact that they use primary energy resources, which are unlimited. The downside comes in the form of extra complexity required for keeping the electrical current characteristics: voltage, frequency within acceptable limits [4].

The wind turbine is one of the most important technologies for renewable energy. Its development started in the 80s, with powers in the order of kW. Compared to its small beginnings, currently installed wind turbines can have more than 1MW of rated power. Although, in the beginning wind power production had no impact whatsoever on the power control system, nowadays, it has taken a well-defined active role in the power grid. As the power range of the turbines increases, the control parameters are becoming more important and it is necessary to introduce power electronics [5] as an interface between the wind turbine and the power grid. Power electronics is changing the basic characteristic of the wind turbine, from an energy source to an active power source. The electrical technology used in wind turbines is not new and it further gaining attention. Especially the last few years have a seen outstanding contributions [6,7,8,9] and with the decreasing price per produced kWh, the power electronics solutions are becoming highly attractive.

In many countries, the investments in energy sources are directed towards a tapping wind power [10, 11] and most of these investments are found in offshore farms. In the future, these wind farms could have a significant contribution to the power injected into the system and consequently play an important part in the control of power system [12], taking into account the power quality of the standards in force [13,14].

The economic viability of offshore wind turbines obviously corresponds to the power and efficiency of the generators and of the power conversion systems. Within this trend, multilevel power electronics converters were considered an eminently suitable technology for the wind energy conversion system, because they can operate at higher power and voltage requirements [8].

Therefore, the elevated technical requirements of the offshore wind farms channel the researches towards ensuring frequency and voltage stability injected into the power system [15, 16] and active and reactive power control. There have also been researches aimed at ensuring a fast response for the transitory regime that involves changing the power injected into the system [17, 18, 19].

The power converters interfacing the AC-DC conversion system, respectively DC-AC, usually depend on the topology of the application, but they must meet three conditions [8, 20]:

- Reliability;
- Efficiency in terms of power quality;
- Lowest possible cost.

Unlike other equipment's, this type of converters, i.e. multilevel converters, presents a capital advantage, namely that they must inject the voltage into the grid at a fixed frequency. The disadvantages are related to the high voltage and power levels and power quality problems. We should bear in mind that the grid into which the voltage is injected is of infinite power. The grid has a very different behavior from the consumers that fall into the category of non-linear loads.

Hence, any converter solution [20] must consider two issues: the choice of switching device, the type of converter chosen and the command principle used for obtaining a sinusoidal voltage with the same frequency as the grid.

The most common multilevel inverters topologies are as follows: diode clamped multilevel inverters DC-MLI (Fig. 1.), flying capacitor multilevel inverters FC-MLI (Fig. 2.) and cascaded H-bridge multilevel inverters CHB-MLI (Fig. 3.).

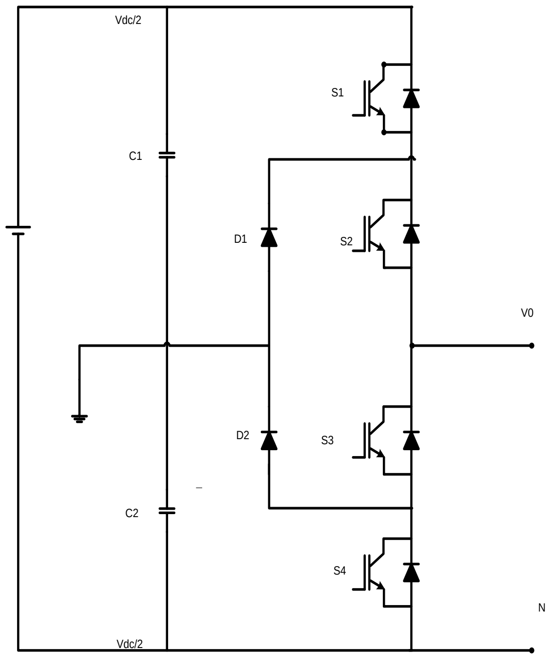

Fig. 1.Three-level DC-MLI

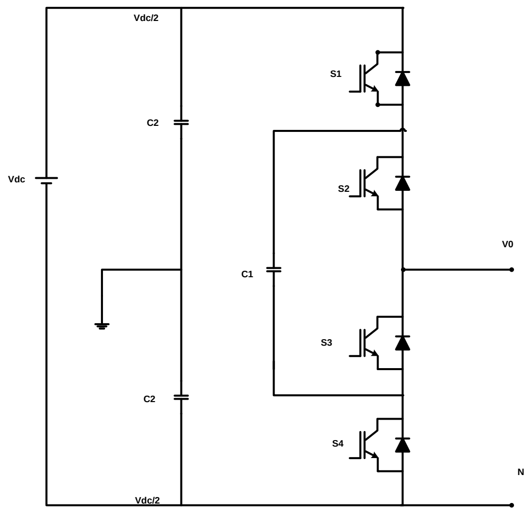

Fig. 2. Three-level FC-MLI

Together with the converter topologies [20], current research in the field of multilevel converters is geared towards finding the optimal switching solution switch. The command strategy aims to minimize the harmonic spectrum of the output values and to minimize switching losses.

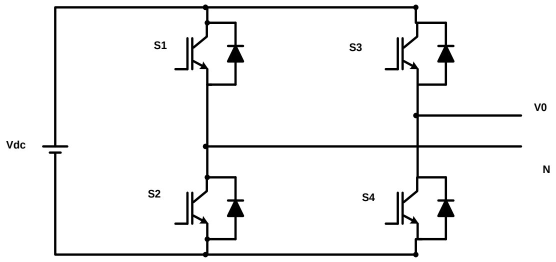

Fig. 3. Three-level CHB-MLI

2. THEORETICAL CONSIDERATIONS

Waveform synthesis is based on the Fourier Series expansions, in which case the scaling function φ_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 α angle.

If we define:

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

and

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

Therefore, notation (1) creates a set of orthogonal functions called an orthogonal base. Since all functions φ_n (x) have their norms equal to *α*, this base is called an orthonormal base.

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

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

where:

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

The expansion (3) is valid for any function *f(x)*. The Fourier series contains an infinite number of elements and makes it possible to approximate a function f(x) by use of an infinite set (a sum) of adequately scaled functions φ_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 the opposite to a typical application of the Fourier series where any function *f(x)* is expanded as a set of harmonics. According to (3) and (4) the expansion of sin(x) in the interval given as:

$$\sin(x) = \sum_{n=0}^{\infty} \left\{ \frac{\int_a^b \sin(x)\varphi_n(x)dx}{\alpha} \varphi_n(x) \right\}, x \in < a,b > \qquad (6)$$

Expression (6) defines a series of consecutive rectangular pulses represented by functions φ_n(x). The value for the each pulse amplitude is different and is determined by calculating the integral. In power electronics, we can apply this statement for the composition of sinusoidal waveforms. 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 mostly concerned an addition of the vertical axis when adding the waveforms The resulting phase voltage was synthesized by the adding the voltages generated by different cells of a cascaded inverter. The presented proposal relates to the addition of pulses “along x axis” or in a time scale. Consecutive pulses form the resulting voltage or current of the converter.

3. SIMULATIONS

Practically, in power electronics an application, the approximation of a sinusoidal waveform is achieved using a finite number N of the series members. The accuracy of approximation depends on it.

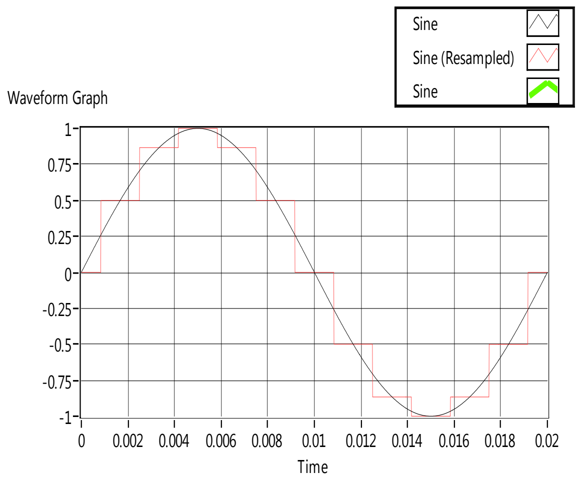

Fig. 4. The approximation of the function f(x) = sin(x) for N = 24 (α = π/12).

In power electronics the most important criterion of the accuracy, or rather the quality of approximated waveforms is THD factor. The example of a very simple approximation is presented in Fig. 4. The stepped waveform was obtained after approximations based on the set defined according to (1) and (2). The simulations used the LabView Software from National Instruments, which allows for a simple implementation and 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 we can paint a better picture of the practical problems that arise when connecting a load and how difficult is 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 <0,2π>. 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, we must not forget the importance of N.

Table 1 Thd Values 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

4. EXPERIMENTAL RESULTS

From an experimental point of view, we have tested the two command variants of the multilevel inverters - with 12 and 24 voltage steps. The attempts were made having as a charge an asynchronous motor with a short circuiting rotor of type 4F130-4A with the following parameters: nominal power P=0.37 kW, speed n=1350rpm, power factor cosφ=0.71, rated voltage Un=220 V, degree of protection IP44. The measured values for the winding resistance are 27.27 Ω, respectively 64.57 mH for the inductance. With the aid of the oscilloscope, we obtained the waveforms for the phase voltage (Fig. 5., Fig.6.), the absorbed phase current(Fig. 7., Fig. 8) and active power (Fig. 9., Fig. 10.).

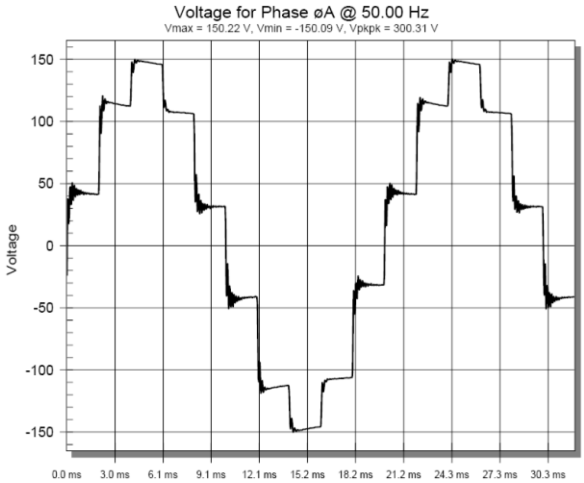

Fig. 5. 12 pulses Voltage

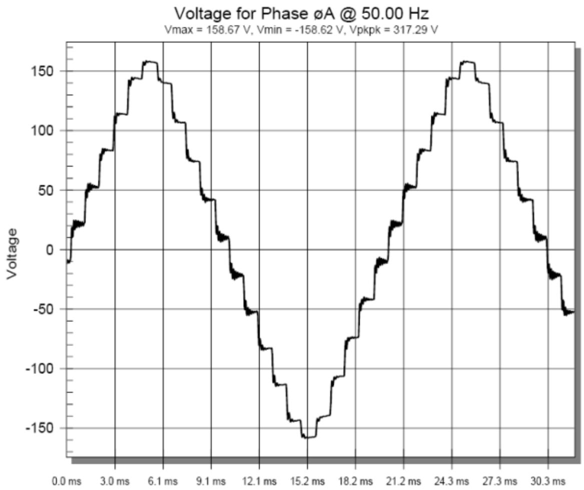

Fig. 6. 24 pulses Voltage

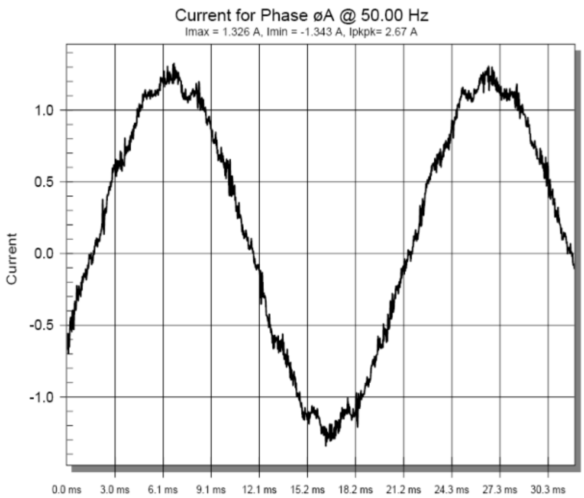

Fig. 7. 12 pulses Load Current

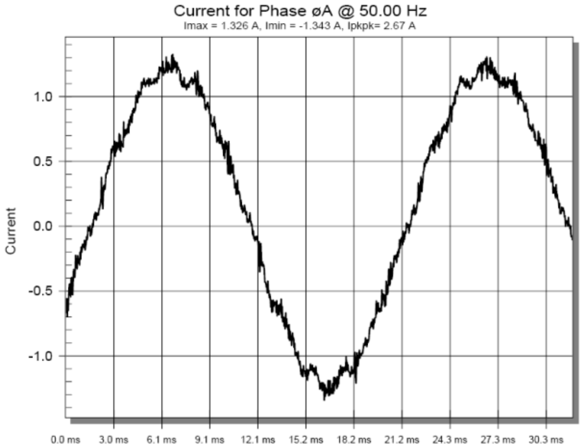

Fig. 8. 24 pulses Load Current

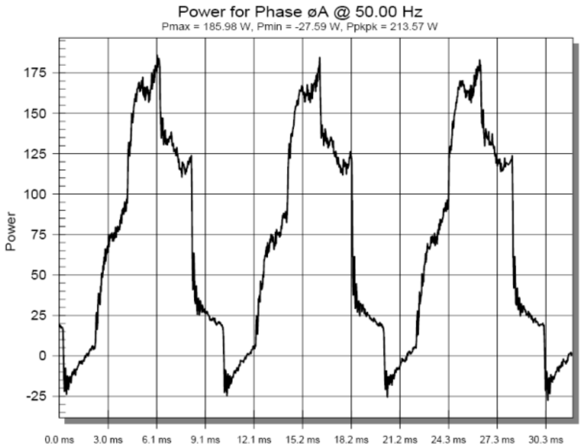

Fig. 9. 12 pulses Active Power

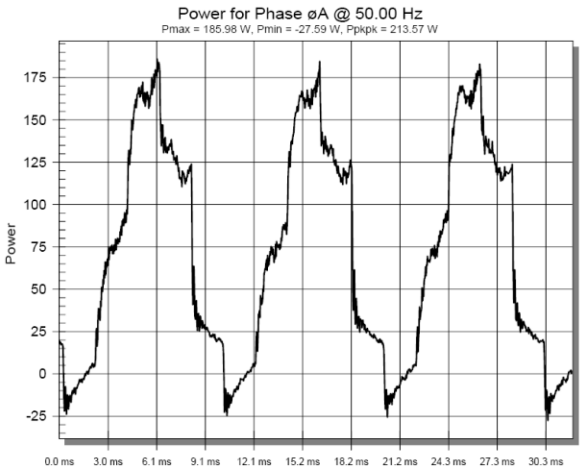

Fig. 10. 24 pulses Active Power

5. CONCLUSIONS

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

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 filter needs to be added since a 40% harmonic distortion on the output voltage is not admissible.

TABLE 2

Converter type	12 pulses	24 pulses
Date	15.04.2014	15.04.2014
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 [%]	16.69	11.67
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

The advantage of the nive 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 5 level inverter and a filter [22, 23, 24, 25] is the better solution.

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 with two significant caveats. First of all this configuration has the highest weight of all which makes it impractical in applications which will later be incorporated in another unstable configuration. Secondly, the cost of this particular inverter is the highest of them all. The flying capacitor multilevel inverter can be used in circumstances where the loss of power tacked precedence over weight and cost.

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

TABLE 3

	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
3rd harmonic component	4.80	9.5
5th harmonic component	0.13	2.60
7th harmonic component	1.93	0.31
9th harmonic component	10.72	0.26
11th harmonic component	8.68	0.10
13th harmonic component	1.10	0.18
15th harmonic component	0.12	0.62
17th harmonic component	0.68	0.58

This analysis of the multi-level inverters highlights the set of problems that arise in connecting the renewable energy sources to the power grid. The main factor that has to 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 in itself constitutes an advantage when choosing the type of converter needed. The distortion factor in such applications needs to follow specific standards, especially since the harmonic distortions generated by the inverter (Table III) spread from the renewable sources to conventional sources increasing the carrier's final CPT parameter.

ACKNOWLEDGMENT

This paper is supported by the Human Resources Development Programme POSDRU/159/1.5/S/137516 financed by the European Social Fund and by the Romanian Government.

REFERENCES

1. 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.
2. H. S. Patel and R. G. Hoft, "Generalized Techniques of Harmonic Elimination and Voltage Control in Thyristor Inverters: Part I-Harmonic Elimination," IEEE Trans. Ind. Applicat., Vol. IA-9, pp. 310-317, 1973.
3. H. S. Patel and R. G. Hoft, "Generalized Techniques of Harmonic Elimination and Voltage Control in Thyristor Inverters: Part II-Voltage Control Techniques," IEEE Trans. Ind. Applicat., Vol. IA-10, pp. 666- 673, 1974.
4. E. Bossanyi. Wind Energy Handbook. John Wiley, 2000.
5. L. H. Hansen, L. Helle, F. Blaabjerg, E. Ritchie, S. Munk-Nielsen, H. Bindner, P. Sorensen, B. Bak-Jensen, Conceptual survey of Generators and Power Electronics for Wind Turbines, Riso-R-1205(EN), Pitney Bowes Management Services Denmark, 2002, ISBN 87-550-2743-1.

6. A. D. Hansen, F. Iov, F. Blaabjerg, L. H. Hansen, Review of contemporary wind turbine concepts and their market penetration, Journal of Wind Engineering, 28(3), 2004, pp. 247-263, ISSN 1095-4244.
7. L. Gertmar, Power Electronics and Wind Power, Proceedings of EPE, 2003, paper ID 1205.
8. F. Blaabjerg, R. Teodorescu, M Lissere, A. Timbus, Overview of control and grid syncronization for distributed power generation systems, IEEE Transactions on Industrial Electronics, Vol. 53, No. 5, pp. 1398-1409.
9. F.. Iov, F. Blaabjerg, UNIFLEX-PM Advanced power converters for universal and flexible power management in future electricity network-Converter applications in future European electricity, Deliverable D2.1, EC Contract no. 019794(SES6), February 2007, pp. 171.
10. J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, “Power-electronic systems for the grid integration of renewable energy sources: A survey,” IEEE Trans. Ind. Electron., vol. 53, no. 4, pp. 1002– 1016, Jun. 2006.
11. Matevosyan, J., Ackerman, T., Bolik S., Lennart, S. “Comparison of international regulations for connection of wind turbines to the network”. Nordic wind power conference, 1-2 march, 2004.
12. F. Blaabjerg, Z. Chen, R. Teodorescu, F. Iov, “Power Electronics in Wind Turbine Systems”, Proceedings of the IPEMC 2006, Shanghai, China, Pages: 1-10.
13. IEEE “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”, IEEE 519-1992.
14. Electromagnetic compatibility “(EMC) – Part 2-12: Environment – Compatibility levels for lowfrequency conducted disturbances and signalling in public medium-voltage power supply systems”, IEC 61000-2-12.
15. Eping, J. Stenzel, M. Pöller, H. Müller, “Impact of Large Scale Wind Power on Power System Stability”, 5th International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, Glasgow, Scotland 2005.
16. M. Liserre, R. Teodorescu, and F. Blaabjerg, “Stability of photovoltaic and wind turbine grid-connected inverters for a large set of grid impedance values,” IEEE Trans. Power Electron., vol. 21, no. 1, pp. 263–272, Jan. 2006.
17. Z. Lubosny; “Wind Turbine Operation in Electric Power Systems” Springer-Verlag Berlin, ISBN 3-540-40340-X.
18. R. Teodorescu, F. Blaabjerg, U. Borup, and M. Liserre, “A new control structure for grid-connected LCL PV inverters with zero steady-state error and selective harmonic compensation,” in Proc. IEEE APEC, 2004, vol. 1, pp. 580–586.
19. L. Xu and L. Ye, "Analysis of a Novel Stator Winding Structure Minimizing Harmonic Current and Torque Ripple for Dual Six-Step Converter-Fed High Power AC Machines," IEEE Trans. Ind. Appl. , Vol. 31, pp. 84-90, 1995.
20. N. Mohan, T.M. Undeland, W.P. Robbins. Power Electronics-Converters, Applications and Design. 1’st Edition, John Wiley & Sons, 1989.
21. R. Teodorescu, F. Blaabjerg, J. K. Pedersen, E. Cengelci, S. U. Sulistijo, B. O. Woo and P. Enjeti, "Multilevel Converters-A Survey" European Conference on Power Electronics and Applications, 1999.
22. Balan, H., Munteanu, R., Buzdugan, M., Vadan, I., “Practical procedures in determining the differential mode characteristics of EMI power supply filters”, Advances in Electrical and Computer Engineering, Volume 9, Issue 2, 2009, Pages 109-114, ISSN: 15827445, DOI: 10.4316/aece.2009.02017.
23. H. Balan, M. I. Buzdugan, R. A. Munteanu, P. Karaissas and C. Psomopoulos, “Testing Wind Variable Speed Driving Systems for Conducted Interferences”, Speedam 2012, 20-22 june 2012, Sorrento, Italy, ISBN: 978-1-4673-1299-8 DOI: 10.1109 /SPEEDAM. 2012.6264482, pp. 565-570.
24. Bălan, H., Vadan, I., Buzdugan, Karaissas, P., “EMI Filters Performances Analysis. Case Study”., International Conference on EDPE, 12-14 October 2009, paper T01-029, Dubrovnik, Croatia.
25. Horia Balan, Mircea I. Buzdugan, Cristina Chiorean, Ana Iacob, Petros Karaisas, “A Passive EMI Filter for the Reduction of ActiveFilter Generated Network Distortions”, Annals of the University of Craiova, No. 36, 2012, ISSN 1842-4805, pg. 235-242.

Horia Bălan
Electrical Engineering Department, Technical University of Cluj-Napoca
Cluj-Napoca, Romania
horia.balan@enm.utcluj.ro