

Innovative Computational Approach to Harmonic Mitigation for Seven-level Cascaded H-Bridge Inverters

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Abstract—Low frequency modulation strategies are a good solution to increase the energy conversion efficiency in high power applications. The paper is devoted to presents an innovative way to low order harmonics mitigation for seven-level Cascaded H-Bridge Inverters. In particular, this approach is based on the mitigation of selected harmonics without solve non-linear equations for an extended range of the fundamental amplitude. In fact, in real-time operation to evaluate the control angles the polynomial equations have been identified. Through circuit simulation analysis in MatLab/PLECS environment, the effectiveness of the harmonic mitigation method has been tested and compared with theoretical results.

Keywords—*Selective Harmonic Mitigation; Cascaded H-Bridge Inverters; Soft Switching Modulation Techniques; Electrical Drive.*

I. INTRODUCTION

For high power applications, the rapid development of power electronics has allow more energy efficient systems. In particular, Multilevel Power Inverters (MPIs) play an important role thanks to their features in respect to the traditional three-level inverters. In particular, Cascaded H-bridge Multilevel Inverters (CHBMI) are promising solutions if separated DC sources are available. For example, the current trend of the ship propulsion systems is to displace the traditional mechanically propulsion by electric or hybrid electric drive with medium voltage. According to [1], the 6.6kV systems appear to be particularly popular. In this context, the MPIs are the good candidates to work with these voltage levels. Generally, multicarrier PWM modulation strategies are used to control the MPIs thanks to their easy implementation feature in electronic devices like microcontroller and FPGA, as demonstrated in [2]-[4]. Nevertheless, these modulation strategies are not suitable

if the switching losses minimization are required. Low frequency modulation strategies are a good solution to increase the energy conversion efficiency and to reduce the Electromagnetic Interferences (EMI) [5].

As well known, there are different study about the Selective Harmonic Elimination (SHE) or Selective Harmonic Mitigation (SHM) reported in literature, also adopted in many fields of applications [9-24]. In [25]-[27], an interesting cataloguing on the kind of mathematical algorithms based on Staircase Voltage Waveform as switching pattern has been introduced. The same topic has been studied in [28], where a methodology with unequal DC sources for a seven-level CHBMI has been suggested.

An interesting technique to evaluate the switching angles for five-level CHBMI, working at fundamental frequency, was proposed in [29] and [30]. This method is based on trigonometric formulations, where by fixing the harmonic and the modulation index, it comeback all probable exact results of couple of control angles. In [31], a general mathematical solution for SHE techniques has been proposed. This method eliminates a number of harmonics regardless the output voltage levels by definition a linear system of equations.

A novel approach to mitigate the lower order harmonics with a staircase voltage pattern has been depicted in [9]-[11]. More in detail, this method is based on the definition of a Distortion Index that allows to mitigate the amplitudes of selected harmonics. Indeed, interesting results have been obtained by using single-phase and three-phase five-level CHBMIs structures. Moreover, the main issue about the calculation of the control angles in real-time operation has been overcome by defining low-order polynomial equations. Simulation and experimental tests have demonstrated the effectiveness of this method.

The purpose of this paper is to extend the innovative approach presented in [9] and [11] for a seven-level CHBML in which the introduction of a new voltage level increases the complexity of the problem with a third variable in the equations. Thus, the goal to evaluate the control angles, without solving non-linear equations, has been reached identifying polynomial equations. The rest of the paper is devoted on the evaluation of the performance of the converter by circuit simulation in Matlab/PLECS environment.

II. MATHEMATICAL FORMULATION

Generally, CHBML is able to provide a staircase voltage waveform where the voltage levels depend on the converter topology.

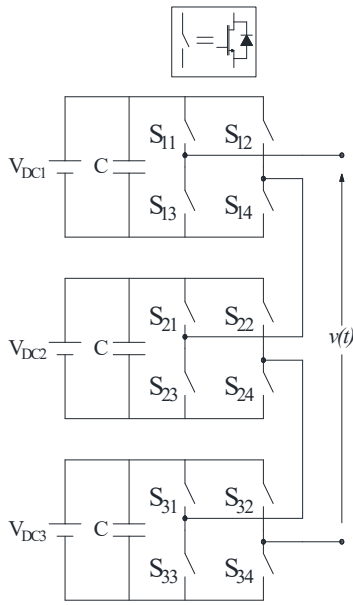


Fig. 1: Topology structure of a seven-level CHBML

For example, by considering the circuitual representation of a seven-level CHBML, shown in Fig. 1, the general voltage trend is illustrated in Fig.2.

The parameters α , β and γ are the control angles that allows to control the turn-on and turn-off of the voltage levels.

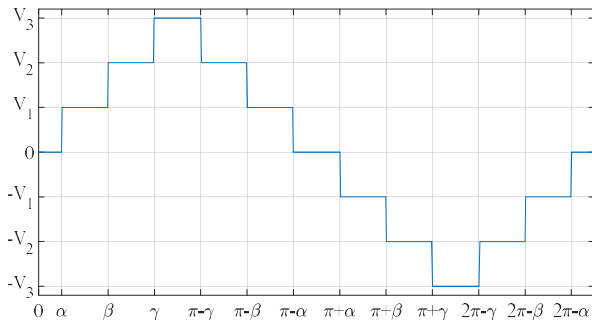


Fig. 2: Seven-level staircase voltage waveform

The V_1 , V_2 and V_3 are the voltage levels that can be obtained with different combinations of the DC voltages thanks to the topology structure of the converter. A possible combination is:

$$\begin{aligned} V_1 &= V_{DC1} \\ V_2 &= V_{DC1} + V_{DC2} \\ V_3 &= V_{DC1} + V_{DC2} + V_{DC3} \end{aligned} \quad (1)$$

where V_{DC1} , V_{DC2} and V_{DC3} are the voltage amplitudes of the DC sources.

By considering the half-wave symmetry, the Fourier-series formulation of the seven-level voltage trend is reported in (2), where h parameter is the harmonic order.

It should be noted that the Fourier-series formulation (2) presents six degrees of freedom: the DC voltage amplitudes (V_{DC1} , V_{DC2} and V_{DC3}) and the control angles (α , β and γ). This consideration represents an interesting point of view to reduce the harmonic components in the output voltage with respect to the traditional selective harmonic mitigation methods.

As described above, aim of this work is to reduce the mathematical complications of the Cascaded H-bridge Multilevel Inverters to evaluate the control angles. For this reason, in this work, in order to reduce the number of variables of the problem, the same DC voltage amplitudes have been considered. Thus, the Fourier-series formulation can be rewritten as in (3). Therefore, expression (3) presents only three degrees of freedom, in order to control the fundamental amplitude and the harmonic amplitudes. In the next section, a novel computational approach to evaluate the control angles for each value of the fundamental amplitude is presented.

III. PROPOSED HARMONIC MITIGATION METHOD

The novel way for the low order harmonics mitigation has been introduced in earlier works and by means of simulations and experimental tests, the effectiveness of this simple computational method have been established [9]-[11].

The Harmonic Mitigation method proposed in this work is based on the definition of a parameter called "Distortion Index" (DH_{RMS}). By considering only the amplitude of the selected harmonics, which can be evaluated as in (4), the DH_{RMS} is defined as the root mean square value of the selected harmonics that meant to mitigate. In order to mitigate the first-five harmonics, the DH_{RMS} can be defined as follow:

where V_{3h} , V_{5h} , V_{7h} , V_{9h} and V_{11h} are the amplitudes of the third, fifth, seventh, ninth and eleventh harmonics, respectively.

From a mathematical point of view, the DH_{RMS} is a non-linear function of the three independent variables: α , β and γ . For this reason, it is possible to imagine a four-dimension graphical representation of DH_{RMS} where the

control angles (α , β and γ) are the 3-d coordinates and the fourth dimension is the colour, as shown in Fig. 3.

$$v(t) = \sum_{h=1}^{\infty} \left\{ \frac{2[1 - \cos(h\pi)]}{h\pi} \cdot [V_{DC1} \cos(h\alpha) + V_{DC2} \cos(h\beta) + V_{DC3} \cos(h\gamma)] \cdot \sin(h\omega t) \right\} \quad (2)$$

$$v(t) = \sum_{h=1}^{\infty} \left\{ \frac{2V_{DC}}{h\pi} \cdot [1 - \cos(h\pi)] \cdot [\cos(h\alpha) + \cos(h\beta) + \cos(h\gamma)] \cdot \sin(h\omega t) \right\}. \quad (3)$$

$$V_h = \frac{2V_{DC}}{h\pi} \cdot [1 - \cos(h\pi)] \cdot [\cos(h\alpha) + \cos(h\beta) + \cos(h\gamma)] \quad (4)$$

$$DH_{RMS} = \sqrt{V_{3h}^2 + V_{5h}^2 + V_{7h}^2 + V_{9h}^2 + V_{11h}^2} \quad (5)$$

Indeed, the red cube, illustrated in Fig. 3, is a discretized volume that represent the DH_{RMS} values for different values of the control angles, in a range from 0 to $\pi/2$. Moreover, the colour bar indicates the amplitude of the DH_{RMS} expressed as percentage with respect to the fundamental amplitude when the control angles are equal to zero (fundamental amplitude equal to $12V_{DC}/\pi$ of a square wave with amplitude equal to $3V_{DC}$).

From Fig. 3, it is interesting to note that there are some sub-volumes, characterized by a dark blue colour, where the amplitude of the DH_{RMS} is lower. Thus, the purpose of the proposed method is to identify these sub-volumes and, to consider the amplitude of the first harmonic in order to find the trajectory of the control angles inside these sub-volumes. In this way, it is possible to drive the converter by using these control angles trajectories in which the reference harmonics are mitigated.

By using a especial designed “search algorithm”, the minimum values of the DH_{RMS} were identified, as depicted in Fig.4. The search algorithm is based on the use of a threshold equal to 15%, thus for each value of the fundamental amplitude, it founds the minimum values of DH_{RMS} in which correspond only a value for each control angle.

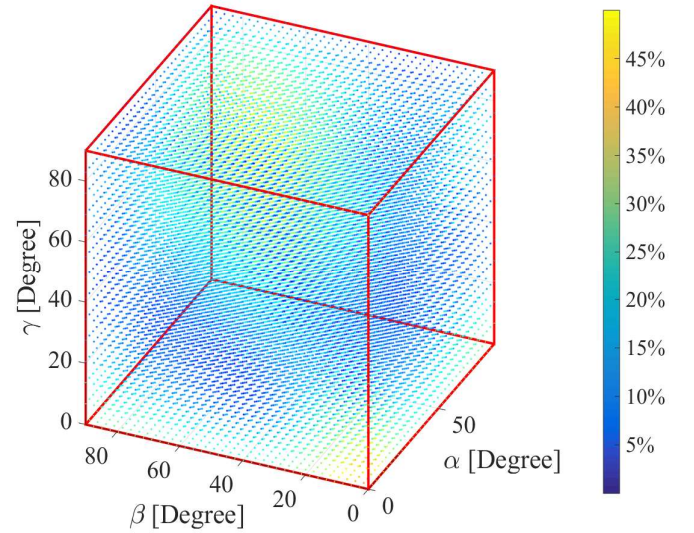


Fig. 3: Graphically representation of DH_{RMS} function of the control angles α , β and γ .

Indeed, Fig. 4 highlights the minimum values of the DH_{RMS} function of the control angles α , β and γ for each value of the fundamental amplitude taken into account.

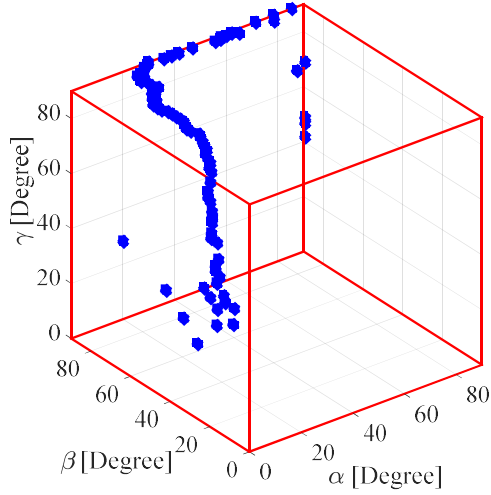


Fig. 4: Minimum values of the DHRMS function of the control angles α , β and γ .

By changing point of view, it is possible to identify the control angles trajectories vs. fundamental amplitude reference, as illustrated in Fig. 5.

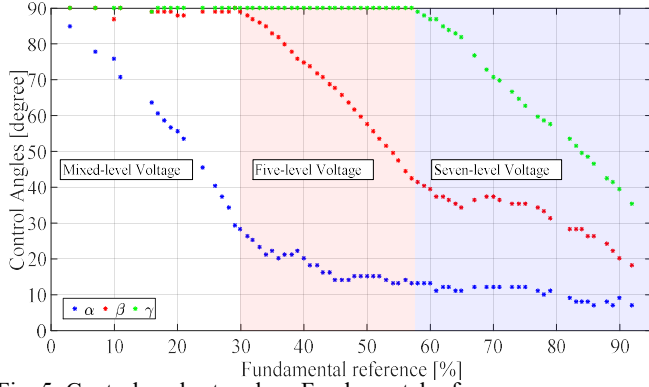


Fig. 5: Control angles trend vs. Fundamental reference.

In this way, in Fig. 5, three operating regions of the converter have been identified where the DH_{RMS} amplitude is lower than 15%. In the first range, from 57% to 93% of the fundamental amplitude, the converter operates with a seven-level voltage waveform. In the second, from 30% to 57% of the fundamental amplitude, the control angle γ is constant and equal to 90° thus the converter operates with a five-level voltage waveform. In the last range, from 3% to 30% of the fundamental amplitude, the converter operates with mixed voltage levels between three and five levels.

It should be noted that to maintain a low DH_{RMS} under the 15% is necessary in order to neglect a voltage level in the second range, but that means that corresponding DC source does not contribute on the AC conversion with a power injected equal to zero. In order to uniform the power absorbed among the DC sources, this issue can be overcome through a sequential exchange of the control angles among the DC sources during real time operation of the system.

Fig. 6 shows the amplitudes of the DH_{RMS} and the first-five harmonics vs. fundamental reference expressed in percent, as above described. In the first range, all harmonic amplitudes are lower than 5% up to 86% of the fundamental reference and after increase the amplitude of the third harmonic. In the second range, fifth and seventh harmonics are predominant in respect to the other components while the third harmonic is lower. In the last range, the amplitude of the third harmonic is predominant. More in detail, in order to evaluate the overall harmonic content, the Total Harmonic Distortion (THD) has been used and calculated as follow:

$$THD\% = 100 \cdot \sqrt{\frac{\sum_{h=2}^N V_h^2}{V_1^2}} \quad (6)$$

where V_1 is the fundamental amplitude, h is the harmonic order, V_h is the h -order harmonic and N is the max harmonic order considered.

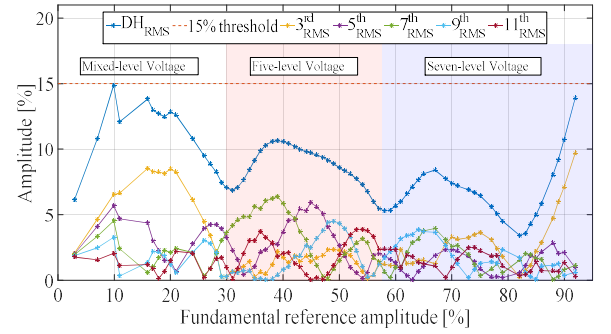


Fig. 6: Amplitudes of the DH_{RMS} and the first-five harmonics vs. fundamental reference.

Fig. 7 shows the THD trend expressed in percent vs. the fundamental reference.

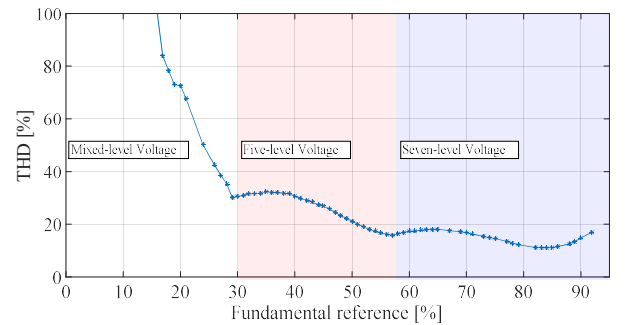


Fig. 7: Total Harmonic Distortion trend vs. vs. fundamental reference.

It is interesting to note that in the first range (seven-level voltage) and in the second range (five-level voltage) the THD% is lower than 35% while in the last range (mixed-level voltage) there are higher values. For this reason, in this work, the last range will be neglected. In the next section, polynomial approximation of the control angles trend will be presented.

IV. POLYNOMIAL APPROXIMATION OF THE CONTROL ANGLES TREND

The main issue of SHE and SHM algorithms is the high computational cost to evaluate the control angles. Thus, in order to reduce the computational cost, the main purpose of this work is to evaluate the control angles, in real-time operation, without solving non-linear equations.

By taking into account, the control angles trend, illustrated in Fig. 5, to evaluate the control angles, polynomial approximation has been used and two cases have been studied. In the Case 1, the α and β trends have been approximated with a 4th-order polynomial equations (5), while for the γ trend a polynomial have been used P_γ (5) has been used in the first range of the fundamental amplitude (from 57% to 93%), as depicted in Fig. 8.

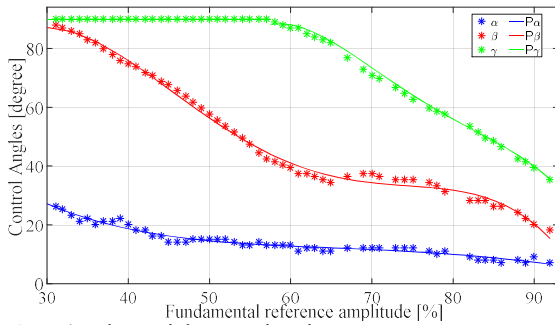


Fig. 8: Case 1 polynomial approximation.

In the Case 2, the fundamental amplitude range has been subdivided in four sub-range where each control angle trend has been approximated with 2nd-order polynomial equations (6), as shown in Fig. 9. In Table I, limits of the sub-ranges and the corresponding polynomial equations are reported.

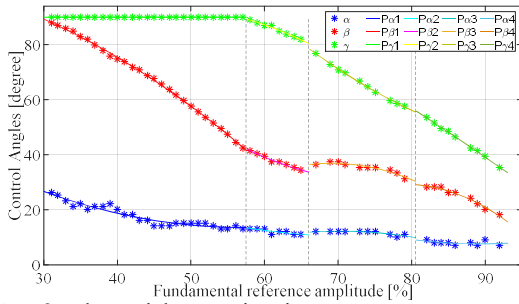


Fig. 9: Case 2 polynomial approximation.

TABLE I: SUB-RANGE APPROXIMATION OF THE CASE 2

Sub-range f_1 [%]	Polynomials
$30\% \leq f_1 \leq 57\%$	$P_{\alpha 1} P_{\beta 1} P_{\gamma 1}$
$57\% < f_1 \leq 66\%$	$P_{\alpha 2} P_{\beta 2} P_{\gamma 2}$
$66\% < f_1 \leq 80\%$	$P_{\alpha 3} P_{\beta 3} P_{\gamma 3}$
$80\% < f_1 \leq 93\%$	$P_{\alpha 4} P_{\beta 4} P_{\gamma 4}$

In both cases, higher order polynomial approximations do not introduce significant improvements on the converter performance. Moreover, it should be noted that in the second case, the lower order polynomial equations allow to reduce the computational costs. In the next section, circuit simulation in Matlab/PLECS environment are reported.

V. SIMULATION RESULTS AND DISCUSSION

In order to establish the effectiveness of the proposed method between the two cases taken into account, a circuit simulation in MatLab/PLECS[®] environment has been carried. The used tool to compare the overall performance among theoretical results and cases under test is the THD% (6), as illustrated in Fig. 10.

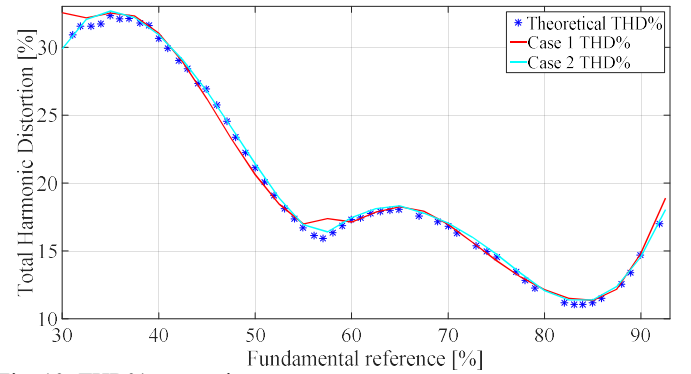


Fig. 10: THD% comparison.

From Fig. 10, it is interesting to note that the case 2 (cyan curve) allows obtaining the best approximation in respect to the case 1 (red curve). Moreover, this result allows reducing the computational cost in real time operation.

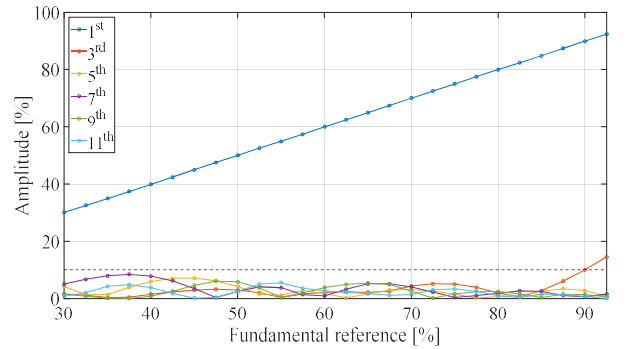


Fig. 11: Circuit simulation results obtained with the case 2.

More in detail, Fig. 11 shows the fundamental amplitude trend, the Distortion Index DH_{rms} and the selected harmonics (3^{rd} , 5^{th} , 7^{th} , 9^{th} and 11^{th}) obtained with the case 2, expressed in percent in respects to the fundamental amplitude with α , β and γ equal to zero.

$$\begin{aligned}
P_{\alpha} &= 2.147 \cdot 10^{-6} V_1^4 - 7.441 \cdot 10^{-4} V_1^3 + 0.090 \cdot V_1^2 - 4.811 \cdot V_1 + 108.328 \\
P_{\beta} &= -3.598 \cdot 10^{-5} V_1^4 + 0.0086 \cdot V_1^3 - 0.727 \cdot V_1^2 + 24.210 \cdot V_1 - 188.146 \\
P_{\gamma} &= -1.096 \cdot 10^{-4} V_1^4 + 0.0336 \cdot V_1^3 - 3.837 \cdot V_1^2 + 191.744 \cdot V_1 - 3440.142
\end{aligned} \tag{5}$$

$$\begin{aligned}
P_{\alpha 1} &= +0.0003 \cdot V_1^2 - 0.0357 \cdot V_1 + 1.2556; & P_{\alpha 2} &= 0.0002 \cdot V_1^2 - 0.0320 \cdot V_1 + 1.3647; \\
P_{\alpha 3} &= -0.0003 \cdot V_1^2 + 0.0535 \cdot V_1 - 1.6657; & P_{\alpha 4} &= 0.0003 \cdot V_1^2 - 0.0570 \cdot V_1 + 2.6843; \\
P_{\beta 1} &= -0.0003 \cdot V_1^2 - 0.00007 \cdot V_1 + 1.8708; & P_{\beta 2} &= 0.0005 \cdot V_1^2 - 0.0862 \cdot V_1 + 3.8505; \\
P_{\beta 3} &= -0.0008 \cdot V_1^2 + 0.1205 \cdot V_1 - 3.5186; & P_{\beta 4} &= -0.0012 \cdot V_1^2 + 0.1910 \cdot V_1 - 7.0315; \\
P_{\gamma 1} &= +90; & P_{\gamma 2} &= -0.0005 \cdot V_1^2 + 0.0479 \cdot V_1 + 0.5768; \\
P_{\gamma 3} &= +0.0004 \cdot V_1^2 - 0.0920 \cdot V_1 + 5.5386; & P_{\gamma 4} &= -0.0001 \cdot V_1^2 - 0.0140 \cdot V_1 + 2.7592;
\end{aligned} \tag{6}$$

As shown in Fig. 11, the fundamental amplitude (blue line) presents a linear trend on all fundamental reference range. Moreover, the harmonic amplitudes are between 10% up to 90% of the fundamental reference. More than 90% of fundamental reference, the third harmonic amplitude overcomes the 10% and becomes the predominant component. In conclusion, from circuit simulation analysis, it is possible to claim that the case 2 is the best approximation.

VI. CONCLUSION

The paper has been concentrated on the presentation of an innovative computational approach to selective harmonic mitigation for seven-level CHBMs. In particular, the main objective is to overcome the issues on the evaluation of the control angles in an extended range of the output fundamental amplitude. In fact, low order polynomial equations have been identified by using the proposed method that allows to mitigate selected harmonics (3rd, 5th, 7th, 9th and 11th). The effectiveness of the proposed method has been confirmed by circuit simulations in Matlab/PLECS environment.

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