Universal Journal of Electrical and Electronic Engineering 2(4): 170-177, 2014 http://www.hrpub.org
DOI: 10.13189/ujeee.2014.020405

Interfacing Renewable Energy Sources to the AC Grid by a CMLI with Voltage Regulation under Low THD

M. El-Bakry

Electronics Research Institute, Egypt
*Corresponding Author: mahmoudrahman40@yahoo.com

Copyright © 2014 Horizon Research Publishing All rights reserved.

Abstract This paper proposes a 27-level cascaded multilevel inverter (CMLI) as an interface between renewable energy sources and the grid, that can provide output voltage regulation against many fluctuations in these sources while keeping low value of the total harmonic distortion (THD) in its output voltage. Renewable energy sources of different types are treated as dc sources (e.g. dc voltage from PV panels, rectified ac voltage from wind turbines, etc.) that represent a part of, or all, the input dc sources of the individual H-bridges of the CMLI. The values of these sources are subject to natural fluctuations. An approach using a mixed integer linear programming (MILP) optimization model is applied to determine the switching angles of the power switches of this CMLI to minimize the values of the undesired low order harmonics equally till the 31st harmonic. . The model is applied for the single phase and three phase cases. For each case, an output voltage amplitude is selected first for normal operation at the nominal values of the dc sources , whose harmonics absolute values agree with the IEEE standards 519-1992 for voltage distortion limits. Then some disturbances are analyzed, including fluctuations of all the dc sources within ±20% of their nominal values, dropping some dc sources to 50% of their values and dropping of some dc sources to zero values, and the model is applied under the required value of the output voltage with an allowed deviation within ±5%. Solutions are obtained that give the switching angles of the inverter at these disturbances in the dc sources while keeping low values of the output voltage THD.

Keywords Cascaded Multilevel Inverters, Harmonic Values Minimization, Mixed Integer Linear Programming, Renewable Energy Utilization, Tied Grid Inverters, Total Harmonic Distortion

1. Introduction

In the next 10 years, the electric grid will change more than it has in the past fifty. In its "Renewable Systems Interconnection Technical Report", the U.S. Department of Energy (DoE) states "Now is the time to plane for the integration of significant quantities of distributed renewable energy into the electricity grid". The challenges of integrating renewable energy sources are becoming familiar to many utilities as the percentage of intermittent generation, such as solar and wind continue to increase over traditional power sources, [1].

The concept of smart grid may be considered as that in which renewable energy systems are integrated into the existing power grid. Nowadays, smart grid technologies must allow the electric grid to better adapt to the dynamic behavior of renewable energy and distributed generation, helping both consumers and utilities to access their resources and harvest their benefits. Today's grid needs to shift from centralized supply sources to fixed predicable loads, and accept power from the renewable and distributed energy sources all over the grid. Since these sources are intermittent in nature, the grid needs integrating monitoring and control, as well as integration with substation automation, to control different energy flows and plan for standby capacity to absorb intermittent generation, [2]. The need for standby capacity, which may be in the form of energy storage units, could be reduced if the interfacing unit between the renewable energy sources and the grid can provide voltage regulation against some disturbances in these sources.

This paper proposes a cascaded multilevel inverter (CMLI) as an interface between renewable energy sources and the grid, since it is the most recent and popular type of inverters, that synthesizes a desired sinusoidal voltage from several separate dc voltage sources. The general construction of a single phase CMLI is shown in Fig. 1. It consists of S number of H-bridges fed with dc voltages sources E_1, E_2, and E_S .The output voltage is usually constructed in a stair case shape with quarter wave symmetry, Fig. 2, to approach synthesizing a sinusoidal wave form, [3].

Renewable energy sources of different types are treated as the dc sources (e.g. dc voltage from PV panels, rectified ac voltage from wind turbines, etc.) on the dc side of the CMLI. These dc sources may be different sources of different nature, or originated from a single dc source using capacitors [4], or transformers, [5-6]. The number of the dc sources may be also be reduced by using input transformers [7]. Natural fluctuations in the renewable energy sources are treated as disturbances in the input dc sources of the CMLI.

The 27-level CMLI is proposed as the interface CMLI, since it can produce an output voltage with nearly sinusoidal wave form ,[8], and was recommended for many applications, such as for induction motors and traction drives, [9-10-11].This paper shows that this inverter can also provide output voltage regulation under different disturbances in its dc sources.

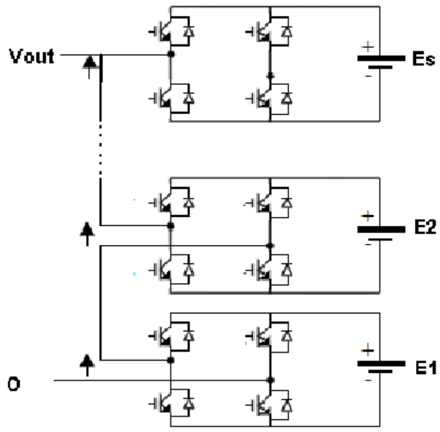

Figure 1. A cascaded multilevel with S dc sources

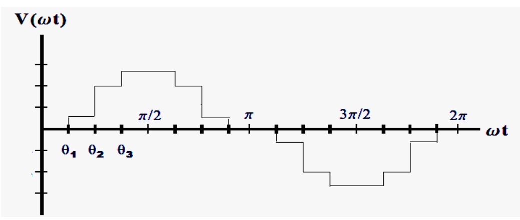

Figure 2. A staircase output voltage wave form with 3 positive levels

The 27-leevl CMLI may be realized either as, [12]

* a symmetric CMLI with 13 identical H-bridges with equal dc sources E= E_1= E_2= …= E_{13}, which are switched on positively sequentially within the positive quarter time cycle of the fundamental voltage to produced 13 positive levels: E, 2E, …., and 13E, or as

* a trinary asymmetric CMLI that consists of only three H-bridges with different dc sources E_1= E, E_2=3E and E_3=9E. The dc sources E_1 and E_2 may be switched positively or negatively with E_3 within the positive quarter time cycle of the fundamental voltage to produce the 13 positive levels: E, 2E… and 13E.

The symmetric 27-level CMLI uses larger number of H-bridges with lower voltage rating than the trinary asymmetric 27-level CMLI, and thus is more suitable for high voltage applications,. The trinary asymmetric 27-level CMLI is simpler, and is more suitable for medium and low voltage applications,[13]. These types produce uniform step output wave form. The same algorithm could be applied for both types, when determining the switching angles of the inverter power switches that minimize undesired harmonics.

A new approach using a mixed integer linear programming (MILP) optimization model was introduced in [8] to determine the switching angles of the 27-level CMLI that minimize the values of the undesired low order harmonics equally till the 31st harmonic. The proposed MILP model was applied for single phase and three phase 27-level CMLI, and showed low THD under wide range of amplitudes of the output main harmonic voltage, which agree with the IEEE standards 519-1992 for voltage distortion limits [14]. In this paper, the basic MILP mathematical model is introduced, with a modification to allow for some types of disturbances in the dc sources. First, the basic model is applied for selecting a normal operation output voltage amplitude, where all the input dc sources of the inverter have their nominal values, for single phase and three phase operation. Then voltage regulation capabilities of this inverter are investigated under some disturbances in the dc sources.

2. The Basic Mathematical Model

The general uniform step asymmetric CMLI, or symmetric CMLI, is considered, where all the inverter levels are spaced equally with a step height E. It is assumed, without loss of generality, that the inverter levels are equally spaced by 1 volt, i.e. normalized with respect to the dc voltage E. It is assumed also that the inverter output voltage wave form F(wt) has a quarter wave symmetry, as that shown in Fig. 2. The pattern of this function is generated by on and off switching of the inverter H-bridges semiconductor power switches, and is completely determined by defining the switching pattern over the interval $0 \le wt \le \pi/2$. The basic approach depends on dividing this interval into N equal small subintervals, starting at the angles 0, τ, 2τ,. . , (I-1) τ, . . , till (N-1) τ., where $\tau = \pi/2N$, Fig. 3, [15].

The positive integer values X_I, I=1, 2, . . , N are defined over each subinterval, to represent the required instantaneous output voltage level value F(wt) of the inverter, so that F(wt) is defined over the interval $0 \le wt \le \pi/2$ by:

$$F(wt) = X_I$$
$$for\ (I-1)\ \tau \le wt \le I\ \tau\ and\ I = 1,2,..,N$$

The Fourier series expansion of F(wt) is an odd - sines series given by:

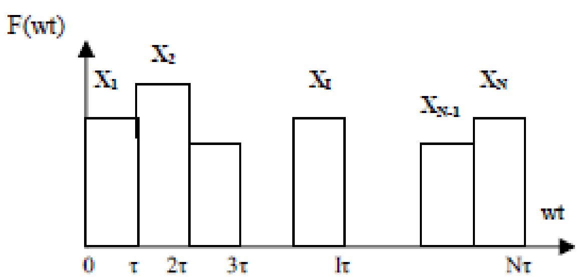

Figure 3. Representation of F(wt) by X_I, I= 1, 2, … ,N over the interval $0 \le wt \le \pi/2$

$$F(wt) = \sum_{m=0}^{m=\infty} V_{2m+1} \sin(2m+1)wt$$

Where

$$V_{2m+1} = (4/\pi) \int_0^{\pi/2} F(wt)\ \sin(2m+1)wt\ \ dwt$$

$$= (8/\pi(2m+1)) \sum_{I=1}^{I=N} X_I \sin(2m+1)\tau/2 \sin(2m+1)(\theta_I+\tau/2) \quad (1)$$

where (2m+1) is the order of the harmonic, m= 0,1, 2, . . , ∞, $\tau = \pi/2N$, and $\Phi_I = (I-1)\ \tau$.

The value of the amplitude of main harmonic corresponds to V_1, and is obtained by substituting m=0 in equation (1).

Equation (1) shows that V_{2m+1} for any value of m is a linear function of the integer values X_I , I=1,2, . ., N.

Variations of the values of X_I from a subinterval to a next one determine the required switching angles of the inverter from one level to another, like the angles θ_1, θ_2 and θ_3 of Fig.2.

It is required to find the values of X_I that minimize the values of some undesired harmonics. A mixed integer linear programming (MILP) problem is formulated as follows, [15]:

Minimize ε, subject to the constraints:

$$* \ V'_1-\Delta \le V_1 \le V'_1+\Delta \quad (2)$$

$$* \ -\varepsilon\ \alpha_{2m+1} \le V_{2m+1} \le \varepsilon\ \alpha_{2m+1}, \text{ for each undesired harmonic of order } (2m+1) \quad (3)$$

$$* \ X_I \le X_{I+1}, \text{ for } I= 1, 2, . . . , N-1, \text{ and } X_N \le L \quad (4)$$

$$* \ X_I \ge 0 \text{ and integer for } I=1, 2, . . . , N \quad (5)$$

In the main harmonic constraint (2) V'_1 is the required amplitude of the main harmonic. Δ is a small incremental value, Δ << V'_1, arbitrary chosen and included in the main harmonic constrain to ensure obtaining an optimum solution, since an equality constraint may give a high value of ε or even an unfeasible solution, due to the trigonometric nature of the constraints. The value of Δ is taken so small, that the obtained value of V_1 does not differ practically from the required value of V'_1.

In constraints (3) V_{2m+1} is given by equation (1), for the undesired harmonics, and α_{2m+1} is a weighting factor for the undesired harmonics, to enable reduction of the absolute values of the harmonics with different upper bounds according to their order.

By constraints (4) the positive staircase wave form shape is assured with maximum height L, where L is the maximum probable number of positive voltage levels of the inverter.

Constraints (5) are the integer constraints on X_I .

Once all the parameters of this MILP model are given, an optimum solution could be obtained that gives the values of X_I and ε using any of the well known operations research software packages, e.g. "LINGO" software [16].

In the following sections this model is applied for the 27-level CMLIs , taking the number of subintervals N= 180, that corresponds to a subinterval angular width of 90˚/180 = 0.5˚, Fig. 3. The switching patterns of the inverter at different values of the output voltage that minimize equally the values of low order harmonics till the 31st harmonic are obtained, i.e. by taking α_{2m+} =1 for all the minimized harmonics in constraint (3). The percentage total harmonic distortion (%THD) is calculated using the expression:

$$\%\,THD = \sqrt{\left\{ \sum_{m=1}^{m=45} \left(V_{2m+1} / V_1 \right)^2 \right\}} x100$$

The %THD is calculated till the 91st harmonic.

When solving this basic model under some disturbances in the input dc sources it may be needed to modify the model, as given in the next section.

3. Modifying the Basic Model for Some Disturbances Cases in the DC Sources

Some disturbances in the dc sources could be analyzed using the basic MILP model given in section 2, so long as the 27-level CMLI keeps its uniform step nature, where the steps of the staircase output voltage wave form, as shown in Fig.2, have equal heights. When disturbances happen unequally for some of the dc sources, the 27-level CMLI must be treated as an inverter with unequal dc sources, [17], or as a non-uniform step inverter,[18]. In these cases the basic MILP model given in section 2 is modified by replacing the integer constraints (5) imposed on the values of X_I by the constraints:

$$X_I = \sum_{J=1}^{J=S} E_J (p_{IJ} - 1) and : p_{IJ} = 0,1 or 2,$$

$$X_I >= 0, I = 1,2,...,N, and : \text{J} = 1,2,...,\text{S}...(7)$$

The values of the dc sources are given by E_J , where J=1, 2, . . , S, and S is the number of the dc sources. According to the values of P_{IJ}: 2, 1, or 0, obtained by solving the model, the values of X_I are determined.

In the next sections, the basic model is solved for single phase and three phase cases to obtain normal operation output voltage amplitude under normal values of the dc sources. Then the model is solved when these dc values are subject to some disturbances, which will need in some cases to apply the model modification given in this section.

4. Solution of the Model for the 27-Level Single Phase CMLI

4.1. Selecting an Output Voltage Amplitude for Normal Operation

The basic model is solved using the voltage constraint (2) for some values of V'_1 between 8 and 15, taking Δ =0.1, to obtain the switching angles of the inverter that minimize the odd harmonics equally from the 3rd till the 31st harmonic. Fig. 4 shows for each value of V_1, that correspond to V'1 = 8, 9, , ., and 14, the value of % THD ,given by equation (6), and the value % V_{hmax} ,which represents the maximum percentage absolute amplitude of the undesired harmonics relative to the main harmonic among all harmonics from the 3rd till the 91st harmonic. It is shown that the % THD is less than 5% and that the % V_{hmax} is less than 3% over a `wide voltage range, which agrees well with the IEEE standard 519-1992 for voltage distortion limits in power systems, for output voltages ≤ 69 kv, [14].

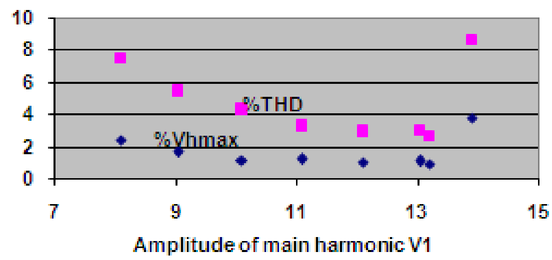

Figure 4. The values of % THD and %V_{hmax} against V_1

Low values of the %THD and %V_{hmam} are obtained for values of V_1 till above 13, normalized w. r. t. the input dc voltage E. However, it will be assumed that normal operation requires to produce an output voltage amplitude V'_1 =12, to allow for voltage regulation under different probable disturbances in the input dc sources.

The detailed solution of the model at V'_1 =12 is given next. The value of % THD = 2.67 % and of % V_{hmax} = 0.9 %. For this value of V_1, Fig. 5 shows the obtained values of X_I . The 13 switching angles of the inverter are : 1.5° , 5° , 12° , 15.5° , 22° , 26.5° , 32.5° , 38° , 45° , 51.5 °, 60° , 70° and 89.5°

Fig. 6 shows the obtained percentage values of the harmonics relative to the main harmonic from the 3rd till the 91st harmonic, and a 5% of the main harmonic at V'_1 =12.

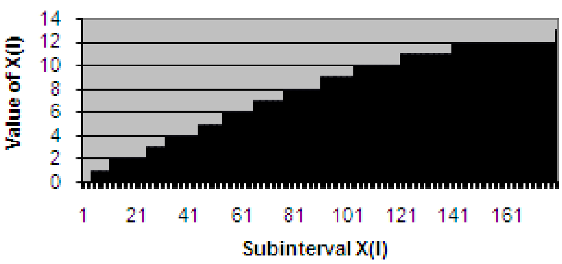

Figure 5. Values of X_I that give V'_1 =12

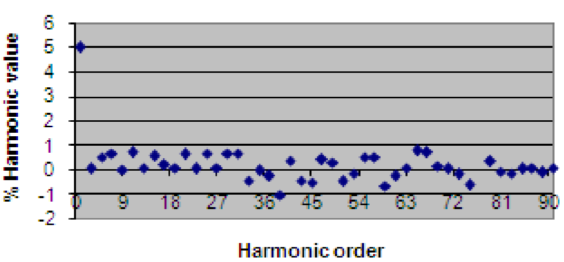

Figure 6. Values of harmonics for V'_1 =12

4.2. Solutions under Fluctuating Values of the DC Sources

The dc sources of the CMLI may be originated from a single dc source, or from separate dc sources, which may be renewable energy sources with values that are subject to natural fluctuations. In the following, it is assumed that all the dc sources of the 27-level CMLI are subject to fluctuation within ±20% of their nominal values. As a result, the voltage levels of the inverter will fluctuate accordingly. The MILP model is solved assuming the following:

* Taking in constraint (2), the output voltage amplitude value V_1'=12, and its value is allowed to deviate within ±5%, i. e .taking Δ=0.6.

* The variable X_I , that represents the value of the voltage level at each subinterval I, must reflect the assumed fluctuations in the dc sources. If all the dc sources vary between 80% and 120% of their nominal value, then the value of X_I will vary accordingly. To introduce this fluctuations in the model, the value X_I is replaced by values between 0.8 X_I and 1.2 X_I in equation (1) for V_{2m+1} for V_1 (m=0) and all the next harmonics (m>0).

Fig.7 shows the values of V_1, THD% and %V_{hmax} obtained by solving the model under the assumed fluctuations in the dc sources. The output voltage amplitude remains regulated within ±5%, of its value, and the harmonic distortion values are within the acceptable limits.

These results apply for both the symmetric and the trinary asymmetric 27-level CMLI.

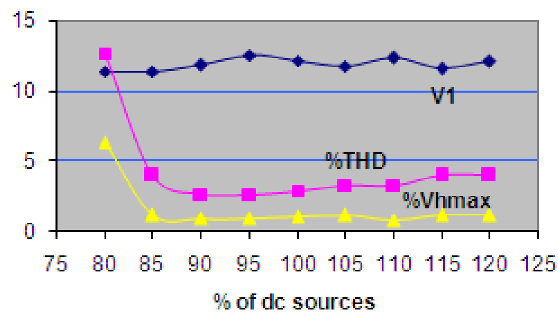

Figure 7. Values of V_1, %THD and %V_{hmax} under disturbances

It should be noted that when only some of the dc sources, not all, fluctuate within ±20% of their nominal values, then the modification given in section 3 must be introduced for solving the model to get the corresponding switching angles. However it is expected that a solution satisfying the regulation limits could be obtained, since the disturbance will be less than that considered above.

4.3. Solutions When Some DC Sources Drop to 50% of Their Values

4.3.1. For Symmetric 27-level CMLI

If the value of one of the 13 dc sources of the 13 H-bridges units drops to 50%, and it could be switched positively or negatively during the positive quarter time cycle of the output voltage, the levels in this interval can take the positive values 0.5, 1, 1.5, 2, .., and 12.5 , normalized w. r. t . the dc source value E. The inverter can operate with a maximum number of 25 uniform step positive levels, thus the basic model could be applied to study the performance of the inverter. Similarly, if the number of the dc sources that drop to 50% of their values increases to 2, 3, 4, 5, and 6, the probable maximum number of the positive levels of the inverter will be 24, 23, 22,21 and 20 respectively. Table 1 gives the obtained values of V_1 , %THD, $\%V_{hmax}$, as defined in the previous section, when solving the model when 6, 5, 4,and 3 dc sources drop to 50% of their values under the same assumption given in section 2.

Table 1. Results When The DC Sources Values Drop To 50%

DC Sources	6	5	4	3
V_1	11.40	11.40	11.40	11.54
%THD	20.7	11.14	3.68	2.22
$\%V_{hmax}$	11.3	5.28	1.44	1.18

Table 1 shows a regulated output voltage, within ±5% of its value, if 6 dc sources drop to 50% of their values.

However, low %THD could be achieved if only the values of 4 or 3 dc sources drop to 50%. This is expected to apply also when the values of 2 or 1 dc sources drop to zero, since the fluctuations will be less.

4.3.2. For Asymmetric 27-level CMLI

If all the three dc sources E_1=E, E_2=3E, and E_3=9E of the asymmetric 27-level CMLI drop to 50% of their values, it is expected that the inverter will be not able to give the required output voltage. However, the inverter may respond to some other dc disturbances which exceed that given in section 4.2. Three separate cases are taken by choosing E1=0.6E, E_2=2.3E and E_3=6.75E in each case respectively, while keeping the other two dc sources at their normal values. The results of applying the modified model with the previous assumptions are given in Table 2.

Table 2. Results for Different DC Sources Values

DC Sources	E_1= 0.6	E_2= 2.3	E_3=6.75
V_1	12.48	12.57	11.4
%THD	5.59	5.07	7.56
$\%V_{hmax}$	1.85	1.72	3.12

Table 2 shows that for these disturbance cases the output voltage is still regulated, while the values of the %THD and $\%V_{hmax}$ deviate slightly from the required IEEE standard for distortion limits [14].

4.4. Solutions When Some DC Sources Drop to Zero Values

4.4.1. For Symmetric 27-level CMLI

The symmetric 27-level CMLI consists of 13 identical H-bridges, each with a dc source of value E. When the value of any one of these dc sources drops to zero, the maximum number of the positive levels of the CMLI reduces by 1. The MILP basic model is solved assuming the number of positive levels are reduced from L=13 to 12, 11 and 10 corresponding to the failure of 1, 2 and 3 dc sources. Table 3 gives the obtained values of V_1, % THD and % V_{hmax} obtained under these disturbances.

Table 3. Solutions Under Failure Of Some DC Sources

L	13	12	11	10
V_1	12.19	11.77	11.69	11.40
% THD	2.93	3.30	3.36	12.27
$\%V_{hmax}$	1.03	1.21	1.27	5.30

If two dc sources drop to zero value, the inverter still provide the required output voltage at low % THD.

4.4.2. For Asymmetric 27-level CMLI

If E_1 drops to zero value, the inverter turns to a 9-level inverter with positive voltage levels 0, 3, 6, 9 and 12. The basic MILP model could be applied with L=4 and replacing X_I in equation (1) for V_{2m+1} by $3X_I$. The solution gives V_1 =12.29, %THD= 11.1% and $\%V_{hmax}$= 5.52%.

If E_2 drops to zero value, the solution gives an output V_1=11.45 with high %THD= 36.75%.

If E_3 drops to zero value, the inverter fails. However if E_3 drops to 8E, 7E or 6E, the inverter operates with 12, 11 or 10 positive levels respectively, and the results obtained for the symmetric case apply as well.

5. Solution of the Model for the 27-Level Three Phase CMLI

In a balanced three phase operation the triplen odd harmonics, i.e. the 3^{rd}, 9^{th}, 15^{th}, and so on, are self cancelled in the output line voltage. The procedure carried out in section 4 with single phase asymmetric CMLI is repeated while excluding the triplen odd harmonics, as follows:

5.1. Selecting an Output Voltage Amplitude for Normal Operation

The model is solved using the voltage constraint (2) for some values of V'_1 between 6 and 15, taking Δ =0.1, to obtain the switching angles of the inverter that minimize the odd harmonics equally from the 3^{rd} till the 31^{st} harmonic, excluding the triplen harmonics.

Fig. 8 shows for each value of V_1, that correspond to V'1 = 6, 7, . . and 15, the value of the % THD and the value % V_{hmax} , as defined in the previous sections. It is shown that the % THD is less than 2.5% and that the % V_{hmax} is less than 1.5% over a from the voltage range $13\leq V'_1 \leq 15$, normalized w. r. t. E .which agree well with the IEEE standard 519-1992 for voltage distortion limits in power systems, for output voltages ≤ 161 kv, [14].

It will be assumed that normal operation requires to produce an output voltage amplitude V'_1 =13, to allow for voltage regulation under different probable disturbances in the input dc sources

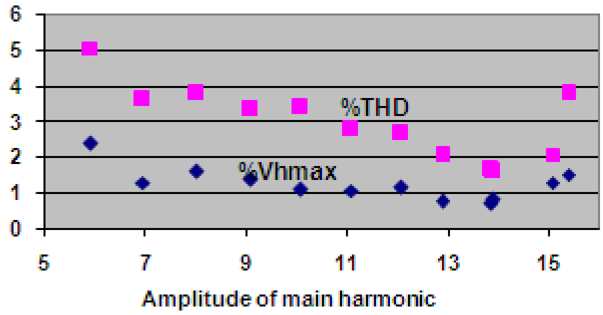

Figure 8. The values of % THD and % V_{hmax} against V_1

The detailed solution of the model at V'_1 =13 is given next. The value of % THD = 2.43 % and of % V_{hmax} = 1.03%. For this value of V_1, Fig. 9 shows the obtained values of X_I. The 13 switching angles of the inverter are : 1° , 4° , 8.5° , 14.5° , 22° , 28°, 32°, 39° , 40.5°, 46.5°, 52° , 70.5° and 75°

Fig. 10 shows the obtained percentage values of the harmonics relative to the main harmonic from the 3rd till the 91st harmonic, and a 5% of the main harmonic at V'_1 =13.

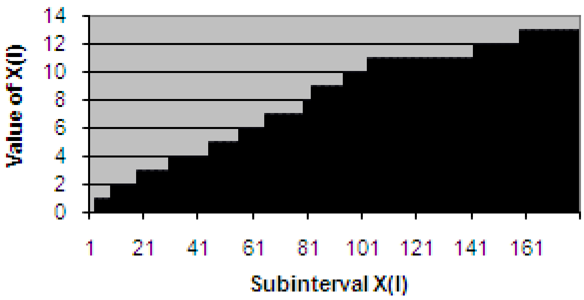

Figure 9. Values of X_I that give V'_1 =13

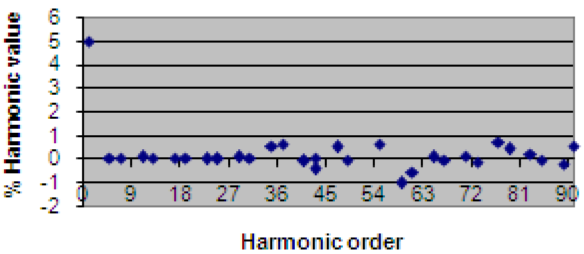

Figure 10. Values of harmonics for V'_1 =13

5.2. Solutions under Fluctuating Values of the DC Sources

In the following, it is assumed that all the dc sources of the 27-level CMLI are subject to fluctuation within ±20% of their nominal values. As a result, the voltage levels of the inverter will fluctuate accordingly.

The MILP basic model is solved assuming the following:

* Taking in constraint (2), the output voltage amplitude value V1'=13, and this value is allowed to deviate within ±5%, i.e. taking Δ=0.65.

* To introduce the fluctuations of the dc sources in the model, the value X_I is replaced by values between 0.8 X_I and 1.2 X_I in equation (1) for V_{2m+1} for V_1 (m=0) and all the next harmonics (m>0).

Fig. 11 shows the values of V_1, THD% and %V_{hmax} obtained by solving the model under the assumed fluctuations in the dc sources. The output voltage amplitude remains regulated within ±5%, of its value, and the harmonic distortion values are within the acceptable limits.

It should be noted that these results apply for both the symmetric as well as the trinary asymmetric CMLI.

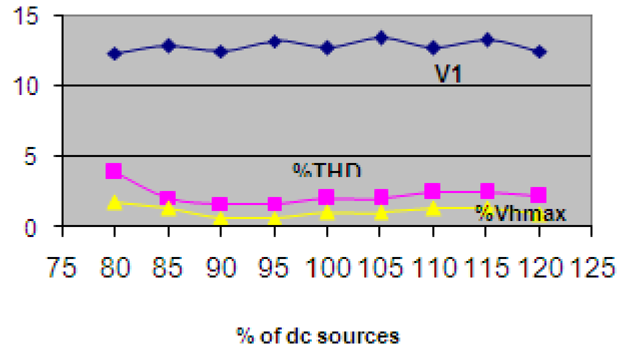

Figure 11. Values of V_1, %THD and %V_{hmax} under disturbances

5.3. Solutions When Some DC Sources Drop to 50% of Their Values

5.3.1. For Symmetric 27-level CMLI

The same procedure given in section 4.3 for symmetric 27-level CMLI is carried out. Table 4 gives the obtained values of V_1 , %THD, %V_{hmax} , as defined before, obtained by solving the basic model when 6, 5, 4,and 3 dc sources drop to 50% of their values under the same assumption given in section 2, noting that the triplen odd harmonics are excluded from the solution.

Table 4. Results When The DC Sources Values Drop to 50%

DC Sources	6	5	4	3
V_1	12.35	12.35	12.74	12.71
%THD	12.73	2.32	1.78	1.61
%V_{hmax}	8.57	0.88	1.07	1.01

Table 4 shows a regulated output voltage, within ±5% of its value, if 6 dc sources drop to 50% of their values, However, low %THD could be achieved if 5, 4 or 3 dc sources drop to 50% of their values. This is expected to apply also when 2 or 1 dc drop to 50%, since the disturbances will be less.

5.3.2. For Asymmetric 27-level CMLI

Three separate cases are taken similar to the cases taken in section 4.3.2, by choosing E1=0.6E, E_2=2.3E and E_3=6.75E in each case respectively, while keeping the other two dc sources at their normal values. The results of applying the modified model with the previous assumptions are given in Table 5.

Table 5. Results for Different DC Sources Values

DC Sources	E_1= 0.6	E_2= 2.3	E_3=6.75
V_1	13.22	13.05	12.48
%THD	2.90	2.60	2.17
$\%V_{hmax}$	1.39	1.74	0.76

Table 5 shows that for these disturbance cases the output voltage is still regulated, while the values of the % THD and $\%V_{hmax}$ deviate slightly from the required IEEE standard for distortion limits [14].

5.4. Solutions When Some DC Sources Drop to Zero Values

5.4.1. For Symmetric 27-level CMLI

The MILP basic model is solved assuming that the maximum number of positive levels are reduced from L=13 to 12, 11 and 10 corresponding to the failure of 1, 2 and 3 dc sources. Table 6 gives the obtained values of V_1, % THD and % V_{hmax} obtained under these disturbances. If two dc sources drop to zero value, the inverter still provide the required output voltage at low % THD.

Table 6. Solutions Under Failure Of Some DC Sources

L	13	12	11	10
V_1	12.73	12.71	11.75	12.35
% THD	2.03	1.46	2.21	12.67
$\%V_{hmax}$	1.03	1.02	1.06	8.57

5.4.2. For Asymmetric 27-Level CMLI

If E_1 drops to zero value, the inverter turns to a 9-level inverter with positive voltage levels 0, 3, 6, 9 and 12. The MILP basic model could be applied with L=4 and replacing X_I in equation (1) for V_{2m+1} by $3X_I$. The solution gives V_1 =12.84, %THD= 8.1% and $\%V_{hmax}$= 4.75%.

If E_2 drops to zero the solution the solution gives an output V_1=12.36 with high %THD= 20.2%.

If E_3 drops to zero, the inverter fails. However if E_3 drops to 8E, 7E or 6E, the inverter operates with 12,11 , or 10 positive levels respectively, and the results obtained for the symmetric case apply here.

6. Conclusions

This paper introduces the 27-level CMLI as a suitable interface unit between renewable energy sources and the smart grid, where these sources represent the input dc sources of the inverter. The switching angles of the power switches of this inverter are calculated using a MILP optimization model that minimizes the absolute values of the low order harmonics till the 31^{st} harmonic. The 27-level CMLI has shown the following advantage:

1. It produces a nearly sinusoidal output voltage wave form under the nominal values of the dc sources, that agree with the IEEE standard 519-1992 for voltage distortion limits in power systems, for output voltages ≤ 69 kv for single phase inverter, and for output voltages ≤ 161 kv for three phase inverter [14].
2. It may be realized as a symmetric CMLI with 13 H-bridges of identical dc sources, or as an asymmetric CMLI with only 3 H-bridge with dc sources of different values.
3. It can provide a regulated output voltage, deviating within ±5%, for different disturbances in the dc sources while keeping low values of the %THD of the output voltage. These disturbances include fluctuations in the dc sources within ±20% of their nominal values, reduction of the values of some dc sources by 50%, and the failure of one or two dc sources. The symmetric 27-level CMLI shows better reliability than the asymmetric one, since it can operate well even when two dc sources drop to zero value from its 13 dc sources.

Other probable disturbances could be analyzed under different allowable deviations in the value of the output voltage by following procedures similar to that given in this paper.

Under each disturbance case in the dc sources, the MILP model should be resolved to determine the corresponding switching angles of the power switches of the inverter. The model is based on dividing the quarter time cycle of the main voltage into a number of subintervals N=180, and associating a specific voltage level with each subinterval. Satisfactory optimal solutions are obtained, and each solution takes few minutes on a usual PC. Solutions with lower values of the THD may be obtained if larger number of subintervals is taken, but this will increase the solution time. On the other hand, the solution time will decrease with smaller number of subintervals, but higher THD values may be obtained. In all these cases, the solution time may be reduced greatly when using a high speed computer, which makes it possible to perform on line adaption with dc sources disturbances. In addition, looking-up tables for the switching angles of the inverter for frequently repeated fluctuation cases may be stored to be applied directly when needed.

Using the 27-level CMLI as an interface unit between renewable energy sources and the smart grid will help in regulating the output voltage obtained from these sources under many probable disturbances, which lead to more stability in the grid and reduce the amount of standby energy storage needs and their associated costs.

REFERENCES

[1] Steven Bushong, “A Foundation for The Grid-Tied Smart Inverter of The Future”, Solar Power World, Feb. 2013.

[2] M. Bouzguenda, A.Gastli, A.H. Al Badi, T. Salmi, “Solar Photovoltaic Inverter Requirements for Smard Grid Applications”, IEEE PES Conf. Middle East Innovative Smart Grid Technologies (ISGT), Saudi Arabia, Jeddah,17-20 Dec.2011.

[3] M. Malinowoki, “A Survey on Cascaded Multilevel Inverters”, IEEE Trans. Industrial Electronics, vol.57, issue 7, 2010, pp. 2197-2206.

[4] M. Tsang, W.L. Chan,”27-level DC-AC Inverter with Single Energy Source”. Energy Conversion and Management, vol.53,issue 1, Jan. 2012, pp.99-107.

[5] J.J. Park, M.H. Lee, C. Kin, “An Efficient Multilevel-Synthesis Approach and its Application to a 27-level Inverter”. IEEE Trans. Industrial Electronics, Dec. 2005, vol.52, issue 6, pp.1600-1606.

[6] A.K. Panda, Y. Suresh, “Performance of CMLI by employing Single and Three Phase Transformers”. IET Power Electronics, vol.5, issue 9, 2012, pp.1694-1705.

[7] M.Rotella, S.A. ABB, G. Penailillo, I. Perdo, J. Dixon, “PWM Method to Eliminate Power Sources in Nonredundant 27 Level Inverter for Machine Drive Applications”, IEEE Trans. Industrial Electronics, vol.56, no. 1, 2009, pp. 194-201.

[8] M. El-Bakry, “Applying MILP for 27-Level CMLI to Obtain Low THD Values Over Wide Voltage Range”, Journal Energy and Power Engineering EPE, June, vol. 5, no.4, 2013, pp.315-321.

[9] K. Ramani & A. Krishnan, “New Hybrid 27 Level MLI Fed Induction Motor Drive”, Int. Journal of Recent Trends in Engineering, Vol. 12, No. 5, Nov. 2009.

[10] J. Dixon, j. Preda, C. Castillo & S. Bosch, “Asymmetrical Multilevel Inverters for Traction Drives Using Only One DC Supply”, IEEE Trans. on Vehicular Technology, Vol. 59, Issue 8, Oct. 2010, pp.3736-3743.

[11] F. Khoucha, M. S. Lagoam, A. Kheloui & M. E. Benbouzid, “Comparison of Symmetrical and Asymmetrical Three Phase H-Bridge MLI for DTC Induction Motor Drives”, IEEE Trans. on Energy Conversion, Vol. 26, No. 1, March 2011, pp.64-72.

[12] C. Hua, C. Wa, c. Chuang, “Control of The 27-Level CMLI with Three H-Bridge Inverter Modules”, IEEE International Conference Industrial Topologies (ICIT), Dec. 2006, pp.277-282.

[13] M. N. Ben Nasr, A. Kebir& F. Ben Ammar, “Cascaded H-Bridges Symmetrical 11-Level Optimization”, Proceedings of 14th Int. Middle East Power Systems Conf. (MEPCON’2010), Cairo, Egypt, Dec. 2010, pp 465-470.

[14] IEEE Standard 519-1992, “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”. IEEE, 1993.

[15] M. El-Bakry, "Using Linear Programming Models for Minimizing Harmonics Values in Cascaded Multilevel Inverters"', Proc. of 2010 IEEE/ASME International Conf. on Advanced Intelligent Mechatronics (AIM'2010), Montereal, Canada, July 2010, pp. 696-702.

[16] Lindo Systems Inc.,"Optimization modeling with LINGO", 2004, www.lindo.com.

[17] M. El-Bakry, “Minimizing Harmonics Values in Cascaded Multilevel Inverters with Unequal DC sources”. IEEE PES Conf. Middle East Innovative Smart Grid Technologies (ISGT), Saudi Arabia, Jeddah,17-20 Dec.2011

[18] M. El-Bakry, “Minimizing Harmonics Values in Non-Uniform Step Asymmetric CMLIs”, International Journal of Emerging Technology and Advanced Engineering, Vol.2, Issue 10 October 2012, pp.5-11.