Performance of Cascade Multilevel H-Bridge Inverter with Single DC Source by Employing Low Frequency Three-Phase Transformers

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***Abstract*: Among the mature multilevel converter topologies, cascade multilevel H-Bridge inverter is promising one which is an alternative for grid-connected photovoltaic/ wind-power generator, flexible alternating current systems and motor drive application. The CMC (cascade multilevel converter) can flexibly expand the output power capability and is favorable to develop. Present paper elevates a new structure of CMC with a low frequency three-phase transformers and a single DC power source. Comparing with conventional CMC this new CMC uses less number of components for same number of output levels. As three phase transformer was employed harmonic components of the output voltage and switching losses can be diminished considerably. Computer aided simulations was performed through matlab/simulink and simulation results for seven, nine, eleven, thirteen & fifteen level are presented to verify the performance of proposed cascade multilevel inverter.**

***Keywords:* Cascade multilevel inverter, harmonics, and low frequency three-phase transformers.**

I. INTRODUCTION

Multilevel power converter has become progressively more popular in recent years due to advantages of high power quality waveforms, low switching losses, high voltage capability, low electromagnetic compatibility (EMC) etc[1]. Multilevel converter can be divided into four remarkable topologies: diode-clamped multilevel converter (DCMC), flying capacitors multilevel converter (FCMC), P_2 Multilevel converter (P2MC) and cascade multilevel converter (CMC) with separate dc source [2]. These entire converters are compared in terms of feasibility of their utilization and its applications [9]. According to the MIL-HDBK-217F standard, the reliability of system is indirectly proportional to the number of its Components [10], so less the components more the reliability. Compared to m-level DCMC, FCMC, and P2MC, which use *m-1* capacitors on the dc bus, the CMC uses only *(m-1)/2* capacitors for same *m-level.* Clamping diodes are not required for FCMC, P2MC and CMC. In overall P2MC undeniably require too many components as compared to other multilevel converters so it is not suitable for higher voltage levels. However on comparing CMC with DCMC, FCMC and P2MC it requires least number of components and its dominant advantage is circuit layout with flexibility. But a primary disadvantage of the CMC is it uses a separate dc source for each H-Bridge, this yield significant cost [3]. In this paper a CMC has been proposed which employ single dc source with isolated three-phase low frequency transformers. The proposed configuration employs reduce number of transformers as compared with traditional three-phase multilevel inverters and so it is economical and efficient. All the relay angles of converter are calculated by Newton Raphson method, on the basis of the area of each switch, relay angles are obtained by linearization method and this approach is useful to eliminate low order harmonic components of output voltages. Necessary simulation results are presented to verify proposed approach [4].

II. GENERALIZED CASCADED TOPOLOGY

Fig.1 shows a basic structure of cascade inverter with separate dc source (SDC's) this converter avoids extra clamping diodes or voltage balancing capacitors. Each separate dc source is associated with single balancing capacitors and with single phase H-bridge converter. All such four inverters together forms cascade multilevel inverter. Fig.2 shows a nine level cascaded H-Bridge multilevel phase voltage waveform. Phase output voltage (V_0) is the sum of all four inverter outputs [5-7]. Fig.3 shows the three phase Y-configured cascade converter. The primary drawback of the H-bridge inverter is that, there is a possibility of short circuit of the input dc voltage sources. Where as in the proposed topology we don't have such a situation.

III. PROPOSED CASCADE H-BRIDGE MULTILEVEL INVERTER

Fig.4 shows the boost type H-bridge multilevel converter employing cascade transformers. Four H-Bridge modules are connected to single dc-source in parallel but in the secondary side four transformers are connected in series, this make the converter size big and their by increasing cost. Fig.5 shows proposed H-Bridge multilevel inverter with single dc source and several low frequency three phase transformers, this make the size of the equipment come down with less price tag [8]. Coming to structure point of view, each primary terminal of the transformer is connected to an H-Bridge module so as to Synthesize output voltages of $+V_{DC}$, Zero, $-V_{DC}$. Every secondary of transformer is connected in series to pile of output level up. Further, each phase terminal is delta connected to restrain the third harmonic component. Fig.5.b shows primary of each phase is three phase and secondary is single phase terminal. All three terminals are series connected

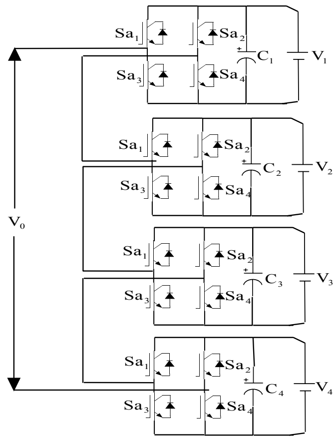

Fig.1 Conventional cascade H-Bridge multilevel inverter (9level).

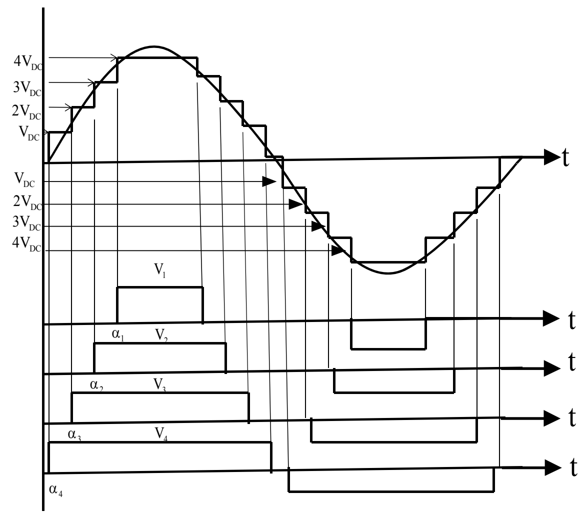

Fig. 2. Operational waveforms for nine level inverter.

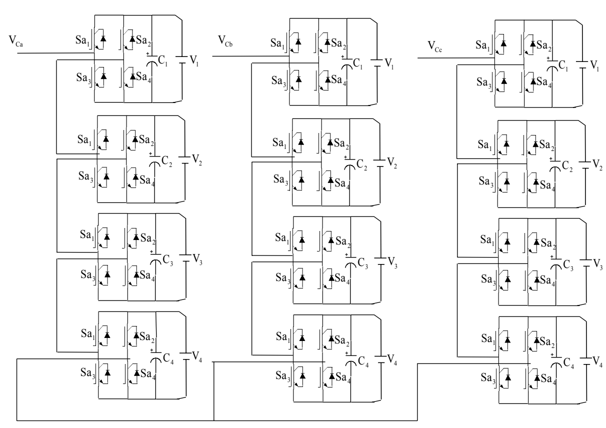

Fig.3 The connection diagram for a Y-configured 9-level converter using cascaded-inverters with four SDC capacitors.

to generate phase voltage. Therefore each phase can be expressed independently. As a result each phase multilevel inverter can be depicted as an isolated H-Bridge cascaded multilevel inverter. We can obtain the relation between input and output voltages of three phase transformer as

$$\begin{bmatrix} V_{ak} \\ V_{bk} \\ V_{ck} \end{bmatrix} = \frac{N}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \tag{1}$$

Where N is the transformation ratio (n_2/n_1) between primary and secondary. If there is a balanced input, then sum of the each phase voltage would become zero.

$$V_{ak} + V_{bk} + V_{ck} = 0 \tag{2}$$

From above two equations we can put across

$$\begin{bmatrix} V_{Ak} \\ V_{Bk} \\ V_{Ck} \end{bmatrix} = T \begin{bmatrix} V_{ak} \\ V_{bk} \\ V_{ck} \end{bmatrix} \tag{3}$$

From equation (3) with our proposed configuration we are obtaining each phase output voltage of transformer as product of input voltage and transformation matrix N. But equation (3) does not satisfy under unbalance conditions, because primary of transformer is connected to an H-Bridge cell generating V_{dc}, zero, $-V_{dc}$, it represents that output voltage is balance when V_{ak}, V_{bk}, and V_{ck} are all V_{dc}. Thus output voltage is unbalance at this condition, so equation (1) holds good for unbalance condition and it is represented by magnetic circuit concept notifying that flux at the primary of phase a will be equally influenced on phase b and phase c and becomes -1, so an unbalance relationship is also included in equation (1). As shown in Fig.5, proposed multilevel inverter secondaries are connected in series so output is the sum of all three voltages. Thus it can be represented as

$$V_{AS} = \sum_{i=1}^{k} X_{Ai}$$
$$V_{BS} = \sum_{i=1}^{k} X_{Bi}$$
$$V_{CS} = \sum_{i=1}^{k} X_{Ci} \tag{4}$$

Line voltages V_{AB}, V_{BC} and V_{CS} are given by

$$\begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} = \begin{bmatrix} V_{AS} \\ V_{BS} \\ V_{CS} \end{bmatrix} = \begin{bmatrix} V_{A1} + V_{A2} + \dots\dots V_{Ak} \\ V_{B1} + V_{B2} + \dots\dots V_{Bk} \\ V_{C1} + V_{C2} + \dots\dots V_{Ck} \end{bmatrix} \tag{5}$$

IV. COMPUTATION OF SWITCHING ANGLES

We have already seen that output voltage of proposed inverter is sum of secondary terminal voltages of transformer which are connected in series and all these are independent of

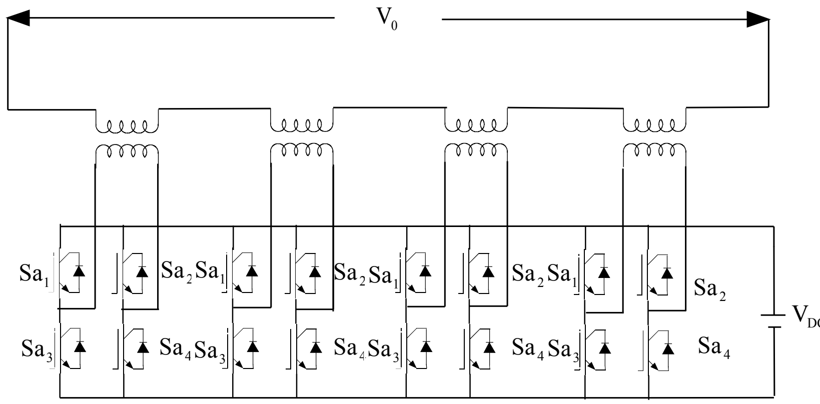

Fig.4 Single phase boost-type H-Bridge multilevel inverter employing 4 single phase transformers and single dc source.

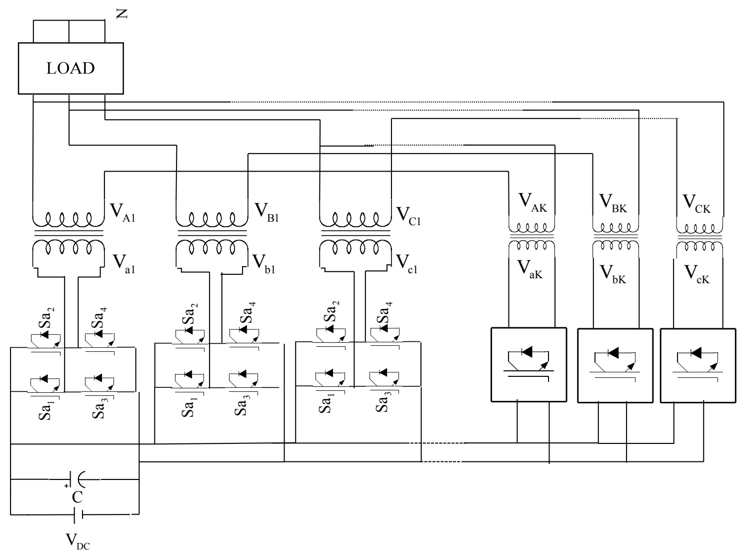

Fig.5 a) Proposed multilevel inverter employing three phase transformer

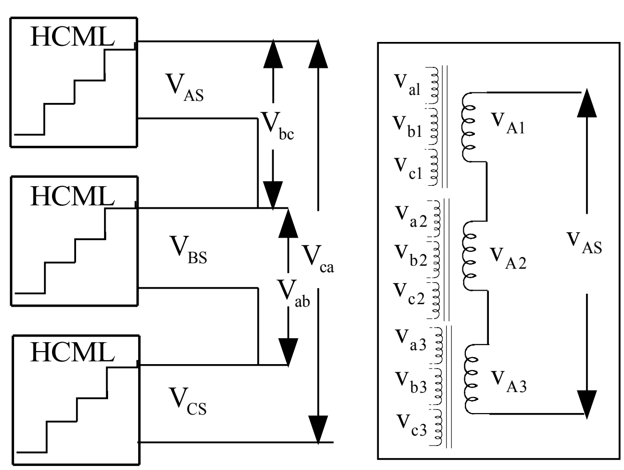

Fig.5 b) Simplified structure for propose multilevel inverter

Switching angles, range from $0<\alpha_k<\pi/2$. Thus output voltage can be represented as

$$V_{AB} = 4V_{DC} / n\pi(\cos(n\alpha_1) + \cos(n\alpha_2) + \cos(n\alpha_3)) \tag{6}$$

Output voltages of converter are controlled by switching angles, which are represented by $\alpha_1, \alpha_2, \alpha_3$, all these angles lie between 0 and $\pi/2$ and it can be represented as $0\leq \alpha_1\leq \alpha_2\leq \alpha_3\leq\pi/2$. Controlling these switching angles we can control the fundamental component and 5th and 7th harmonic components were suppressed. The 3rd harmonic component can be completely eliminated because of transformer connections.

A set of nonlinear equation can be written to find optimized harmonic switching angles.

$$\begin{aligned} &\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) = 3m\pi / 4 \\ &\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) = 0 \\ &\cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) = 0 \end{aligned} \tag{7}$$

Where m is the modulation index, which is varied from 0.1 to 1. In order to find the switching angles of non linear equation, we follow Newton Raphsons method. In this method from the generalized equation the switching angle matrix is found and then it is transposed.

$$\alpha^j = \begin{bmatrix} \alpha_1^j & \alpha_2^j & \alpha_3^j \end{bmatrix}^T \tag{8}$$

The non linear system matrix is derived from equation (7).

$$F^j = \begin{bmatrix} \cos(\alpha_1^j) + \cos(\alpha_2^j) + \cos(\alpha_3^j) \\ \cos(5\alpha_1^j) + \cos(5\alpha_2^j) + \cos(5\alpha_3^j) \\ \cos(7\alpha_1^j) + \cos(7\alpha_2^j) + \cos(7\alpha_3^j) \end{bmatrix} \tag{9}$$

Then corresponding Jacobean matrix of above equation is found.

$$F^j = \begin{bmatrix} -\sin(\alpha_1^j) - \sin(\alpha_2^j) - \sin(\alpha_3^j) \\ -\sin(5\alpha_1^j) - \sin(5\alpha_2^j) - \sin(5\alpha_3^j) \\ -\sin(7\alpha_1^j) - \sin(7\alpha_2^j) - \sin(7\alpha_3^j) \end{bmatrix} \tag{10}$$

$$T = \begin{bmatrix} \frac{m*3*\pi}{4} & 0 & 0 \end{bmatrix} \tag{11}$$

Thus above equations can be written in one matrix format.

$$F(\alpha) = T \tag{12}$$

As Newton Raphson starts with initial guessing, so some initial value for α are guessed with j=0 and thus linearized the equation by using

$$F(\alpha^0) + \left[\frac{\partial f}{\partial \alpha}\right]^0 \partial\alpha^0 = T \tag{13}$$

Further updating the initial values, we can obtain the switching angles α_1, α_2, α_3 which are less than $\pi/2$.

TABLE I
CALCULATED SWITCHING ANGLES BASED ON THE MODULATION INDEX

M modulation Index	α1	α2	α3
0.1	76.42		
0.2	61.93		
0.3	50.22	86.24	
0.4	44.24	74.33	
0.5	41.00	66.00	89.40
0.6	39.44	58.63	83.10
0.7	29.21	54.45	64.52
0.8	29.23	54.44	64.50
0.9	17.50	43.14	64.15
1	11.75	31.22	58.65

V. SIMULATION RESULTS

Fig.6 shows the calculated switching angles and actual switching angles, at different modulation index. It can be observed that at modulation index 1 switching angle of transformer is 11.70^0 and its extinction angle is 168.3^0, which produces output voltage V_{AI} shown in Fig.5b. Similarly for transformers two and three switching angles are 31.2^0 and 58.6^0 and there corresponding extinction angles are 148.8^0 and 121.4^0 respectively. Rest of the switching angles from M=0.1 to 1 were given in table 1. This entire switching angle is obtained by Newton Raphsons method. With help of above switching angles magnitude of fundamental component are controlled and fifth and seventh harmonic components are completely eliminated. In order to verify proposed structure we performed simulation analysis for seven, nine, eleven, thirteen and fifteen level inverters, with different modulation indexes varying from 0.1 to 1. Fig.7 represents the voltage waveforms, current waveforms and harmonic spectrums for different levels of inverters at the modulation index 1.0. Fig.8 shows the different THD values obtained for different modulation indexes. It is observed that THD of voltage harmonics of seven level inverter is 14.14% as compared to 6.4% that of fifteen level inverter. Thus power quality has improved predominantly. Conversely, the proposed topology

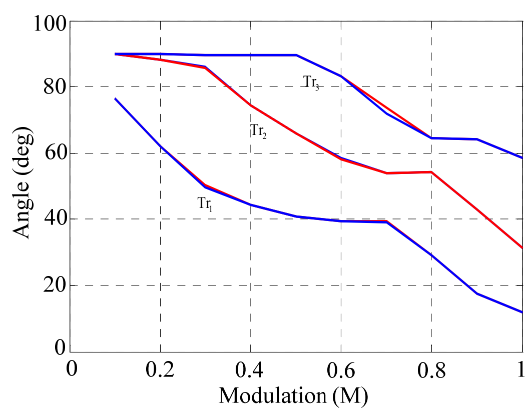

Fig.6 Variation of switching angles based on different modulation indexes

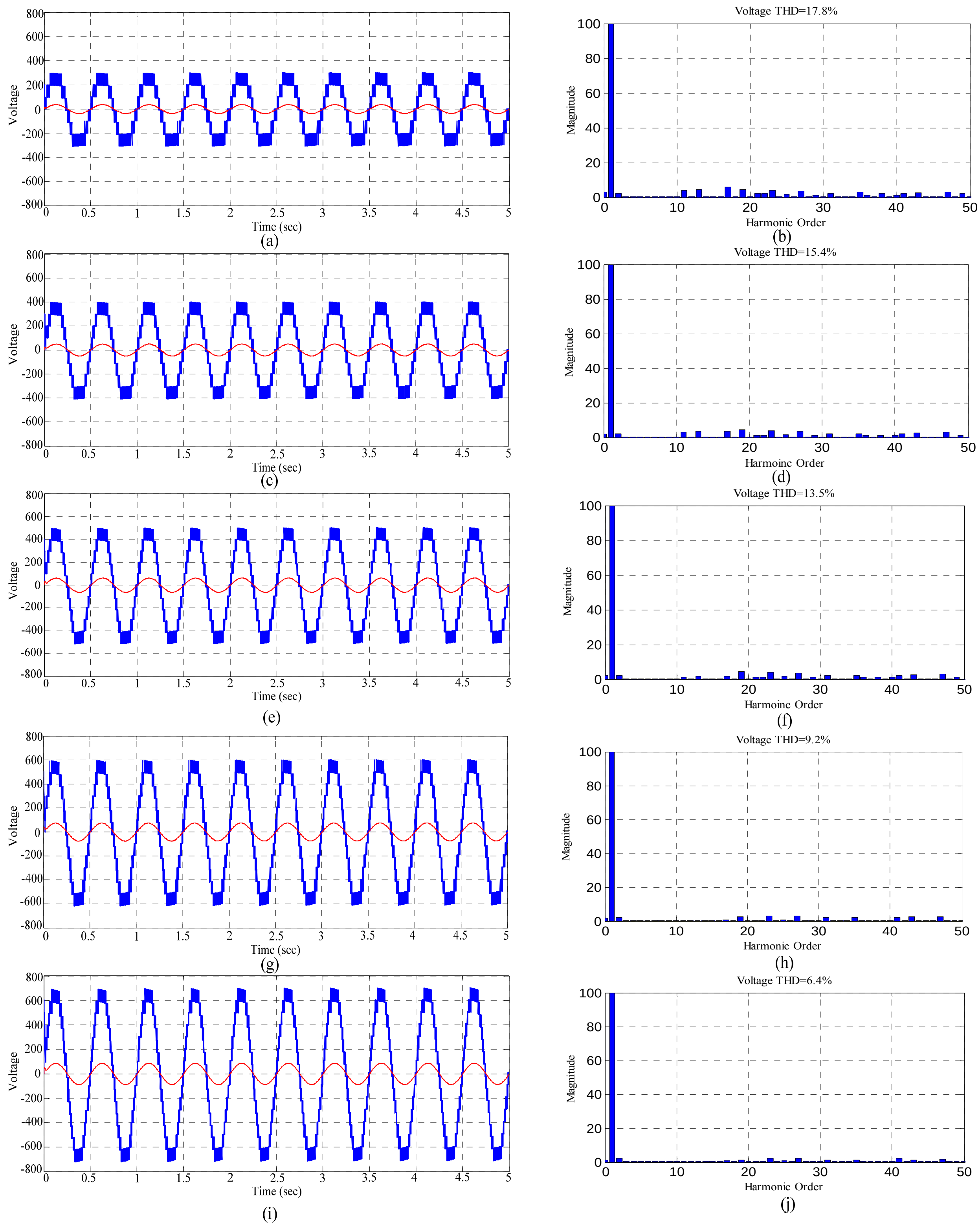

Fig.7 Output voltage waveforms, current wavefroms and harmoinc spectrums at modulation index 1: (a) & (b) seven level inverter, (c) & (d) nine level inverter, (e) & (f) eleven level inverter, (g) & (h) thirteen level inverter, (i) & (j) fifteen level inverter.

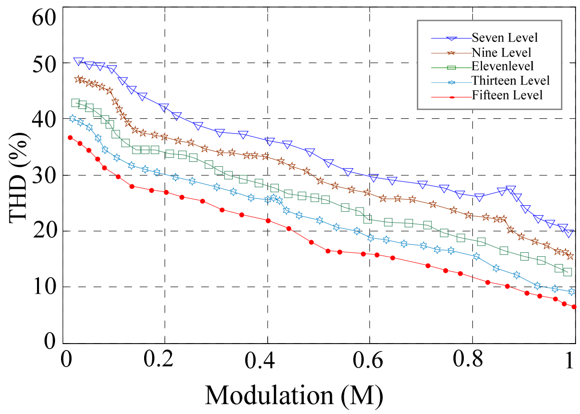

Fig.8 THD of output voltage on the variation of modulation index

has some drawbacks, such as, these are not suitable for variable frequency application, because of the transformers on the ac side. Further since three three-phase transformers are used in the proposed topology, the cost and size will be slightly increased. But since this inverter employs single dc input power source and three isolated three-phase transformers and considering that the output voltage is synthesized by an accumulation of each transformer output, it does not require an additional transformer for galvanic isolation, which results in an economical & efficient inverter.

VI. CONCLUSION

This paper proposed a cascaded multilevel inverter, which employed a single dc input source and low frequency three-phase transformers. The proposed circuit reduces a number of transformers required compared with conventional structure, and simulation results validate the proposed CMC structure. Harmonic spectrums for seven, nine, eleven, thirteen and fifteen level are presented. Comparing the results, it is seen that harmonic content has been predominately reduced. The other advantages of this converter are; increasing utilization rate as only one dc source is used with isolated transformers. Again since less number of equipments are used, the size and weight will trim down. Low switching frequency ensures less transition loss which reduces EMI problems. With the help of Newton Raphsons method different relay angles are computed, which is responsible for removing higher order harmonics.

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