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A NEW TOPOLOGY FOR CASCADED MULTILEVEL INVERTERS WITH SINGLE DC INPUT

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ABSTRACT

This paper proposes two methodologies that are extended from the existing Cascaded Multilevel Inverter Employing Three-Phase Transformers and Single DC Input topology. The proposed circuit configuration can reduce the number of switches required to convert the input DC power into AC power when compared with traditional method. However Simulation results reveals that the THD variation of the proposed methods have no considerable changes from the existing one even though we reduce the number of switches. To verify the performance of the proposed approach, we implemented computer-aided simulations using Matlab/Simulink.

KEY WORDS: Cascaded multilevel inverter, harmonics, switching phase angle control, three-phase transformers.

1. INTRODUCTION

Multilevel inverters can be divided into three remarkable topologies: diode-clamped, flying capacitors, and cascaded H-bridge cells with separate dc sources. In this paper, we propose a new topology for cascaded H-bridge multilevel inverters which employs one single dc input power source and isolated three-phase low-frequency transformers. The new topology can be applicable to both single and three phase applications. By the proposed circuit configuration, a number of switching devices can be reduced, compared with traditional three-phase and single-phase multilevel inverters employing transformers and single DC input.

2. BASIC OPERATION CASCADED H-BRIDGE MULTILEVEL INVERTER

One multilevel converter topology incorporates cascaded single-phase H-bridges with separate dc sources (SDCSs) [1], [2], [7]–[10]. This requirement makes renewable energy sources such as fuel cells or photovoltaic's a natural choice for the isolated dc voltage sources needed for the cascade inverter [8],[9],[15],[17]. Fig. 1 shows a single-phase structure of an m-level cascaded inverter.

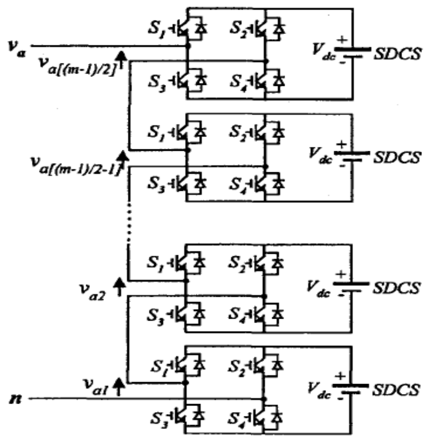

Figure 1 : Single Phase Structure of a Multi level cascaded H-Bridge Inverter

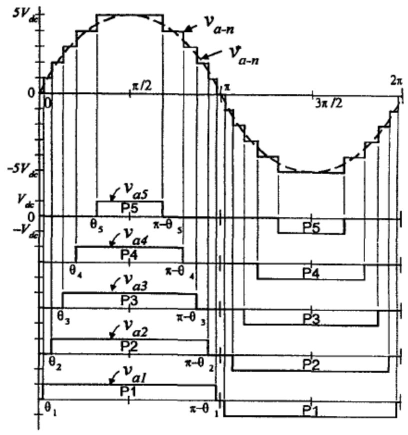

Figure 2 : Waveforms and switching method of the 11-level cascaded inverter

Each **SDCS** is connected to a single phase full-bridge, or H-bridge, inverter. Each inverter level can generate three different voltage outputs, $+V_{dc}$, 0, and $-V_{dc}$, by connecting the dc source to the ac output by different combinations of the four switches, S_1,S_2,S_3 and S_4 . To obtain $+V_{dc}$ switches S_1 ***and*** S_4 are turned on. Turning on switches S_2 and S_3 yields $-V_{dc}$. By turning on S_1 and S_2 or S_3 and S_4, the output voltage is 0. The ac outputs of each of the different full-bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs. The number of output phase voltage levels *m* in a cascade inverter is defined by m = 2s+l, where **s** is the number of separate dc sources (photovoltaic modules or fuel cells). These multilevel inverters are widely used in manufacturing factories and acquired public recognition as one of the new power converter fields because they can overcome the disadvantages of traditional pulse width – modulation (PWM) inverters [1]-[9],[16].

An example phase voltage waveform for an 11- level cascaded H-bridge inverter with ***5*** **SDCSs** and ***5*** full bridges is shown in Fig.2 . The phase voltage $V_{an}=V_{a1}+V_{a2}+V_{a3}+V_{a4}+V_{a5}$ The conducting angles □***1,***□***2,***□***3,***□***4*** and □***5*** can be chosen such that the voltage total harmonic distortion is a minimum. Normally, these angles are chosen so as to cancel the predominant lower frequency harmonics. For the 11-level case in Fig. 2, the 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics can be eliminated with the appropriate choice of the conducting angles. One degree of freedom is used so that the magnitude of the fundamental waveform corresponds to the reference waveform's amplitude or modulation index [11].

3. CASCADED MULTI-LEVEL INVERTER EMPLOYING THREE-PHASE TRANSFORMERS AND SINGLE DC INPUT

Fig. 3 shows a circuit configuration of the Multi-level inverter for three-phase applications. It consists of one single dc input source and several low-frequency three-phase transformers [19]. By using the three-phase transformers, the number of transformers and the volume of system can be reduced. Each primary terminal of the transformer is connected to an H-bridge module so as to synthesize $+V_{DC}$ zero, and $-V_{DC}$. Every secondary of the transformer is connected in series to pile the output level up. Moreover, each phase terminal is delta connected to restrain the third harmonic component. Fig. 4 shows a predigested representation of Fig. 3. As shown in Fig. 4, the primary of each transformer is a three-phase one, and each secondary is a single-phase terminal. Three terminal outputs are series connected to generate the voltage V_{AS}. In this configuration, each phase can be expressed independently, and we call each phase multilevel inverter as isolated H-bridge cascaded multilevel inverter. In Fig. 3, V_{ak}, V_{bk}, and V_{ck} mean the output voltages of the H-bridge inverter connected to the k^{th} transformer. Here, V_{Ak}, V_{Bk}, and V_{Ck} are the output voltages of the transformers in each phase.

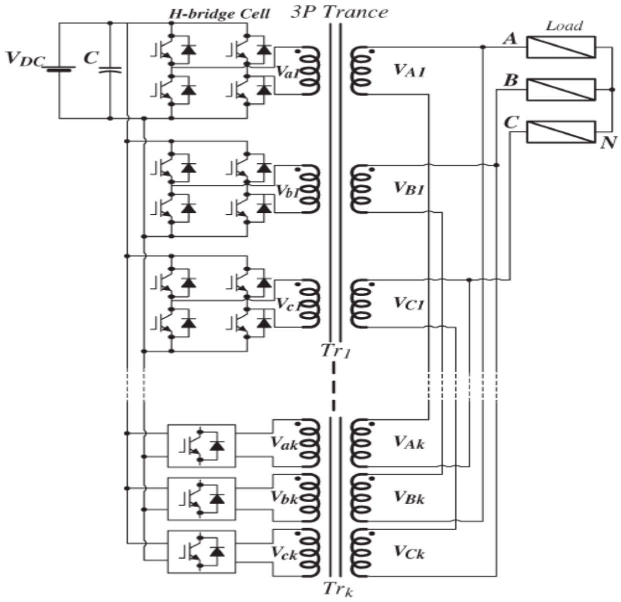

Figure 3 : Traditional multilevel inverter using 3 phase transformers

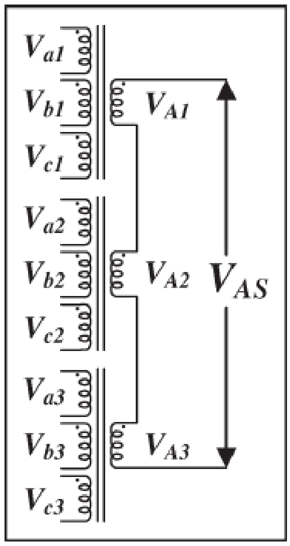

Figure 4 : Simplified Structure of Fig. 3

4. PROPOSED CASCADED H-BRIDGE MULTILEVEL INVERTER

4.1 Circuit Configuration

Fig. 5 shows a circuit configuration of the proposed multilevel inverter for three-phase applications. It consists of one single dc input source and several low-frequency three-phase transformers. By using the three-phase transformers, the number of transformers and the volume of system can be reduced. As a result, the price of the system is deservedly down. Each primary terminal of the transformer is connected to an H-bridge module so as to synthesize $+V_{DC}$, zero, and $-V_{DC}$. Every secondary of the transformer is connected in series to pile the output level up. Moreover, each phase terminal is delta connected to restrain the third harmonic component.

In Fig. 5, V_{ak}, V_{bk}, and V_{ck} mean the output voltages of the H-bridge inverter connected to the k^{th} transformer. Here, V_{Ak}, V_{Bk}, and V_{Ck} are the output voltages of the transformers in each phase. Therefore, the relationship between the input and the output voltages of the three-phase transform er is given as

$$\begin{bmatrix} V_{Ak} \\ V_{Bk} \\ V_{Ck} \end{bmatrix} = \frac{T}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} V_{ak} \\ V_{bk} \\ V_{ck} \end{bmatrix} \quad (1)$$

Where T is the transformation ratio ($n2/n1$) between the primary and the secondary of the transformer. If the input voltage is balanced in three phases, the sum of each phase voltage becomes zero.

$$V_{ak}+V_{bk}+V_{ck}=0 \quad (2)$$

From (1) and (2), the output voltage is expressed as

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

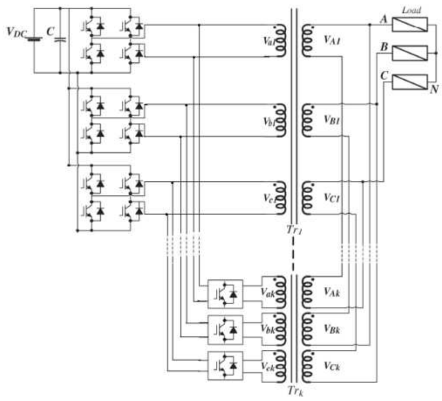

Figure 5 : Proposed circuit diagram

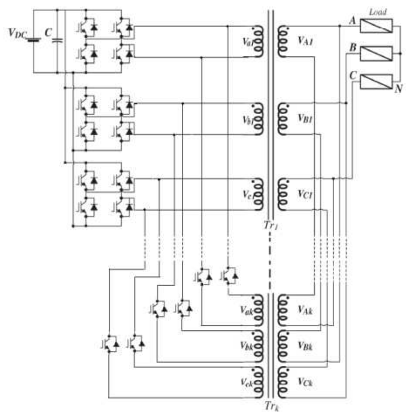

Figure 6 : Detailed view of proposed circuit

From (3), we can notice that each phase output voltage of the transformer is given by the product of each phase input voltage and turn ratio of the transformer. However, in the proposed circuit configuration, it is often unbalanced in three phases because the primary of the transformer is connected to an H-bridge cell generating $+V_{DC}$, zero, and $-V_{DC}$. It means that the output voltage is balanced at $V_{ak} = +V_{DC}$, $V_{bk} =-V_{DC}$, and $V_{ck} = 0$; however, when V_{ak}, V_{bk}, and V_{ck} are all V_{DC}, the output voltage is unbalanced. Therefore, the proposed circuit relies on (1) instead of (3). Equation (1) has been expressed by the magnetic concept. For example, a formed flux at the primary of phase "*a*" will be equally influenced on phases "*b*" and "*c*." Assuming that the quantity of the formed flux is two, the flux of both phases "*b*" and "*c*" becomes −1. By this concept, we can include the unbalanced relationship to (1).

As shown in Fig. 6, the output voltage of the proposed multilevel inverter is synthesized by the series-connected secondary of the transformer outputs. Hence, line voltages V_{AB}, V_{BC}, and V_{CA} can be given by

$$\begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} = \begin{bmatrix} V_{AS} \\ V_{BS} \\ V_{CS} \end{bmatrix} = \begin{bmatrix} V_{A1} + V_{A2} + ... + V_{AK} \\ V_{B1} + V_{B2} + ... + V_{BK} \\ V_{C1} + V_{C2} + ... + V_{CK} \end{bmatrix} \tag{4}$$

The aforementioned equation can be rewritten as

$$\begin{aligned} V_{AS} &= \sum_{i=1}^{k} V_{Ai} \\ V_{BS} &= \sum_{i=1}^{k} V_{Bi} \\ V_{CS} &= \sum_{i=1}^{k} V_{Ci} \end{aligned} \tag{5}$$

4.2 Circuit Operation

The proposed cascaded multilevel inverter consists of a series of single phase half and full wave H-bridge inverter units. The general function of this multilevel inverter is to synthesize a desired voltage from single dc source. Each inverter bridge can generate three different voltage outputs, $+V_{dc}$, 0 and $-V_{dc}$ by connecting the dc source.

From Fig. 2, note that the duty cycle for each of the voltage levels is different. If this same pattern of duty cycles is used the level-1 inverter is cycled on for a much longer than level-5 inverter .If level-1 inverter was switched on at an angle α_1 , the switching angles of the remaining levels of inverters must be greater than α_1 hence $\alpha_1 > \alpha_2 > \alpha_3 > \alpha_4 > \alpha_5$. Actually we use the full wave bridges for polarity reversals. In this proposed circuit only one three phase transformer have full bridge inverters for its three windings. The switches S_1, S_2, S_3 and S_4 of the inverter bridges were switched on and off to get the alternate supply from the input dc source. We can call this as Base three phase transformer.

The same phase windings of the remaining transformers were directly connected in parallel to the windings of the Base three phase transformer through two igbts. Based on the conduction period of these two igbts the total circuit operation can be divided into two modes. Even though the proposed circuit can be operated in two modes the resultant output is same but differ in the conduction period.

Mode-1 Operation

In the positive half cycle the 'a' phase winding of the base three phase transformer gets connected to the input at an angle α_1. After some time at an angle α_2 the 'a' phase winding of the second transformer will get connected to the base transformer winding by switching on the igbts in both ends. The extinction angle for the second transformer will be $180 - \alpha_2$. At this angle the two igbts were switched off so that it gets disconnected from the supply .In this way the similar phases of remaining transformers will be connected and disconnected at pre defined intervals.

In the negative half cycle the polarity of the 'a' phase winding will be reversed in the base transformer. Again the similar phases of remaining transformers will get connected and disconnected from the supply with the igbts.

In Full Wave Bridge two switches will conduct for one half cycle and another two switches will conduct for other half cycle. But in the proposed circuit the switches connected in transformers other than base transformer will operate at double frequency. These switches will be operated in both the positive and negative half cycles.

Mode-2 Operation

In this mode the operation of the base transformer is same as in mode-1.The windings of the similar phases of other transformers will get connected with igbt at one end and with anti parallel diode at other end. Hence the controlling is needed at only one end per cycle because at the other end the anti parallel diode will conduct.

The mode-2 operation is a little bit superior to mode-1 operation. Because in this mode we use of the anti parallel diode there by reducing the switching frequency of the igbts.

4.3 Output Characteristic

Fig. 7 shows the k^{th} phase input voltage of a three-phase transformer and the output voltage of the *A* phase. The switching frequency of the H-bridge inverter is equivalent to that of the fundamental frequency. Switching signals in *B* and *C* phases are 120° ahead of or behind the signal of the *A* phase. Hence, a key to control is a switching angle α_k. When a *k* number of transformers are used, the control key becomes switching angles $\alpha_1, \alpha_2, \ldots, \alpha_k$, and the output voltage can be adjusted by regulating the switching angles. Extinction and firing angles are symmetrical on the basis of $\pi/2$; thus, the extinction angle is given as $\pi - \alpha_1$, $\pi - \alpha_2, \ldots, \pi - \alpha_k$. Therefore, the control range of the switching angle becomes $0 \le \alpha_k \le \pi/2$.

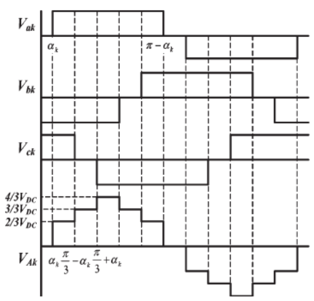

Figure 7(a) : $0 \le \alpha_k \le \pi/6$

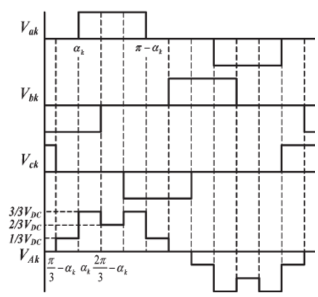

Figure 7(b) : $\pi/6 \le \alpha_k \le \pi/3$

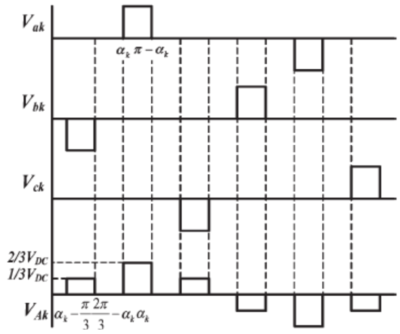

Figure 7(c) : $\pi/3 \leq \alpha_k \leq \pi/2$

However, considering that it cannot be balanced in three phases, the output voltage of the three-phase transformer will be determined by combinations of *A*-, *B*-, and *C*-phase voltages. There are three possibilities in the output voltage of the transformer based on the switching angles.

The switching patterns of each phase and output voltage of the three-phase transformer shown in Fig. 7 are a case when each turn ratio of the transformer is set to one. The range of the switching angle α_k is $0 \leq \alpha_k \leq \pi/6$ in Fig. 7(a), $\pi/6 \leq \alpha_k \leq \pi/3$ in Fig. 7(b), and $\pi/3 \leq \alpha_k \leq \pi/2$ in Fig. 7(c). In each range, the output voltage of the *A* phase (V_{Ak}) is symmetrical, and the Fourier progression of odd function can be written as

$$V_{Ak} = \sum_{n=1}^{\infty} b_{nk} \sin(n\theta) \tag{6}$$

Here, the constant b_{nk} is given as follows.

1) Case 1 - $0 \leq \alpha_k \leq \pi/6$***:***

$$b_{nk} = \frac{4V_{DC}}{\pi}\left[\frac{2}{3}\int_{\alpha_k}^{\frac{\pi}{3}-\alpha_k}\sin(n\theta)\,d\theta + \frac{3}{3}\int_{\frac{\pi}{3}-\alpha_k}^{\frac{\pi}{3}-\alpha_k}\sin(n\theta)\,d\theta + \frac{4}{3}\int_{\frac{\pi}{3}+\alpha_k}^{\frac{\pi}{2}}\sin(n\theta)\,d\theta\right]$$

$$b_{nk} = \frac{4V_{DC}}{n\pi}\cos(n\alpha_k) \tag{7}$$

2) Case2 - π/6 ≤ α_k ≤ π/3:

$$b_{nk} = \frac{4V_{DC}}{\pi}\left[\frac{1}{3}\int_{\frac{\pi}{3}-\alpha_k}^{\alpha_k}\sin(n\theta)d\theta + \frac{3}{3}\int_{\alpha_k}^{\frac{2\pi}{3}-\alpha_k}\sin(n\theta)d\theta + \frac{2}{3}\int_{\frac{2\pi}{3}-\alpha_k}^{\frac{\pi}{2}}\sin(n\theta)d\theta\right]$$

$$b_{nk} = \frac{4V_{DC}}{n\pi}\cos(n\alpha_k) \tag{8}$$

3) Case 3—π/3 ≤ α_k ≤ π/2:

$$b_{nk} = \frac{4V_{DC}}{\pi}\left[\frac{1}{3}\int_{\alpha_k-\frac{\pi}{3}}^{\frac{2\pi}{3}-\alpha_k}\sin(n\theta)d\theta + \frac{2}{3}\int_{\alpha_k}^{\frac{\pi}{2}}\sin(n\theta)d\theta\right]$$

$$b_{nk} = \frac{4V_{DC}}{n\pi}\cos(n\alpha_k) \tag{9}$$

Here, $n = 1, 5, 7, 11, \ldots, l-2, l$. It can be known that the results of the Fourier progression in each range are all the same and b_{nk} is uniform in the range of $0 \le \alpha_k \le \pi/2$. It is tenable by using (10). The Fourier transforms of the primary voltages of the transformer V_{ak}, V_{bk}, and V_{ck} are given as

$$V_{ak} = \sum_{n=1}^{\infty} b_{nk}\sin(n\theta)d\theta$$

$$V_{bk} = \sum_{n=1}^{\infty} b_{nk}\sin(n\theta - \frac{2n\pi}{3})d\theta$$

$$V_{ck} = \sum_{n=1}^{\infty} b_{nk}\sin(n\theta + \frac{2n\pi}{3})d\theta \tag{10}$$

Here, $n = 1, 3, 5, \ldots, l-2, l$. In (10), the coefficients b_{nk} and V_{ak} are half-wave symmetries. Hence, the odd function is written as

$$b_{nk} = \frac{4V_{DC}}{n\pi}\cos(n\alpha_k) \tag{11}$$

By using (1) and (10), the output voltage of the *A* phase (V_{Ak}) can expressed as

$$V_{Ak} = \sum_{n=1}^{\infty} b_n \sin(n\theta) - \frac{1}{3}\times\sum_{n=1}^{\infty} b_n (\sin(n\theta) + 2\sin(n\theta)\cos(\frac{2n\pi}{3})) \tag{12}$$

If $n = 3, 9, \ldots, 3(l-2), 3l$

$$V_{Ak}=0 \tag{13}$$

If $n = 1, 5, 7, 11, \ldots, l-2, l$

$$V_{Ak} = \sum_{n=1}^{\infty} b_n \sin(n\theta) \tag{14}$$

Consequently, the output voltage V_{Ak} of the k^{th} transformer occurs only when n is 1, 5, 7, 11, . . . , $l - 2$, and l. As a result, we can notice that the third harmonic component does not appear in the three-phase inverter output.

4.4 Switching Function

In the proposed multilevel inverter, the output voltage can be expressed by the sum of the terminal voltages of each transformer because the secondary terminals of the transformers are series connected by phase. Moreover, the output voltage of each transformer is independent of the switching angle in the range of $0 \le \alpha_k \le \pi/2$. Thus, the output voltage is given as (15) when three three-phase transformers are employed in the proposed multilevel inverter.

$$V_{AS} = \frac{4V_{DC}}{n\pi}\left(\cos(n\alpha_1) + \cos(n\alpha_2) + \cos(n\alpha_3)\right) \tag{15}$$

Where $0 \le \alpha_1 \le \alpha_2 \le \alpha_3 \le \pi/2$.

If the output voltage is controlled by switching angles α_1, α_2, and α_3, it can control the switching angles to synthesize the fundamental component, eliminating special harmonic components. In (15), by controlling three switching angles, the fundamental component can be generated while two harmonic components are eliminated. As mentioned earlier, the third harmonic component is not exited; the fifth and seventh harmonics are tried to be reduced and are given as

$$\begin{aligned} &\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) = \frac{3m\pi}{4} \\ &\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) = 0 \\ &\cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) = 0 \end{aligned} \tag{16}$$

Here, *m* means the modulation index. From (16), we can find that these equations are nonlinear. They can be solved by an iterative method such as the Newton–Raphson [3], [11], [14]. It is impossible to be solved by a real-time calculation [3]. To solve this problem, the modulation index is set from 0.1 to 1.0, and ten group switching angles are previously calculated per 0.1 unit. The calculated switching angles are listed in below

m	α1	α2	α3
0.1	76.4	-	-
0.2	61.9	-	-
0.3	50.2	86.2	-
0.4	44.2	74.3	-
0.5	40.8	65.8	89.4
0.6	39.4	58.6	83.1
0.7	39.3	53.9	74
0.8	29.2	54.4	64.5
0.9	17.5	43.1	64.1
1	11.7	31.2	58.6

5. SIMULATION RESULTS

Fig. 8 shows the variation of voltage levels, where the calculated switching angles were used. Here, the dc input voltage (V_{DC}) is 100 V, and the turn ratio of the transformer is set to one. In Fig. 8, V_{A1}, V_{A2}, and V_{A3} are *A*-phase output voltages of each transformer. V_{a1}, V_{a2}, and V_{a3} are the input voltage of the transformer. V_{AS} is the terminal voltage of the *A* phase, and V_{A_ref} is the reference voltage.

At a modulation index of 0.9, the switching angle α_1 of the first transformer is 17.5°, and the extinction angle is 162.5°, as shown in V_{A1} of Fig. 8(a). In the second transformer, the switching angle α_2 is 43.1°, and the extinction angle is 136.9°, as shown in V_{A2} of Fig. 8(a). The switching angle α_3 of the third transformer is 64.1°, and the extinction angle is 115.9°, as shown in V_{A3} of Fig. 8(a). We can find that the switching angle of each transformer, at the modulation index of 0.9, completely satisfies cases 1, 2, and 3 shown in Fig. 5.

At modulation index 1.0, the switching angle α1 of the first transformer is 11.7°, and the extinction angle is 168.3°, as shown in V_{A1} of Fig. 8(b). In the second transformer, the switching angle α_2 is 31.2°, and the extinction angle is 148.8°, as shown in V_{A2} of Fig. 8(b). The switching angle α_3 of the third transformer is 58.6°, and the extinction angle is 121.4°, as shown in V_{A3} of Fig. 8(b).

Fig. 9 shows variations of each switching angle when the modulation index is changed from 0.1 to 1.0. It compares the switching angles of each H-bridge, obtained by using the Newton–Raphson method, with those calculated by the first linearization method using ten calculated switching angle values. As shown in Fig. 9, both have similar switching angles, without a major difference between them. Fig. 10 shows the total harmonic distortion (THD) and distortion factor (DF) of the output voltage. It compares actual switching angles with calculated ones. It is shown that there are some differences near the modulation index of 0.2 and that, by adjusting this value, the problem can be solved.

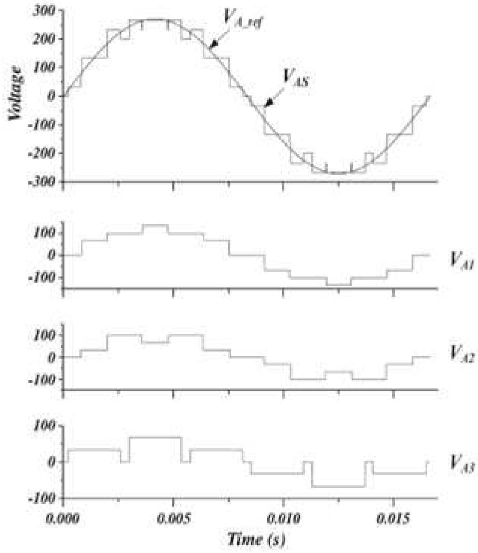

Figure 8(a) : Simulation Results for Modulation Index 0.9

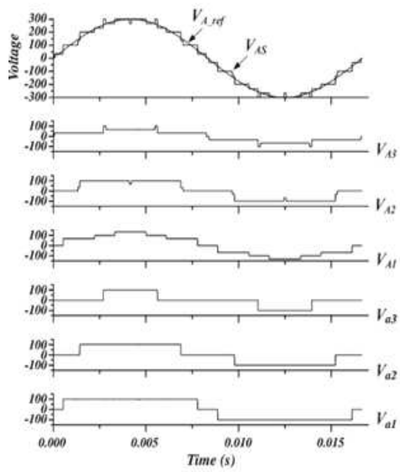

Figure 8(b) : Simulation Results for Modulation Index 1.0

The proposed multilevel inverter was designed for the use of grid-connected photovoltaic/wind power generator, flexible alternating-current systems, and other similar applications. The output frequency of these systems is usually fixed to a grid frequency. Therefore, there is no problem when using the low frequency transformers. However, for motor drive applications with a variable frequency control scheme, the proposed topology has some problems because of the transformers on the ac side. In the experiment, the proposed multilevel inverter was designed to synthesize 13 output levels. If we want to generate the same number of output levels with conventional multilevel inverters, we can find that they need many components compared with the proposed schemes as given in Table I.

Generally, the conventional multilevel inverters use a circulating switch pattern in order to maintain the same ratio in switch utilization [3]. Therefore, they employ switches which are equivalent in the voltage and current ratings. Assuming that the magnitude of the output voltages and output power are equivalent, the voltage ratings of each switch are determined by the number of series-connected switches. Consequently, we can say that the proposed method is more advantageous in switch cost and system size compared with the conventional approaches because the proposed method can reduce the number of switches. In addition, usually, these traditional multilevel inverters employ a three-phase low-frequency transformer at the output terminal for a high-power grid connection. In this point, the proposed circuit topology has a valuable merit. Considering that the output voltage is synthesized by an accumulation of each transformer output, it does not require an additional transformer for galvanic isolation. Although the proposed scheme needs three three-phase transformers, the cost and size will be slightly increased because the capacity of the transformer is 1/3 of the transformer which is applied to the conventional method.

Fig 11 shows the THD variation of the proposed Multi level inverter with modulation index m in Mode-1 operation and Fig 12 shows the THD variation in Mode-2 operation. Both these waveforms were generated by implementing the proposed circuit in **Matlab/Simulink**. In both these cases the THD variation is similar with modulation index m. So the proposed multilevel inverter can be used effectively in both these modes. Eventhough the simulation results are shown only for three phase systems the proposed method can also be used for single phase systems with single phase transformers.

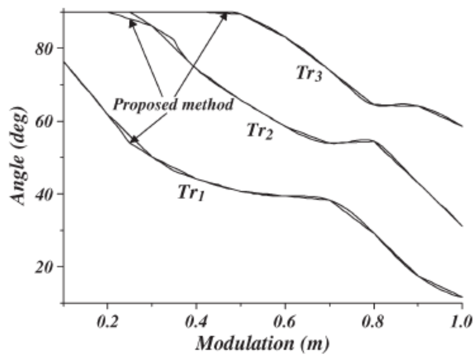

Figure 9 : Variation of switching angles based on different modulation indexes

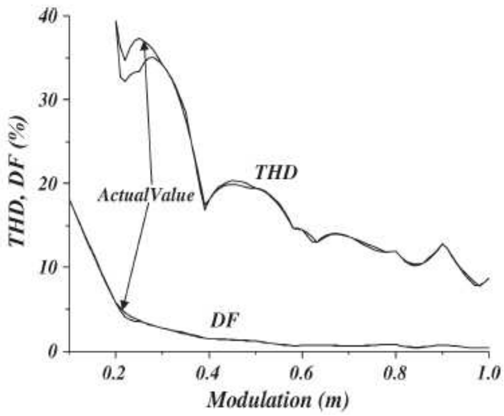

Figure 10 : THD and DF of output voltage based on the variation of modulation index

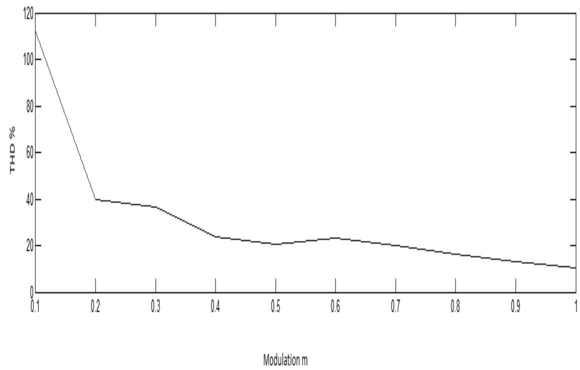

Figure 11 : THD of proposed inverter with Mode-1 operation

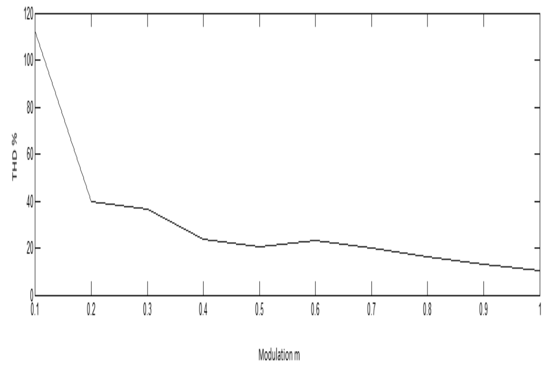

Figure 12 : THD of proposed inverter with Mode-2 operation

Table 1

Components	**traditional multilevel inverter employing 3-phase t/fs**	**Proposed Circuit**
Switch	36	24
Capacitor	1	1
Input DC Source	1	1
Output Transformer	3	3

6. CONCLUSION

This paper proposed a cascaded multilevel inverter employing low-frequency three-phase transformers and a single dc input power source with reduced number of switches. All switching angles can be decided by using the liberalization method in each area on the basis of the Newton–Raphson method. Valuable advantages of the proposed approach are summarized as follows:

1. Efficient and economical circuit configuration to synthesize multilevel outputs by using three-phase transformers.
2. Increase of utilization rate and decrease of volume .
3. Little transition loss of switch due to low switching frequency and reduced electromagnetic interference, which is suitable for high-voltage applications [3];
4. Removing high-order harmonics by using the liberalization relay angle control in each area on the basis of the Newton–Raphson method.
5. This technique can also be used in single phase cascaded multi-level inverters provided the input source must be a single dc source.

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