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CMLI Based Statcom Employing Single DC Input Source

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Abstract:

This paper proposes an isolated cascaded multilevel inverter employing low-frequency three-phase transformers and a single dc input power source. The proposed circuit configuration can reduce a number of transformers compared with traditional three-phase multilevel inverters using single-phase transformers. It controls switching phase angles to obtain an optimal switching pattern identified with the fundamental frequency of the output voltage. The major problem in the electrical power quality is the harmonic content. There are several methods indicating the quantity of harmonic content and the most widely used measure is the Total Harmonic Distortion (THD). Owing to this control strategy, harmonic components of the output voltage and switching losses can be diminished considerably.This technique is applied for any number of levels of multilevel inverter. A 7 level cascaded multilevel inverter power circuit is simulated in MATLAB 7.8 simulink with sinusoidal PWM technique. To verify the performance of the proposed approach, we implemented experiments using a prototype.

1.Introduction

The Pulse Width Modulated (PWM) inverters can control their output voltage and frequency simultaneously and also they can reduce the harmonic components in load currents. These features have made them suitable in many industrial applications such as variable speed drives, uninterruptible power supplies, and other power conversion systems. The popular single-phase inverters adopt the full bridge type using approximate sinusoidal modulation technique as the power circuits. The output voltage of them has three values: zero, positive and negative of supply DC voltage levels. Therefore, the harmonic components of their output voltage are determined by the carrier frequency and switching functions [1].

Recently the multilevel inverter topology has drawn tremendous interest in the power industry since it can easily provide the high power required for high power applications for such uses as static VAR compensation, active power filters, and so that large motors can also be controlled by high power adjustable frequency drives. Multilevel inverters synthesize the AC voltage from several different levels of DC voltages. Each additional DC voltage level adds a step to the AC voltage waveform. These DC voltages may or may not be equal to one another [3]. From a technological point of view, appropriate DC voltage levels can be reached, allowing use of multilevel power inverter for the medium voltage for adjustable speed drives ASD [4].Multilevel inverters can reach high voltage and reduce harmonics by their own structures. There are three main types of multilevel inverters: diode-clamped, flying capacitor, and cascaded H-bridges [9]. If the DC supply voltage increased (adding more batteries in series to maintain the voltage or to decrease the current) for the larger power requirement, the inverter component must be able to withstand the maximum DC supply voltage. Apart from other multilevel inverters, is the capability of utilizing different DC voltages on the individual H-bridge cells. The cascaded topology has many inherent benefits with one particular advantage being its modular structure. In particular, the cascaded inverter has been reported for use in applications such as medium voltage industrial drives, electric vehicles and grid connection of photovoltaic cell generation systems.

In this paper, we propose a cascaded H-bridge multilevel inverter which employs one single dc input power source and isolated three-phase low-frequency transformers. By the proposed circuit configuration, a number of transformers can be reduced, compared with traditional three-phase multilevel inverters using single-phase transformers. Therefore, an economical and efficient inverter can be designed. Basically, the switching frequency of each H-bridge inverter is uniform with output fundamental frequency. The relay angles of each switch are calculated by the Newton–Raphson method on the basis of the area of each switch [3], [11], [14]. All relay angles can be determined by applying the linearization method to each area.This approach is useful to eliminate low harmonic components of the output voltage. To verify the performance of the proposed cascaded multilevel inverter, we carried out computer-aided simulations and experiments using a prototype.

2.Cascaded Multilevel Inverter

A cascaded multilevel inverter consists of a series of H-bridge (single phase, full bridge) inverter units. The general function of this multilevel inverter is to synthesize a desired voltage from several separate dc sources (SDCSs), which may be obtained from batteries, fuel cells, or solar cells[10]. Fig. 1 shows a circuit configuration and key waveforms of a traditional cascaded H-bridge multilevel inverter composed of four H-bridge cells. It generates a nine-level output voltage. The output voltage is a pile of low voltages which are generated by series-connected topologies of multi-level inverter, cascaded type is considered for this work. In H-bridge cells. By selecting proper switching functions, positive, negative, and zero voltages can be synthesized. The output voltage *Vo* is the sum of the output voltage produced by each H-bridge cell. Hence, every H-bridge module requires an independent voltage source [1], [2], [7]–[10]. Among three types of general, the number of bridges required for an m level inverter is ((m-1)/2). All the switches in the inverter are switched only at the fundamental frequency and the voltage stress across the switches is only the DC source voltage magnitude

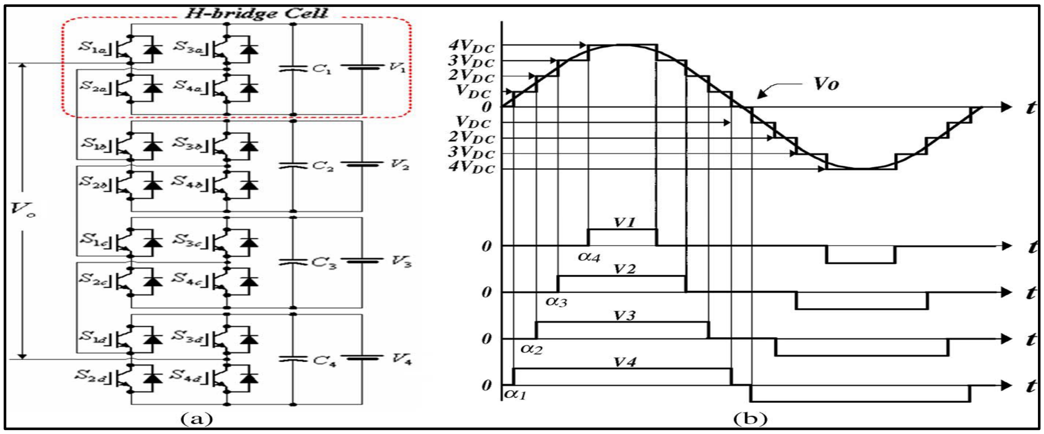

Figure 1: Conventional cascaded H-bridge cell multilevel inverter (nine levels). (a) Circuit configuration. (b) Operational waveforms.

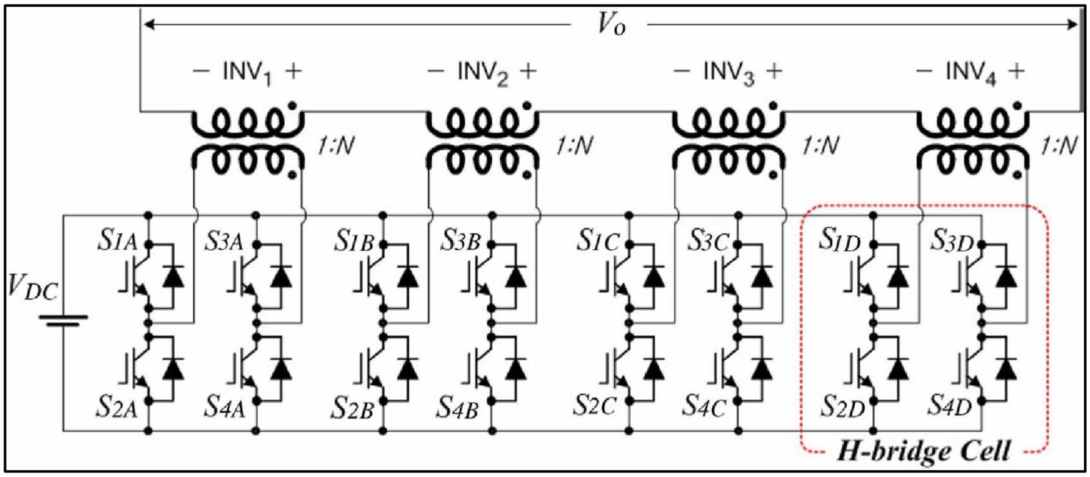

Figure 2: Configuration of single-phase boost-type H-bridge multilevel inverter employing four transformers and single dc input power source

Fig. 2 shows a configuration of a boost-type H-bridge multilevel inverter employing a cascade transformer. Four H-bridge modules are connected to the same dc input source in parallel, and each secondary of the four transformers is connected in series. In this configuration, the output voltage becomes the sum of the terminal voltages of each H-bridge module. The amplitude of the output voltage is determined by the input voltage and turn ratio of the transformer. Usually, a traditional cascaded H-bridge converter employs a multipulse isolation transformer to obtain the input dc source. When the traditional cascaded H-bridge converter needs to isolate from the ac output, it requires a three-phase transformer between the inverter and the ac outputs. On the other hand, the proposed inverter has an advantage of galvanic isolation between the source and the output voltages, which comes from being combined with transformers [8], [9]. However, when the circuit, shown in Fig. 2, needs to modify its configuration for use in three-phase applications, there is a drawback, which is the requirement of more transformers, considering that the same number of transformers needs to be used in each phase.

3.Proposed Cascaded H-Bridge

3.1.Multilevel Inverter

3.1.1.Circuit Configuration

Fig. 3 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.

Fig. 4 shows a predigested representation of Fig. 3 when it employs three three-phase transformers. 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.

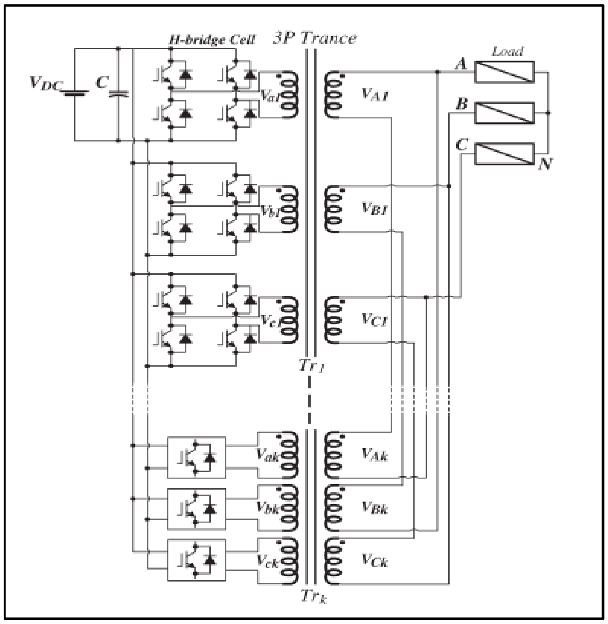

Figure 3: Circuit configuration of the proposed multilevel inverter

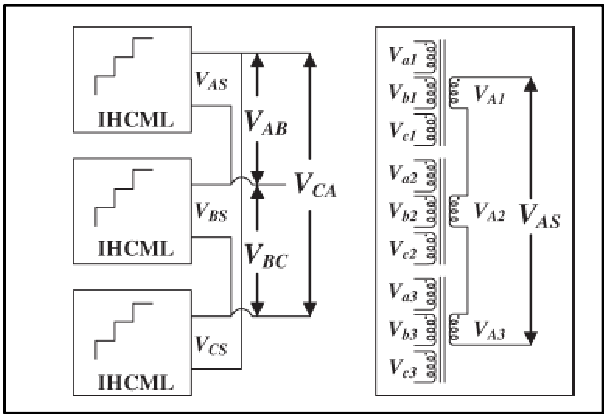

Figure 4: Simplified structure of the proposed multilevel inverter

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, *Vak*, *Vbk*, and *Vck* mean the output voltages of the H-bridge inverter connected to the *k*th transformer. Here, *VAk*, *VBk*, and *VCk* are the output voltages of the transformers in each phase. Therefore, the relationship between the input and the output voltages of the three-phase transformer is given as

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

where *T* is the transformation ratio (*n*2/*n*1) between the primary and the secondary of the transformer. If the input voltageis balanced in three phases, the sum of each phase voltage becomes zero

$$V_{ak}+V+V_{ck} = 0. \quad \textbf{(II)}$$

From (I) and (II), the output voltage is expressed as

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

From (III), 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 Vak = VDC, Vbk = −VDC, and Vck = 0; however, when Vak, Vbk, and Vck are all VDC, the output voltage is unbalanced. Therefore, the proposed circuit relies on (I) instead of (III).Equation (I) 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 (I). As shown in Fig. 4, the output voltage of the proposed multilevel inverter is synthesized by the series-connected secondary of the transformer outputs.

4.Harmonic Reduction Technique

The power electronic equipment such as inverter have switching devices and their operation produces current and voltage harmonics into the system from which they are working. These harmonics affect the operation of their equipments connected o the same system through the injection of harmonics. The even order harmonics are eliminated by using filters. The odd order harmonics can be eliminated by various techniques.The analysis of the harmonics and harmonic reduction by PWM techniques are described in this section.frequency and harmonics contents of the output voltage [6].

The SPWM aims at generating a sinusoidal inverter output voltage without low-order harmonics. Sinusoidal pulse width modulation is one of the primitive techniques, which is used to suppress harmonics presented in the quasi-square wave. In the modulation techniques, there is an important parameter i.e., the ratio M = Ar/Ac known as modulation index, where Ar is reference signal amplitude and Ac is carrier signal amplitude.

4.1.Harmonic Elimination Switching Angles (HESA)

The HESA is assumed to be the quarter-wave symmetric. Fourier series of the quarter-wave symmetric S H-bridge cell multilevel inverter output waveform is written as follows

$$V_{(wt)} = \sum_{n=1}^{\infty} \frac{4V_{dc}}{n\pi} \left[\sum_{k=1}^{s} \cos(n\theta_k) \right] \sin(nwt) \quad (1)$$

Where the optimized switching angles, which must satisfy the following condition

$$\theta_1 < \theta_2 < \cdots < \theta_s < \frac{\pi}{2} \qquad (2)$$

The amplitude of all odd harmonic components including fundamental one, are given by

$$h_{(n)}\frac{4V_{dc}}{n\pi}\sum_{k=1}^{s}\cos\left(n\theta_k\right) \qquad (3)$$

The switching angles of the waveform will be adjusted to get the lowest output voltage THD.If need to control the peak value of the output voltage to be V_1 and eliminate the third and fifth order harmonics, modulation index is given by

$$M = \frac{\pi V_1}{4V_{dc}} \qquad (4)$$

The resulting harmonic equations are

$$\frac{4V_{dc}}{\pi}\left[\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4)\right] = V_1 (5)$$

$$\left[\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) + \cos(5\theta_4)\right] = 0 \quad (6)$$

$$\left[\cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) + \cos(7\theta_4)\right] = 0 \quad (7)$$

$$\left[\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4)\right] = M \qquad (8)$$

The Newton Raphson method is used to solve the harmonic elimination switching angles of 5th and 7th order for cascaded multilevel inverter.

4.2.Output Characteristic

Fig. 5 shows the kth 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 αk. When a k number of transformers are used, the control key becomes switching angles α1, α2, . . . , αk, and the output voltage can be adjusted by regulating the switching angles. Extinction and firing angles are symmetrical on the basis of π/2; thus, the extinction angle is given as π −α1, π −α2, . . . , π −αk. Therefore, the control range of the switching angle becomes 0 ≤αk ≤π/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. 5 are a case when each turn ratio of the transformer is set to one. The range of the switching angle αk is $0 \leq \alpha k \leq \pi/6$ in Fig. 5(a), $\pi/6 \leq \alpha k \leq \pi/3$ in Fig. 5(b), and $\pi/3 \leq \alpha k \leq \pi/2$ in Fig. 5(c).

4.3.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 $0 \leq \alpha k \leq \pi/2$. Thus, the output voltage is given as (9) when three three-phase transformers are employed in the proposed multilevel inverter

$$V_{AS} = \frac{4V_{\mathrm{DC}}}{n\pi}\left(\cos(n\alpha_1) + \cos(n\alpha_2) + \cos(n\alpha_3)\right) \quad (9)$$

where $0 \leq \alpha 1 \leq \alpha 2 \leq \alpha 3 \leq \pi/2$. If the output voltage is controlled by switching angles $\alpha 1$, $\alpha 2$, and $\alpha 3$, it can control the switching angles to synthesize the fundamental component, eliminating special harmonic components. In (9), 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

$$\begin{aligned} \cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) &= \frac{3m\pi}{4} \\ \cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) &= 0 \\ \cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) &= 0. \end{aligned} \quad (10)$$

Here, *m* means the modulation index. From (10), we can find that these equations are nonlinear. They can be solvedby an iterative method such as the Newton–Raphson. It is impossible to be solved by a real-time calculation [3]. Tosolve 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. Then, the switching angle between the calculated modulation indexes can be obtained by using the first function. The calculated switching angles are listed in Table I.

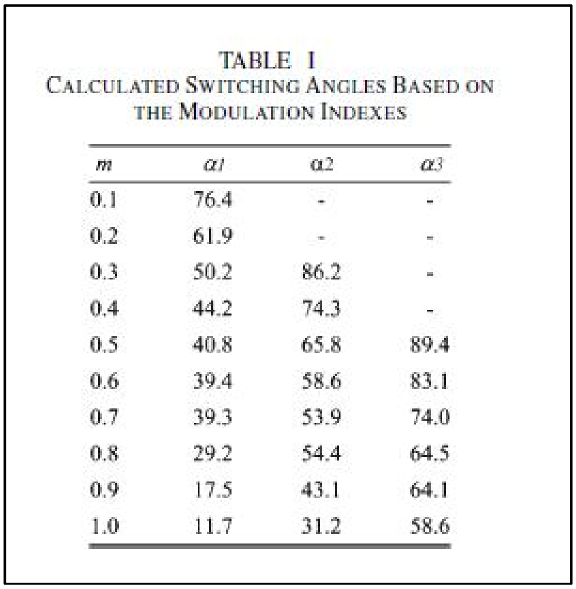

TABLE I
CALCULATED SWITCHING ANGLES BASED ON THE MODULATION INDEXES

m	$\alpha 1$	$\alpha 2$	$\alpha 3$
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
0.8	29.2	54.4	64.5
0.9	17.5	43.1	64.1
1.0	11.7	31.2	58.6

Table 1

5.Simulations And Experimental Results

Fig. 6 shows the simulation results by MATLAB, where the calculated switching angles given in Table I are used. Here,the dc input voltage (VDC) is 100 V, and the turn ratio of the transformer is set to one. In Fig. 6, $VA1$, $VA2$, and $VA3$ are A-phase output voltages of each transformer. $Va1$, $Va2$, and $Va3$ are the input voltage of the transformer. VAS is the terminal voltage of the A phase, and VA_ref is the reference voltage.

At a modulation index of 0.9, the switching angle $\alpha 1$ of the first transformer is 17.5◦, and the extinction angle is 162.5◦, as shown in $VA1$ of Fig. 6(a). In the second transformer, the switching angle $\alpha 2$ is 43.1◦, and the extinction angle is 136.9◦, as shown in $VA2$ of Fig. 6(a). The switching angle $\alpha 3$ of the third transformer is 64.1◦, and the extinction angle is 115.9◦, as shown in $VA3$ of Fig. 6(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 $\alpha 1$ of the first transformer is 11.7◦, and the extinction angle is 168.3◦, as shown in $VA1$ of Fig. 6(b). In the second transformer, the switching angle $\alpha 2$ is 31.2◦, and the extinction angle is 148.8◦, as shown in $VA2$ of Fig. 6(b). The switching angle $\alpha 3$ of the third transformer is 58.6◦, and the extinction angle is 121.4◦, as shown in $VA3$ of Fig. 6(b).

Fig. 7 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 given in Table I.

As shown in Fig. 7, both have similar switching angles, without a major difference between them. Fig. 8 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.

We can find that the experimental output voltage waveforms show larger *dv/dt* voltage peaks for a small time after a change in the output voltage level occurs. These occur at those times when both of the sources are being switched on or off simultaneously. In these cases, the *dv/dt* voltage peaks appear in the voltage waveform due to the difference in the dead time of the H-bridge switches, as well as if the timing of turning the switches on and off is not exactly the same between the H-bridges.

As given in Table I, three H-bridge inverters work under switching angle control at a modulation index of 1.0. Therefore, the magnitude of fundamental component can be controlled, and the fifth and seventh harmonics can be eliminated. At a modulation index of 0.4, two H-bridge inverters work under switching angle control; thus, the fundamental component can be controlled, and the fifth harmonic component can be reduced.

With a modulation index of 0.2, one H-bridge inverter works under switching angle control; thus, only the fundamental component can be adjusted. Therefore, it contains several harmonics. we can find that the FFT result of the output voltage does not contain the third harmonic component regardless of variable modulation indexes because the output voltage of each transformer is delta connected in the proposed circuit configuration. From this result, we can say that the Newton–Raphson method applied for the purpose of eliminating special harmonic components is more useful at high-voltage output applications with a low THD.

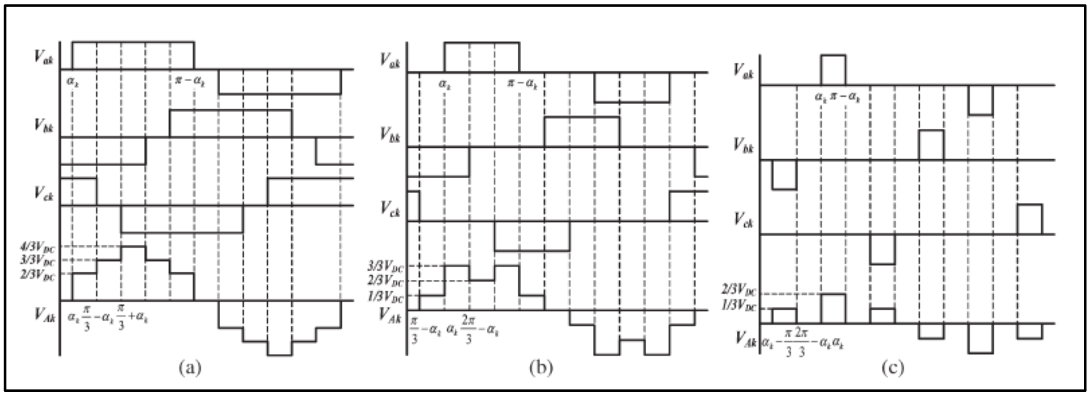

Figure 5: Switching patterns of each phase and output voltage of the three-phase transformer. (a) Case 1, 0 ≤αk ≤π/6. (b) Case 2, π/6 ≤αk ≤π/3 (c) Case 3, π/3 ≤αk ≤π/2

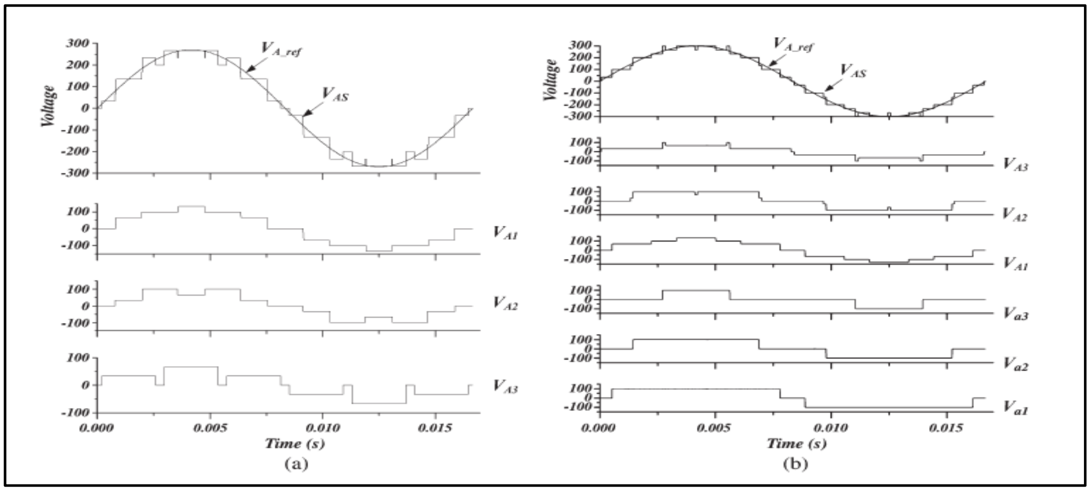

Figure 6: Simulation results. (a) Modulation index of 0.9. (b) Modulation index of 1.0

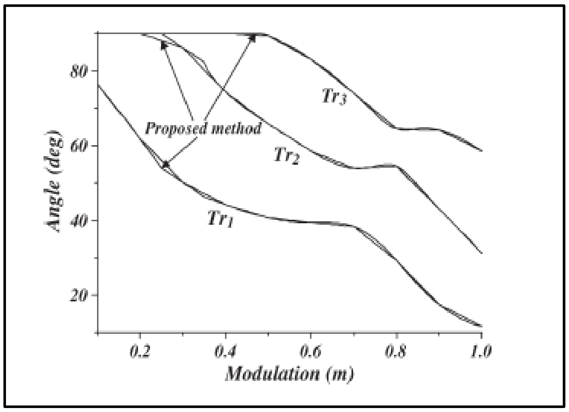

Figure 7: Variation of switching angles based on different modulation indexes

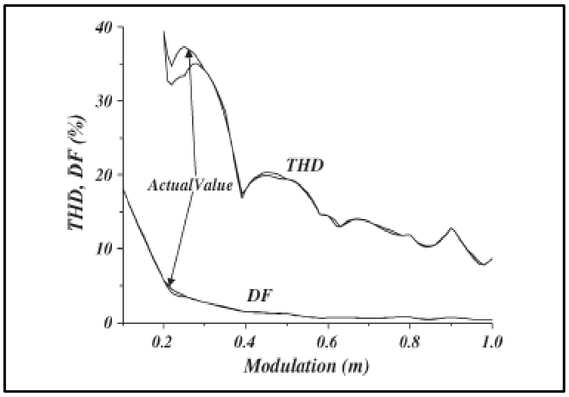

Figure 8: THD and DF of output voltage based on the variation of modulation

6.Conclusion

This paper proposed a cascaded multilevel inverter employing low-frequency three-phase transformers and a single dc input power source. The proposed circuit configuration can reduce a number of transformers compared with conventional three-phase multilevel inverters using single-phase transformers. 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:

- Efficient and economical circuit configuration to synthesize multilevel outputs by using three-phase transformers.
- Increase of utilization rate and decrease of volume by using three-phase transformers.
- Possibility of using a single dc source by using isolated transformers.
- Little transition loss of switch due to low switching frequency and reduced electromagnetic interference, which is suitable for high-voltage applications [3], [33].
- Removing high-order harmonics by using the liberalization relay angle control in each area on the basis of the Newton–Raphson method.
- Additionally, we inform that the proposed circuit configuration can also use a general switching method, whose operating frequency is equal to that of the fundamental.

7.Reference

1. Haiwen Liu, Leon M. Tolbert, Surin Khomfoi, Burak Ozpineci, Zhong Du, " Hybrid Cascaded Multilevel Inverter with PWM control Method", conference and proceedings , pp: 162-166 , June 2008.
2. P.C. Loh, D.G. Holmes, T.A. Lipo, "Implementation and control of distributed PWM cascaded multilevel inverter with minimum harmonic distortion and common moode voltages", IEEE Transactions on Power Electronics, vol. 20, no. 1, pp. 90-99 , Jan. 2005.
3. Chiasson, J.N.; Tolbert, L.M.; McKenzie, K.J.; Zhong Du,"A Unified approach to solving the harmonic Elimination Equation in multilevel converters", IEEE Transactions On Power Electronics, Vol. pp: 478 – 490, March 2004
4. B. P. McGrath and D. G. Holmes, "Multicarrier PWM Strategies for multilevel inverters," IEEE Trans. Ind. Electron.vol. 49, no. 4, pp. 858–867, Aug. 2002.
5. Leon M. Tolbert, Senior member, IEEE, Fang Zheng Peng, Senior Member,IEEE, and Thomas G. Habetler, Senior Member, IEEE, " Multilevel PWM methods at Low modulation Indices" , IEEE Transactions On power Electronics, Vol. 15, No. 4,July 2000.
6. L.M.Tolbert and T.G.Habetler, "Novel Multilevel Inverter Carrier Based PWM methods", Proc.IEEE trans. Ind Applications, Vol.35, pp. 1098-1107, Sept.1999.
7. G. Carrara, S. Gardella, M. Marchesoni, R. Salutari, and G. Sciutto, "A new multilevel PWM method: A theoretical analysis," IEEE Trans. Power Electron., vol. 7, pp. 497–505, July 1992.
8. N.S. Choi, J. G. Cho, and G.H. Cho, "A general circuit topology of multilevelinverter," in Proc. IEEE PESC'91, pp. 96-103.
9. C. K. Duffey, R. P. Stratford, "Update of harmonic standard IEEE-519, IEEE recommended practices and requirement for harmonic control in electric power systems," IEEE Transactions on Industry Applications, vol. 25, no. 6, pp.1025-1034,Nov. /Dec. 1989.
10. S. Walfram, Mathematica, a System for Doing Mathematics by Computer, 2nd ed. Reading MA: Addison-Wesley, 1992.
11. H. S. Patel and R. G. Hoft, "Generalized harmonic elimination and voltage control in thyristor converters: Part I-harmonic elimination," IEEE Trans. on Ind. Appl., Vol. 9, pp. 310-317, May/June 1973.

12. H. S. Patel and R. G. Hoft, “Generalized harmonic elimination and voltage control in thyristor converters: Part II-voltage control technique,” IEEE Trans. on Ind. Appl., Vol. 10, pp. 666-673, Sept. /Oct. 1974.
13. N. Mohan, T. M. Undeland and W. P. Robbins, 2003 -Power Electronics: Converters , Applications, and Design, 3rd Edition. J. Wiley and Sons.
14. Khomfoi, S., Tolbert, L. M., “Fault Diagnostic System for a Multilevel Inverter Using a Neural Network”, in IEEE Transactions on Power Electronics, Vol. 22, No. 3,pp. 1062-1069, May 2007.