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Generation of Equal Step Multilevel Inverter Output Using Two Unequal Batteries

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Abstract: In response to the growing demand for high power inverter unit, multilevel inverters have been attracting extensive attention from academia as well as industry in the recent decade. Among the best-known topologies are the H-bridge cascade inverter, the capacitor clamping inverter and the diode clamping inverter. In a three phase multilevel inverter, each phase of a cascaded multilevel inverter requires n DC sources to obtain 2n+1 output voltage levels. This study proposes a cascaded multilevel inverter with 2 unequal battery sources instead of three equal voltage battery sources for one phase to generate 7 level equal step output voltage waveform. This system can be used to drive a 3 phase Induction Motor of electric/hybrid electric vehicle, so that the cost and size of batteries can be reduced.

Key words: Cascaded H-bridge multilevel inverter, unequal battery sources, induction motor, capacitor clamping inverter

INTRODUCTION

Multilevel inverters provide more than two voltage levels. A desired output voltage waveform can be synthesized from the multiple voltage levels with less distortion, less switching frequency, higher efficiency and lower voltage devices. There are three major multilevel topologies: cascaded, diode clampedand capacitor clamped For the number of levels (M) no greater than three (i.e., M• 3), or some applications such as reactive and harmonic compensation in power systems, these multilevel converters do not require a separate dc power source to maintain each voltage level. Instead, each voltage level can be supported by a capacitor and proper control. However, for M>3 and applications involved in active power transfer, such as motor drives, these multilevel converters all require either isolated dc power sources or a complicated voltage balancing circuit and control to support and maintain each voltage level. In this aspect, the three existing multilevel converters are neither operable nor complete for real (active) power conversion because they all depend on outside circuits for voltage balancing (Fang, 2001). Multilevel inverters produce a stepped output phase voltage with a refined harmonic profile when compared to a two-level inverter-fed drive system. However, these configurations are also complex for higher number of levels (Somasekhar and Gopakumar, 2005).

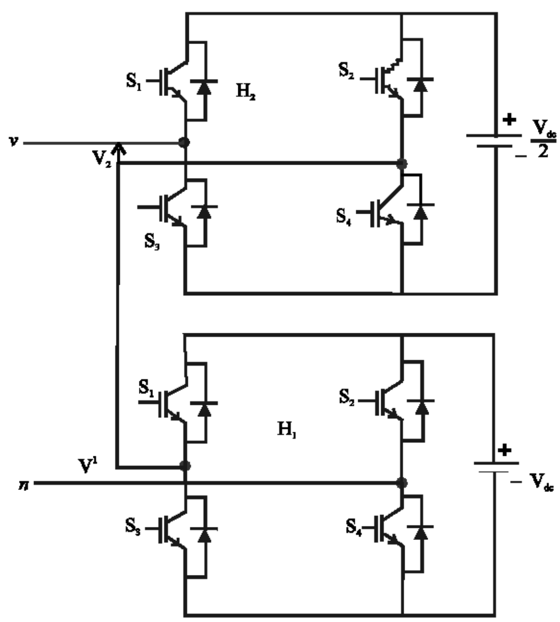

Fig. 1: Topology of single phase of the proposed H bridge inverter

For many applications, to get many separate DC sources is difficultand too many DC sources will require many long cables and could lead to voltage unbalance among the DC sources. To reduce the number of DC

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sources required when the cascaded H-bridge multilevel converter is applied to a motor drive, a scheme is proposed in this study that allows the use of two unequal DC sources to generate 7 level equal step multilevel inverter output. This scheme provides the capability to produce higher voltages at higher speeds (where they are needed) with a low switching frequency, which has inherent low switching losses and high conversion efficiency. For electric/hybrid electric vehicle motor drive applications, two H-bridges for each phase is a good tradeoff between performance and cost.

Working principle: To operate a cascaded multilevel converter using two unequal DC source, I have proposed to use the first DC sources (i.e., the battery connected to first H-bridge, H_1) as V_{dc} and the magnitude of voltage of second battery as

$$\frac{V_{dc}}{2}$$

To understand the concept, consider a cascaded multilevel inverter with two H-bridge as shown in Fig.1. The DC source for the first H-bridge (H_1) is a battery or fuel cell V_1 with an output voltage of V_{dc} and the DC source for the second H- brudge (H_2) is V_2 with an output voltage of

$$\frac{V_{dc}}{2}$$

The output voltage of the cascaded multilevel converter is

$$V(t) = v_1(t) + v_2(t) \tag{1}$$

By giving the triggering pulses to the switches of H_1 appropriately, the output voltage V_1 can be made equal to V_{dC}, 0, or $-V_{dC}$. while the output voltage of H_2 i.e., V_2 can be made equal to

$$\frac{V_{dc}}{2},\ 0,\ \text{or} -\frac{V_{dc}}{2}$$

by giving the triggering pulses to the switches of H_2 appropriately.

Therefore, the output voltage of the converter can have the values

$$\left(\frac{V_{dc}}{2}+V_{dc}\right), V_{dc}, \left(\frac{V_{dc}}{2}\right), 0, -\left(\frac{V_{dc}}{2}\right), -V_{dc}, -\left(\frac{V_{dc}}{2}+V_{dc}\right)$$

which are 7 possible output levels. Figure 2 shows the 7 level equal step output voltage waveform.

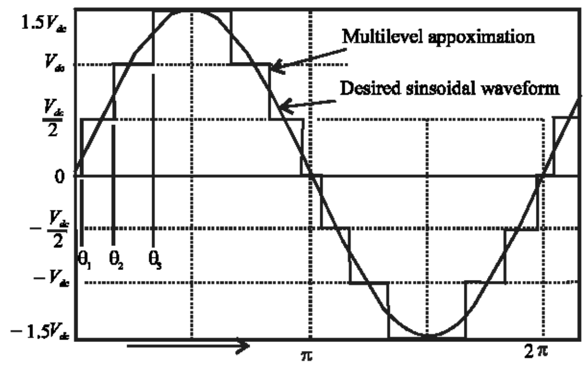

Fig. 2: Multilevel converter output with two unequal batteries

MODULATION AND SWITCHING CONTROL

Generally, traditional PWM control methods and space vector PWM methods are applied to multilevel converter modulation control. The disadvantage of the traditional PWM methods is the power loss in the switches due to the high switching frequency (Steinke, 1988; Tolbert *et al*., 2000; Loh *et al* ., 2005). For these reasons, low switching frequency control methods, such as a fundamental frequency method (Chiasson *et al*., 2003) and the active harmonic elimination method (Du *et al*., 2004) has been proposed for motor drive applications. If the voltage V_2 is chosen as $V_{dc}/2$, then the fundamental frequency switching scheme angles for equal DC sources can be used in the proposed multilevel motor drive control. This is the simplest switching control method for the proposed multilevel motor drive. It also is an effective modulation control method for the proposed cascaded multilevel converter motor drive.

The Fourier series expansion of the 7 level equal step output voltage waveform is

$$V(\omega t) = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_{dc}}{n\pi}(\cos n\theta_1) + (\cos n\theta_2) + (\cos n\theta_3)\sin(n\omega t) \tag{2}$$

where n is the harmonic number of the output voltage of the multilevel converter. Given a desired fundamental voltage V1, one wants to determine the switching angles $\bullet_1$, $\bullet_2$, $\bullet_3$ so that V ($\bullet$ t) = $V_{1\ sin}$ ($\bullet$ t) and specific higher harmonics of *V*(*n$\bullet$ t*) are eliminated (Patel and Hoft, 1973, 1974; Enjeti *et al*., 1990). For three-phase motor drive applications, the triplen harmonics in each phase need not be canceled as they automatically cancel in the line-to-line oltages. In this study, the goal is to eliminate the 5th and 7th harmonics. Mathematically, this can be formulated as the solution to the following equations:

$$\begin{aligned} \cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) &= m \\ \cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) &= 0 \\ \cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) &= 0 \end{aligned} \quad (3)$$

This is a system of three transcendental equations in the three unknowns $\bullet_1$, $\bullet_2$ and $\bullet_3$. There are many ways one can solve for the angles (Du *et al*., 2004, 2005; Kato, 1999; Chiasson *et al*., 2003). Here the resultant method (Enjeti *et al*., 1990; Sirisukprasert *et al*., 2002) was used to find the switching angles. The modulation index m is defined as

$$m = \frac{\pi V_1}{2V_{dc}} \quad (4)$$

and the Total Harmonic Distortion (THD) up to the 50th harmonic (odd, non-triplen) is computed as

$$THD = \frac{\sqrt{V_5^{\,2} + V_7^{\,2} + \ldots\ldots V_{49}^{\,2}}}{V_1} \quad (5)$$

APPLICATION CONSIDERATIONS

One possible application for the cascaded multilevel motor drive is an electric/hybrid vehicle. Electric/hybrid vehicles use batteries to run an electric motor. Presently, a three phase full bridge PWM converter is used for electric/hybrid electric vehicles. The battery voltage limits the instantaneous output powerand a high power DC-DC boost converter is required to utilize braking energy to charge the batteries. The proposed cascaded multilevel motor drive also can be used to absorb braking energy at low speeds.

EXPERIMENTAL RESULTS

To experimentally validate the proposed cascaded H-bridge multilevel motor drive control scheme, a mathematical model of three-phase cascaded H-bridge multilevel inverter has been developed and simulated using MATLAB. A 3-phase induction motor is selected with the specifications shown in the Table 1.

The parameters of this motor are calculated by conducting No-load test, Blocked Rotor test and Retardation test. This motor model is simulated using MATLAB and the simulated results are compared with that of practical results for load test (Table 2 and 3). It is found that these two results are very close to each other. Then the motor model is simulated with the proposed cascaded multilevel inverter.

This study developed a new hybrid cascaded H-bridges multilevel motor drive control scheme that required only two-battery source for each phase. A 7-level equal step output voltage switching control method has been applied to the motor drive Fig. 3. It can be derived from the simulation results that this motor drive scheme will give better performance than that of SPWM inverter. This can be observed from the shape of the waveform of stator current drawn by the motor when fed from SPWM inverter and Multi Level inverter shown in the Fig. 4 and 5. The proposed scheme is cheaper needs less space for batteries.

Table 1: Specifications of the motor

Type of the motor	3-• Induction motor
Rated output power	3700 watts (5 HP)
Rated line-to-line voltage	415 volts
Rated current	8.4 amps
Number of poles	4
Frequency of the supply voltage	50 Hz.
Rated speed	1485 rpm
Type of winding	Y-connected

Table 2: Experimental results of motor on load test, at rated voltage (415V)

S.No.	V_{LL} Volts.	I_L Amps	W_1 Watts	W_2 Watts	S_1 Kgs.	S_2 Kgs.	T_L N-m	N rpm	I/p Watts	O/p Watts	(%) •	Power factor
1.	415	4.5	1000	-800	0	0	0	1480	200	0.0	0.0	0.06
2.	415	4.9	1400	-500	5	8	2.53	1463	900	387.6	43.0	0.26
3.	415	5.5	1700	-100	7	16	7.6	1413	1600	1124.5	70.2	0.4
4.	415	6.1	2100	0	9	22	10.96	1376	2100	1579.0	75.2	0.5
5.	415	6.8	2400	700	11	29	15.18	1320	3100	2098.0	67.6	0.63

Table 3: Simulation results of motor model on load test, at rated voltage (415V)

S.No.	I_L Amps	T_L N-m	N rpm	O/p Watts	I/p Watts	(%) •
1.	4.52	0.0	1482	0	195	0
2.	4.6	2.53	1463	387	859	45.0
3.	5.3	7.06	1423	1133	1523	74.0
4.	5.7	10.96	1448	1547	2048	75.5
5.	6.7	15.18	1293	2055	3034	67.7

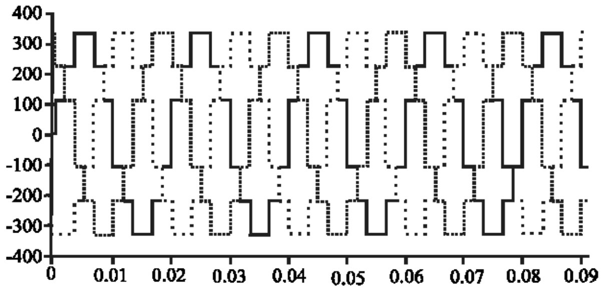

Fig. 3: Output voltage wave form (Line-to-Line)

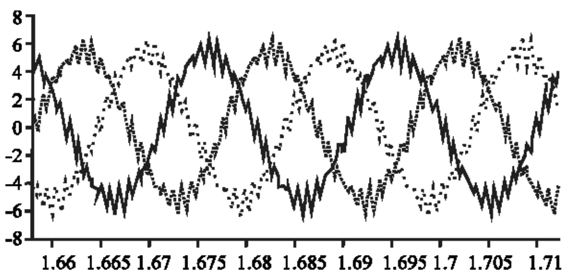

Fig. 4: Stator current, Motor fed from SPWM Inverter

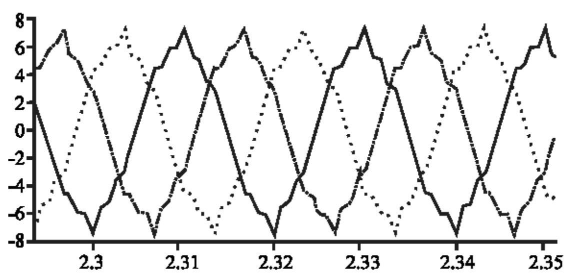

Fig. 5: Stator current, motor fed from ML Inverter

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