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A New Control Method for Single-DC-Source Cascaded H-Bridge Multilevel Converters Using Phase-Shift Modulation

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Abstract—Multilevel converters have gained popularity in high-power applications due to their low switch voltage stress and modularity. Cascaded H-bridge converters are a promising breed of multilevel converters, which generally require several independent dc sources. Using phase-shift modulation, a new control method for cascaded H-bridge multilevel converters with only one independent dc source per phase is presented in this paper. Unlike the conventional approaches, the proposed method has a wide voltage regulation range over the capacitors replacing the dc sources in the H-bridge converter cells.

Keywords—cascaded converters, H-bridge cell, multilevel converter

I. INTRODUCTION

Multilevel converters are mainly utilized to synthesize a desired single- or three-phase voltage waveform. The desired output voltage is obtained by combining several separate dc voltage sources. Solar cells, fuel cells, batteries, and ultracapacitors are the most common independent sources used [1, 2]. Multilevel converters have found wide applications in motor drives, static VAR compensators [3], and uninterruptible power supplies. Their main advantages are low harmonic distortion of the generated output voltage, low electromagnetic emissions, high efficiency, capability to operate at high voltages, and modularity. In general, multilevel converters are categorized into diode-clamped, flying capacitor, and cascaded H-bridge [4, 5].

Fig. 1 shows the block diagram of a three-phase cascaded H-bridge inverter. As it can be observed, the inverter consists of main and auxiliary H-bridge cells in each phase. In early implementations [6, 8, 9], each H-bridge cell was supplied by an independent dc source. Later, it was shown that only one cell needs to be supplied by a real dc power source and the remaining cells could be supplied with capacitors [7, 10]. However, studies show that voltage regulation of capacitors is not an easy task [11]. The proposed method in [10] uses the switching state redundancy for capacitor voltage regulation. Existence of redundant switching state has been assumed to be adequate for capacitor voltage regulation. However, output current of the inverter as well as the time duration of redundant switching states greatly impact the charging or discharging patterns of the replacing capacitors.

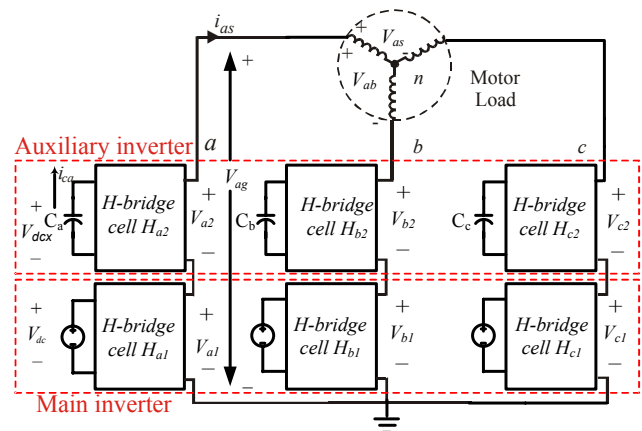


Fig. 1. Block diagram of a three-phase cascaded H-bridge inverter.

This paper proposes a new control method applicable to single-dc-source cascaded H-bridge multilevel inverters to improve their capacitor voltage regulation. The proposed method, phase-shift modulation, is more robust and has less computational burden. The main inverter switches at the fundamental frequency and the auxiliary inverter switches at the PWM frequency. The working theory of the cascaded H-bridge multilevel inverter is briefly introduced in Section II. In Section III, application of phase-shift modulation is described. Simulation results and harmonic analysis are also presented in this section. Concluding remarks and overall evaluation of the proposed method are included in Section IV.

II. MULTILEVEL H-BRIDGE CONVERTERS - FUNDAMENTALS OF OPERATION

The structures of the main and auxiliary cells are very similar and the only difference is that the main inverter uses a battery while the auxiliary inverter uses a capacitor (see Fig. 1). In Fig. 2, n is either 1 or 2 depicting the main or auxiliary inverters, respectively. As it can be seen, depending on the conduction status of four switches S_1 , S_2 , S_3 , and S_4 , each converter cell can generate three different voltage levels of $+V_n$, 0, and $-V_n$. H-bridge cells in each phase are connected in series; hence, the synthesized per-phase voltage waveform is the sum of all individual cell outputs. The output voltage of phase a can be described as (see Fig. 1)

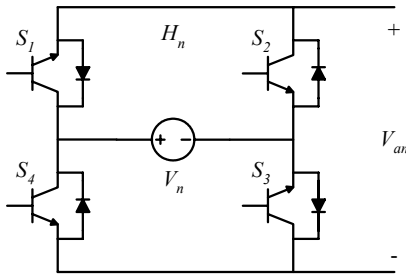


Fig. 2. Circuit diagram of the main and auxiliary H-bridge cells

$$V_{ag} = V_{a1} + V_{a2} \quad (1)$$

In this case, the desired output voltage waveform of a cascaded H-bridge multilevel inverter is a sinusoidal waveform, which can be described as

$$V_{ag,ref} = V_{ag,amplitude} \sin(\omega_e t), \quad (2)$$

where ω_e is the electrical angular frequency.

Fig. 3 describes how the desired output voltage waveform is synthesized using the main and auxiliary converter cells. Main converter is supplied by V_{dc} and generates a rectangular waveform, which is at the same frequency of the reference. Equation (3) describes the relationship between the amplitude of the desired output voltage and the dc voltage level of the main converter cell.

$$V_{ag,amplitude} = \frac{4V_{dc}}{\pi} \cos(\alpha), \quad (3)$$

where phase shift α (or conduction angle of the main converter cell) is denoted in Fig. 3. The remaining of the output voltage, second trace in Fig. 3, which is described in (4), is synthesized by the auxiliary cell at high frequency using a PWM technique (see Fig. 4).

$$V_{a2} = V_{ag} - V_{a1} \quad (4)$$

In a three-phase system, the third harmonic will automatically be canceled. The fifth order harmonic in V_{a1} can be found as

$$V_{a1,5} = \frac{2V_{dc}}{5\pi} \left(\cos \frac{5\pi\alpha}{2/T} - \cos \frac{5\pi(2/T - \alpha)}{2/T} \right) \quad (5)$$

where T is the fundamental period. By choosing an appropriate value for α , the fifth order harmonic of the output voltage will be diminished.

$$\alpha = \frac{2K + 5}{20} T (K = 0, \pm 1, \dots) \quad (6)$$

In this case, $\alpha = 18^\circ$ would eliminate the fifth harmonic. Therefore, the waveform generated by the main H-bridge cell is composed with zero fifth harmonic.

In order to let the output of the auxiliary inverter track the ideal signal shown in the second trace in Fig. 3, sub-harmonic PWM (SHPWM) technique is used. The control principle of the SHPWM method is to use several triangular carrier signals.

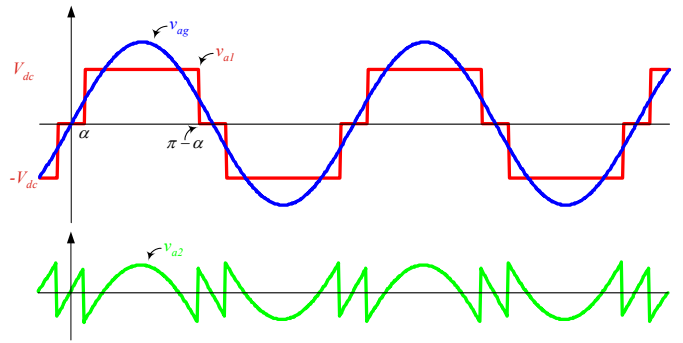


Fig. 3. Desired output, main, and auxiliary voltage waveforms.

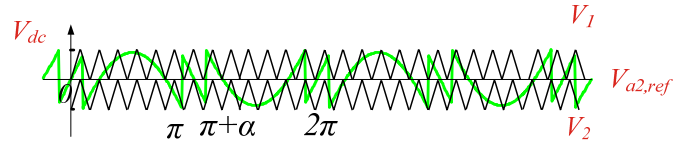


Fig. 4. Sub-harmonic PWM (SHPWM) technique.

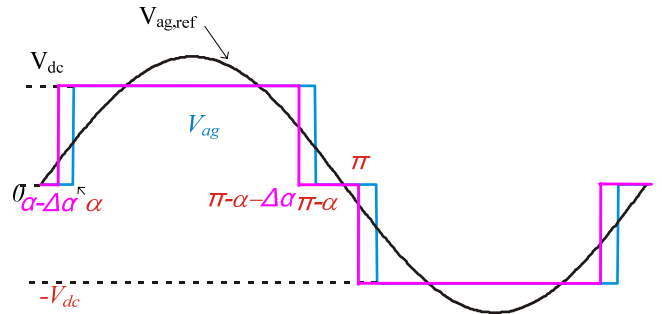


Fig. 5. Left shift of α .

Here, the output voltage of the auxiliary inverter has 3 levels; therefore, two triangular carriers of the same frequency f_c , as depicted in Fig. 4, are used. The control logic can be described as

1. If $V_1 < V_{a2,ref}$, the output is $+1 * V_{dcx}$
2. If $V_2 < V_{a2,ref} < V_1$, the output is 0
3. If $V_{a2,ref} < V_2$, the output is $-1 * V_{dcx}$

where V_1 and V_2 indicate the modulating signals. In this case, the voltage of the main inverter is 200V and auxiliary inverter is 100V. So the output voltage has 7 levels which are $\pm 300V$, $\pm 200V$, $\pm 100V$ and 0.

III. APPLICATION OF PHASE-SHIFT MODULATION

Voltage regulation of the capacitor in the auxiliary converter is a challenging task [7, 10, 11]. In the proposed method, capacitor voltage regulation is achieved by adjusting the active and reactive power that the main converter injects to the load. The main converter injects only active power if α is chosen to be exactly 18° . By shifting the voltage waveform synthesized by the main converter (see Fig. 5), one could also inject some reactive power, which can be used to charge or discharge the capacitor on the auxiliary converter. Phase-shift modulation is used to find the required phase shift.

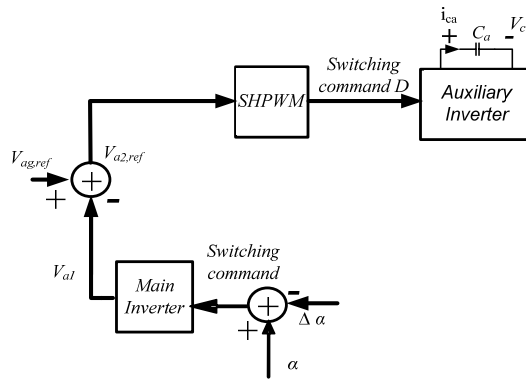


Fig. 6. Control diagram of the system.

Each phase of the Y-connected load is assumed to be comprised of a resistor in series with an inductor or capacitor. This type of load covers all of the operating modes of an induction machine. The control diagram of the system is shown in Fig. 6.

Here power factor is considered to be variable from 0 to 1 for both lagging and leading situations and amplitude value of the load current is assumed to be constant which is 50A in this case. According to the value of the given voltage, current and power factor, the values of the resistor, capacitor or inductor of the load can easily be calculated.

The relationship between average current across the capacitor in cell H_{a2} $\langle i_{ca} \rangle$ and $\Delta\alpha$ is sketched in Fig. 7 for inductive (Fig. 7(a)) and capacitive (Fig. 7(b)) loads with different power factors.

From Fig. 7, one can see if the load is inductive, the point of intersection of the average current waveform and x-axis is at 0. Furthermore, the capacitor average current and $\Delta\alpha$ have a linear relationship. Therefore, one can regulate the voltage of the capacitor by adjusting $\Delta\alpha$ within the range of $\pm 0.5^\circ$. However, if the load is capacitive, the point of intersection of the average current waveform and x-axis is placed at 1° . The curve of the average current is nonlinear. Fortunately, one can regulate the voltage of the capacitor by controlling $\Delta\alpha$ between 0.5° to 1.5° where the curve of the average current is almost linear.

The simulation result is shown in Fig. 8, where power factor=0.866 leading and $\Delta\alpha = -1^\circ$ in (a) while $\Delta\alpha = 1^\circ$ in (b). Load is considered to be inductive. According to the figure, when $\Delta\alpha$ is positive, the capacitor voltage will continuously increase while the capacitor voltage will continuously decrease if $\Delta\alpha$ is negative. Hence, one can regulate the voltage of the capacitor by appropriately adjusting $\Delta\alpha$.

Based on the discussion above, one could devise a closed-loop control system for capacitor voltage regulation as depicted in Fig. 9. $\Delta\alpha$ is adjusted to regulate the capacitor voltage in auxiliary cells. Simulation results of the closed loop phase-shift system, with an induction motor as load, are depicted in Fig. 10.

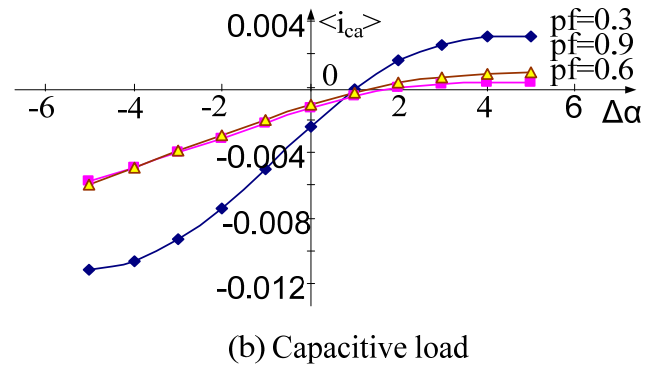
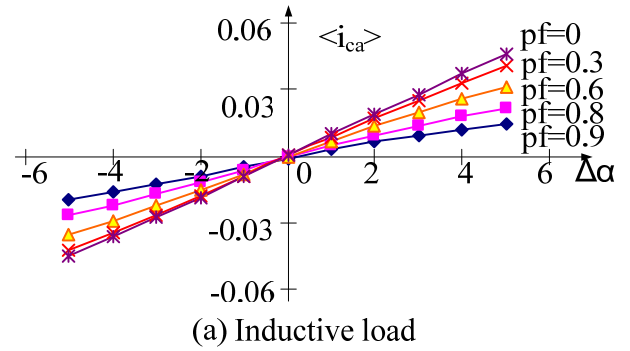


Fig. 7. Relationship between capacitor average current and $\Delta\alpha$ (a) Inductive load and (b) Capacitor load.

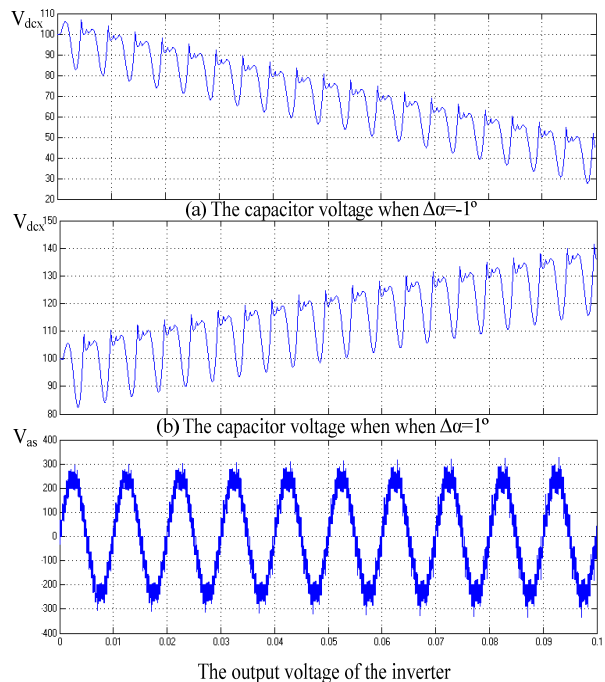


Fig. 8. Simulation results of open loop phase-shift modulation.

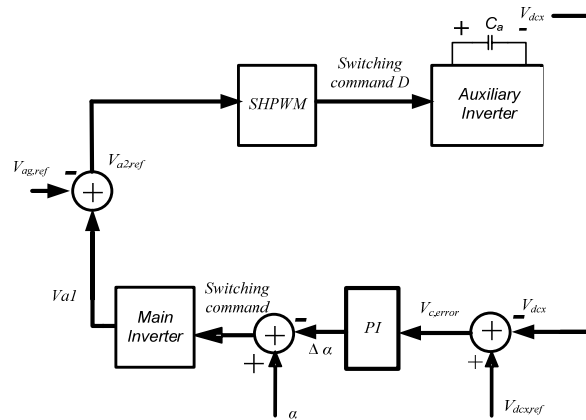


Fig. 9. Closed-loop control block diagram of the system.

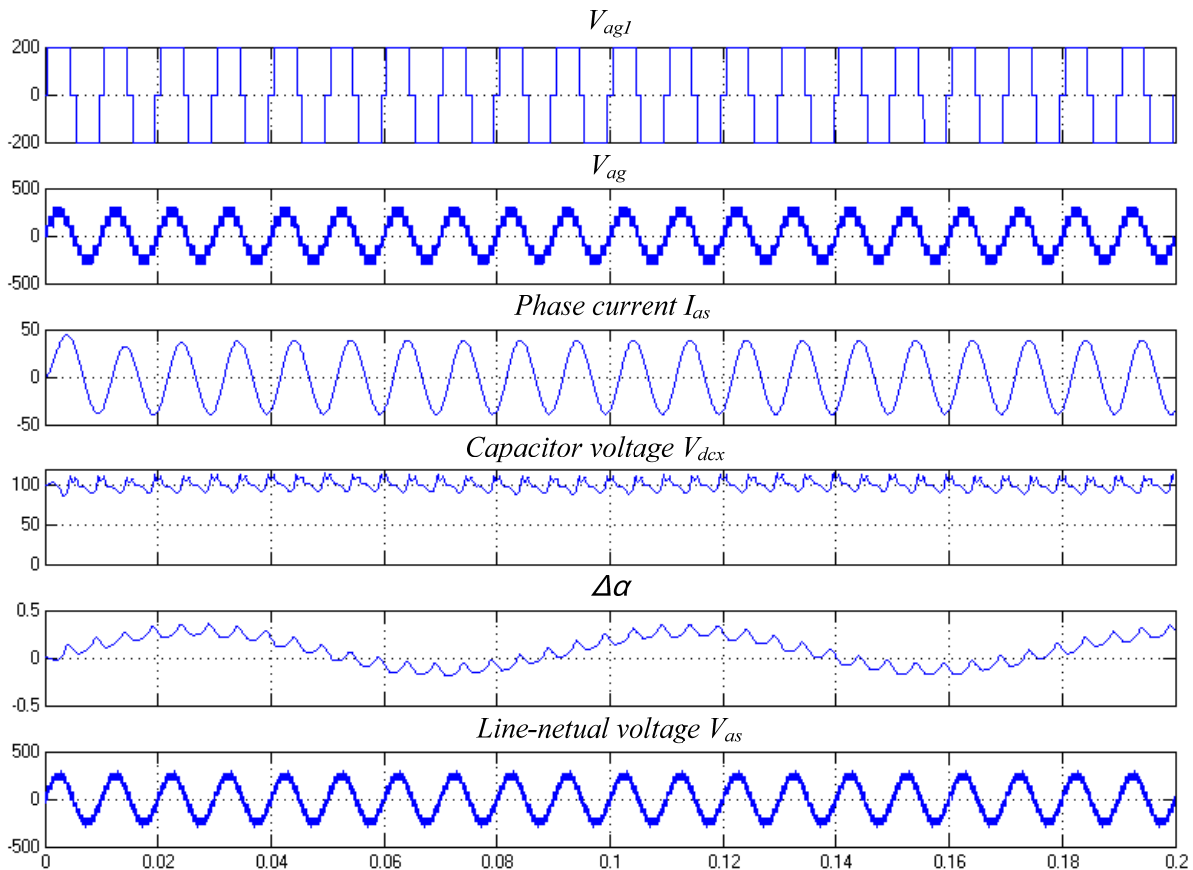


Fig. 10. Simulation results of the closed-loop phase-shift modulation.

From Fig. 10, it can be observed that $\Delta\alpha$ is very small, so it will not generate drastic harmonic distortions. Based on the results, $\Delta\alpha$ only changes from -0.2 to 0.35, which guarantees that the fifth harmonic component of V_{ag} is negligible.

IV. CONCLUSIONS

A single-dc-source cascaded H-bridge multilevel converter driving an electric motor has been analyzed. A new control method, phase-shift modulation, is used to achieve voltage

regulation for the capacitors replacing the independent dc sources in the auxiliary H-bridge cells. The main H-bridge cells switches at the fundamental frequency while the auxiliary inverter switches at the PWM frequency. The proposed approach has less computational burden and has more robust capacitor voltage control. The simulation results agree with the analysis and show that the regulation of the capacitor voltage is achievable without deteriorating the total harmonic distortion.

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