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A Four-Level Hybrid-Clamped Converter with Natural Capacitor Voltage Balancing Ability

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ABSTRACT

This paper presents a novel four-level hybrid-clamped converter topology which is composed of eight switches and one flying capacitor per phase. The operating principle is introduced and phase-shifted pulse width modulation is used to control this converter. A detailed analysis of the average currents through the flying capacitor and neutral points of the dc-link is presented. Based on the analysis, it can be concluded that the voltages across the flyingcapacitor and dc-link capacitors can be naturally balanced under ideal and steady-state condition. A low-power three-phase prototype is built up and experimental results are presented to validatethe proposed topology and modulation method.

INTRODUCTION

Multilevel converters have been widely used in high power and high-voltage applications. Among the existing multilevel converters, diode-clamped, flying-capacitor, and cascaded H-bridge multilevel converters are three classical multilevel topologies which are the most widely used in the industry. They are all clamped by a single-type device such as diode or capacitor. The generalized multilevel topology proposed in is regarded as the most comprehensive and complicated multilevel topology. Both passive devices (diodes and capacitors) and active switches are used for clamping in this topology and so it can be regarded as a hybrid-clamped converter. The main disadvantage of this topology is a large number of clamping switches and capacitors are adopted, which makes it difficult to be commercialized and used in practical applications. Recently, an emerging multilevel converter topology which gains increasing attentions is the modular multilevel converter (MMC). It is comprised of a number of cascaded halfbridges without transformer, so that the output voltage can reach

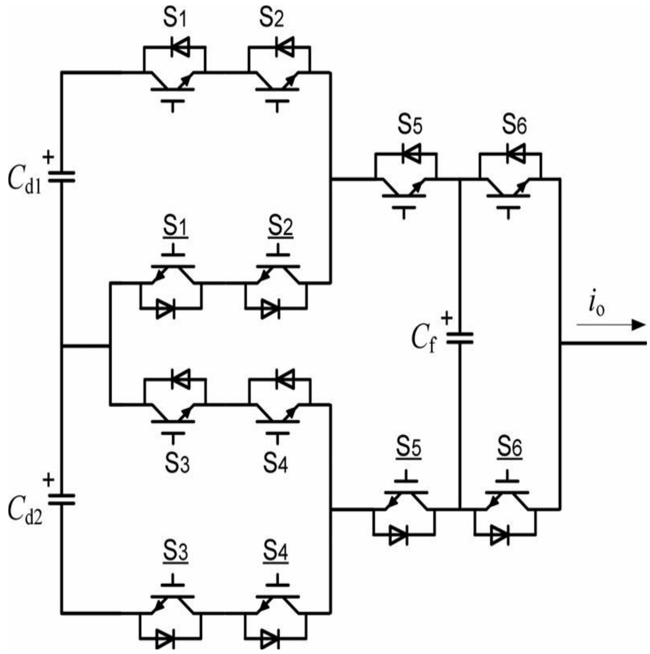

Figure. 1. Single phase of the five-level ANPC converter.

to hundreds of kilovolts. The most successful commercial application of this topology is in high-voltage direct current transmissions. When it is used in medium-voltage motor drives, it suffers from low-frequency fluctuation in the floating capacitors. Therefore, MMC would not be suitable for constant-torque loads that require the rated torque in a low-

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speed region. Five-level active neutral-point clamped (ANPC) converter is another attractive hybrid-clamped converter which is more suitable for high-performance medium-voltage motor drives. A single phase of this topology is shown in above Fig.

It can be seen as the combination of a three-level ANPC converter and a two-level cell. A drawback of this topology is the requirement of two switches connected in series to ensure all theswitches withstand the same voltage stress, which may reduce the reliability of the converter. In order to avoid the series connection of two switches in thefive-level ANPC converter, this paper presents a novel four-level hybrid-clamped converter for medium-voltage motor drives, as shown in Fig. Compared to the five-level ANPC converter, this four-level hybrid-clamped converter contains only eight switches and the nominal voltages across the upper and lower dc-link capacitors are the same as the flying capacitor, hence each switch withstands the same voltage stress.

In the other hand, in order to increase the voltage levels, an extra capacitor is inserted into the dc-link so that each phase can output four voltage levels. This four-level hybrid-clamped topology can also be regarded as a modification of four-level flying-capacitor topology. The high-voltage flying capacitor near the dc-link is replaced by two clamping switches, hence the total size and weight can bereduced.

Compared to four-level diode-clamped converter, the proposed topology also has many advantages. Four-level diode clamped converter need six clamping diodes per phase and each voltage level only corresponds to one switching state, which makes it difficult to balance the dc-link capacitor voltages. The proposed four-level hybrid-clamped converter uses only two switches and a flying capacitor for clamping and has plenty of redundant switching states, which makes it possible to balance the dc-link and flying capacitor voltages.

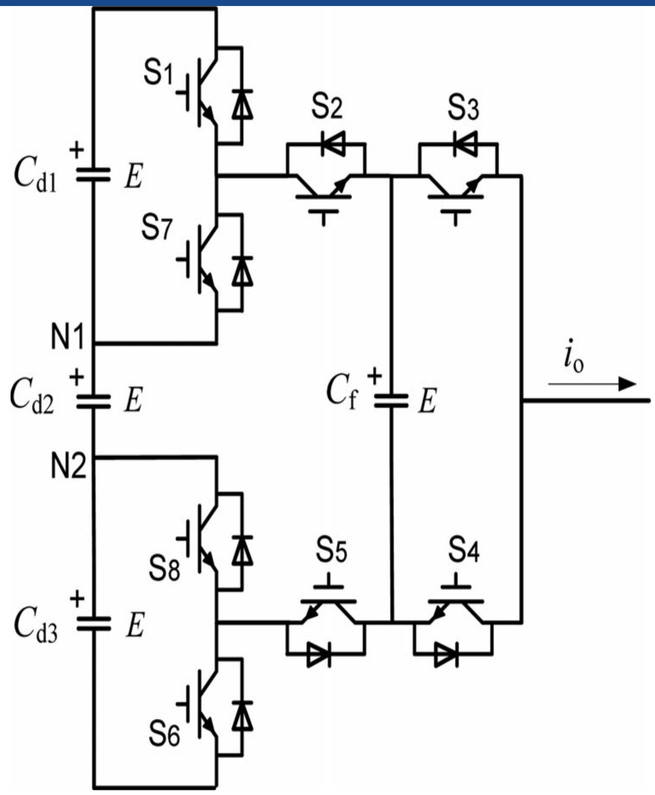
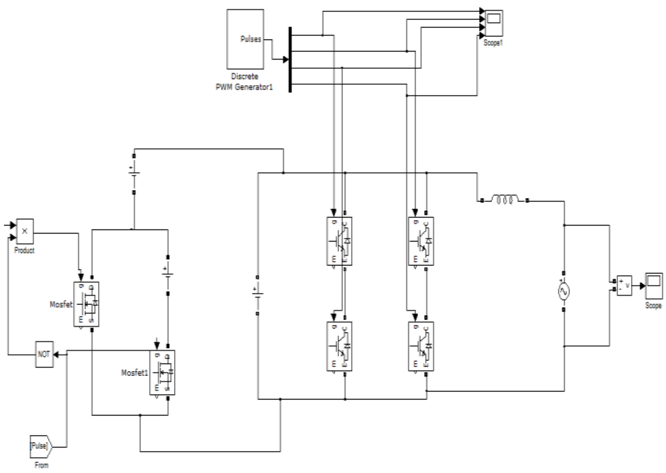


Figure.2: Single phase of the proposed four-level hybrid-clamped converter.

CIRCUIT DIAGRAM



PULSE WIDTH MODULATION

Pulse Width Modulation (PWM) is the most effective means to achieve constant voltage battery charging by switching the solar system controller's power devices. When in PWM regulation, the current from the solar array tapers according to the battery's condition and recharging needs Consider a waveform such as this: it is a voltage switching between 0v and 12v. It is fairly

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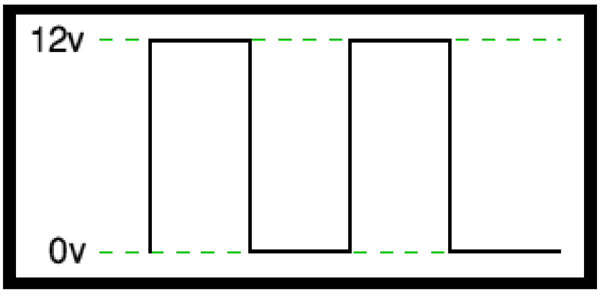
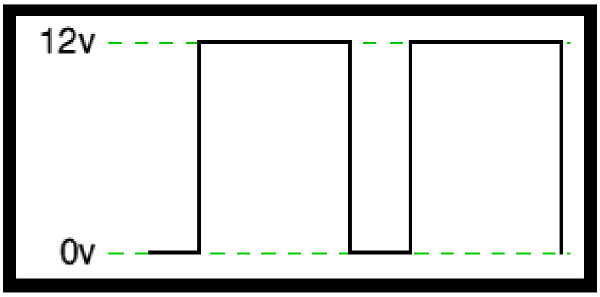
obvious that, since the voltage is at 12v for exactly as long as it is at 0v, then a 'suitable device' connected to its output will see the average voltage and think it is being fed 6v - exactly half of 12v. So by varying the width of the positive pulse - we can vary the 'average' voltage.



Similarly, if the switch 444 keep the voltage at 12 for 3 times as long as at 0v, the average will be 3/4 of 12v - or 9v, as shown below.



and if the output pulse of 12v lasts only 25% of the overall time.

By varying - or 'modulating' - the time that the output is at 12v (i.e. the width of the positive pulse) we can alter the average voltage. So we are doing 'pulse width modulation'. I said earlier that the output had to feed 'a suitable device'. A radio would not work from this: the radio would see 12v then 0v, and would probably not work properly. However a device such as a motor will respond to the average, so PWM is a natural for motor control.

Pulse Width modulator

So, how do we generate a PWM waveform? It's actually very easy, there are circuits available in the TEC site. First you generate a triangle waveform as shown in the diagram below. You compare this with a d.c voltage, which you adjust to control the ratio of on to off time that you require. When the triangle is above the 'demand' voltage, the output goes high. When the triangle is below the demand voltage.

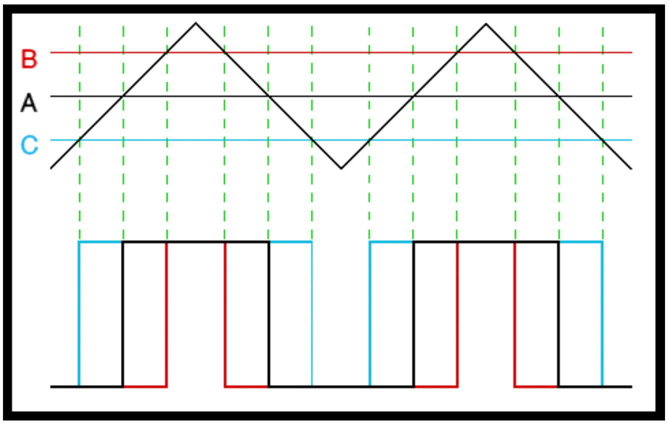


Figure 4.1.1: Pulse width waveform.

When the demand speed it in the middle (A) you get a 50:50 output, as in black. Half the time the output is high and half the time it is low. Fortunately, there is an IC (Integrated circuit) called a comparator: these come usually 4 sections in a single package. One can be used as the oscillator to produce the triangular waveform and another to do the comparing, so a complete oscillator and modulator can be done with half an IC and maybe 7 other bits.

The triangle waveform, which has approximately equal rise and fall slopes, is one of the commonest used, but you can use a saw tooth (where the voltage falls quickly and rinses slowly). You could use other waveforms and the exact linearity (how good the rise and fall are) is not too important.

Traditional solenoid driver electronics rely on linear control, which is the application of a constant voltage across a resistance to produce an output current that is directly proportional to the voltage. Feedback can be used to achieve an output that matches exactly the control signal. However, this scheme dissipates a lot of power as heat, and it is therefore very inefficient.

A more efficient technique employs pulse width modulation (PWM) to produce the constant current through the coil. A PWM signal is not constant. Rather, the signal is on for part of its period, and off for the rest. The duty cycle, D, refers to the percentage

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of the period for which the signal is on. The duty cycle can be anywhere from 0, the signal is always off, to 1, where the signal is constantly on. A 50% D results in a perfect square wave.

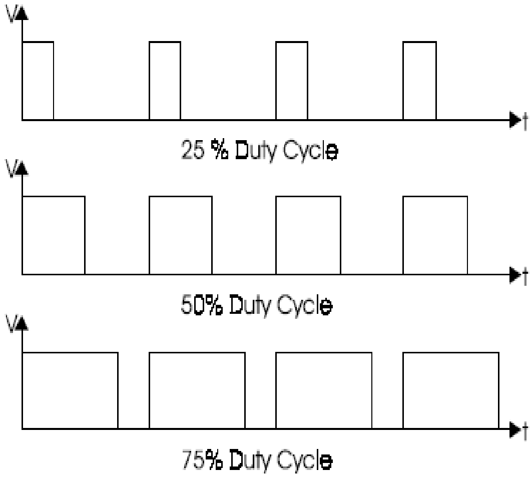
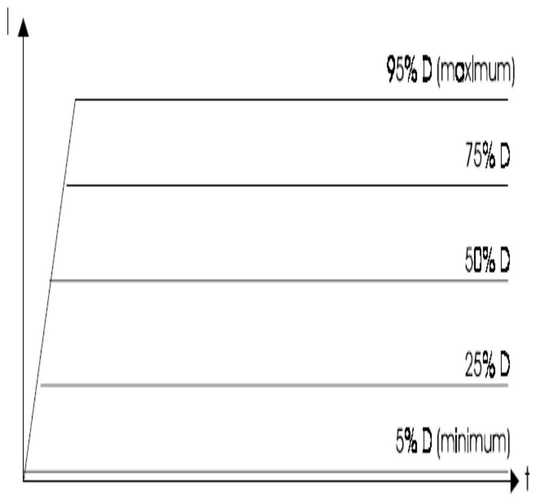


Figure 4.1.2:Different dutycycles waveforms.

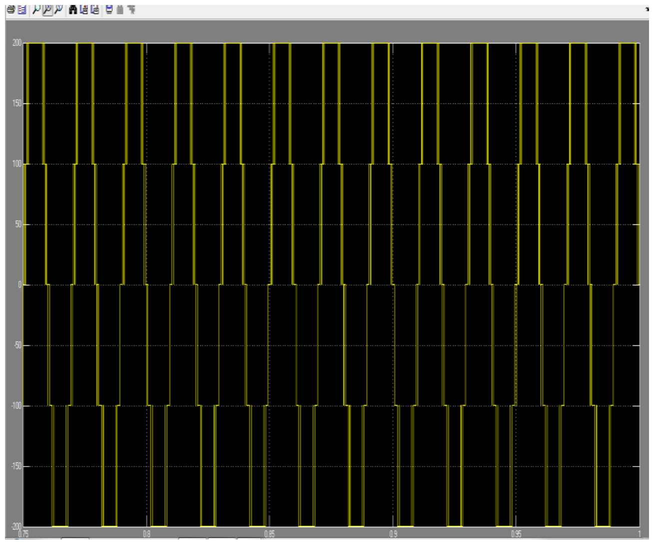
A solenoid is a length of wire wound in a coil. Because of this configuration, the solenoid has, in addition to its resistance, R, a certain inductance, L. When a voltage, V, is applied across an inductive element, the current, I, produced in that element does not jump up to its constant value, but gradually rises to its maximum over a period of time called the rise time. Conversely, I does not disappear instantaneously, even if V is removed abruptly, but decreases back to zero in the same amount of time as the rise time.Therefore, when a low frequency PWM voltage is applied across a solenoid, the current through it will be increasing and decreasing as V turns on and off. If D is shorter than the rise time, I will never achieve its maximum value, and will be discontinuous since it will go back to zero during V's off period. In contrast, if D is larger than the rise time, I will never fall back to zero, so it will be continuous, and have a DC average value. The current will not be constant, however, but will have a ripple.

At high frequencies, V turns on and off very quickly, regardless of D, such that the current does not have time to decrease very far before the voltage is turned back on. The resulting current through the solenoid is therefore considered to be constant. By adjusting the D, the amount of output current can be controlled.

With a small D, the current will not have much time to rise before the high frequency PWM voltage takes effect and the current stays constant. With a large D, the current will be able to rise higher before it becomes constant.



SIMULATION RESULT



CONCLUSION

A novel four-level hybrid-clamped converter topology is introduced in this paper. The switching function model of average currents through the flying capacitor and neutral points is analyzed, which indicates that the voltages across the flying capacitors and the dc-link capacitors can be naturally balanced under ideal and steady-state condition using PS-PWM. Experimental results have demonstrated the validity of this topology and modulation method. The main application of this topology is medium-voltage motor drives. Compared

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to 3 L-NPC VSC, 3 L/4 L-FC VSC, and 5 L-ANPC VSC, the 4 L-HC VSC features comparable total installed switch power, the best harmonic characteristic, and relatively low stored energy of flying capacitors. So, it is an attractive and competitive topology for medium-voltage motor drives.

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