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A Cascade Multilevel Converter of Switched Reluctance Motor and Its Control Timing Sequence

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Abstract: A kind of cells cascaded multilevel converter of switched reluctance motor was proposed, which can be made up of low voltage power electronic devices and can be applied to drive high voltage switched reluctance motor. Based on introducing the main circuit topology, the operating modes and the voltage superposition law of proposed converter, the control strategy for the switched reluctance drive by the use of proposed converter was analyzed and a kind of corresponding control time sequence was established. By means of Matlab/Simulink simulation and actual system experiment, the system controlled under proposed timing sequence was validated to have good driving performance. In addition, the experiment result shows that the power converter has almost no harmonic pollution to the power source and has a high grid-side power factor because of employing phase-shifting transformer and multi-pulse rectifier in the input port, the threat against insulation of the motor winding decreased with the lessening of voltage gradient of the motor winding by making the winding voltage to vary in multi-level. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Switched reluctance motor, Cascaded cells, Power converter, Grid-side harmonic, Voltage gradient.

1. Introduction

Owing to the nature of robustness, high efficiency and high power density, the switched reluctance motor drive (SRD) has been used in many fields. Especially, the SRD is suitable for poor environment or other harsh operating condition such as in traction, mining, metallurgy and aviation which need heavy load starting and have high speed requirements because of its series of advantages: simple and firm structure, low cost, high starting torque, low starting current, wide range of speed regulation and high reliability [1-7]. However, due to lack of high voltage full-controlled power electronic devices, the present SRDs are mostly applied in only low or medium voltage condition, and thus the system power is limited and the application of SRDs in the field of high-voltage drive was restricted. So, it is essential to have a research into high voltage and high power SRDs to help improve efficiency and save energy.

The manufacture process of switched reluctance motor (SRM) is extremely simple and the withstand voltage is easy to exceed 6/10 kV. To form a reliable high voltage SRD, the key is to construct reasonable high voltage and high power converters. But with traditional SRM power circuit topology, existing power electronic devices can not be directly used to constitute the 6/10 kV SRD. On the other hand, it is

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difficult to equalize the static and dynamic voltage among devices by cascading the devices directly. Some researches on high power SRD converters have been reported. The conventional asymmetrical half-bridge topology had been adopted in reference [8] to enlarge driving power and only reached a maximum power of 280 kW, although 3300 V IGBTs are employed as main switch devices. In reference [9], a kind of multi-port SRM has been proposed, in which, each phase of stator windings was divided into multiple sets corresponding the ports and every port was driven by traditional low-voltage power circuit and controller. Multiple controllers synchronously control the machine and drive multiple sets of stator windings at the same time. Thus, it achieves the synthesis of multiple sets of power, and finally achieves the purpose of driving high-power motor by using low-voltage SRD technology. This scheme is a kind of effective way in the current conditions, but because its every input port needs a set of power circuit and controller, as power increases, the number of SRM input port (i.e. the number of stator winding group) will be increased, which makes the number of power circuit and controller increase correspondingly. On one hand, it doubles the cost of SRD. On the other hand, as the power system is more and more complicated, the reliability of system operation cannot be easily guaranteed.

The withstand voltage problems specific to high voltage variable-frequency speed control of squirrel-cage asynchronous motor had been solved by means of building up cascade multilevel inverter [10-12], from which some inspiration could be gotten to work out high voltage SRM converter. In this paper, a kind of multilevel converter for high voltage SRM was presented, which can be made up of several cascaded low voltage power cells.

2. System Composition of High Voltage SRD and the Cascaded Multicell Circuit Topology

The basic structure of the presented high voltage SRD system, shown in Fig. 1, is composed of power converter, high voltage SRM, controller, isolate and drive circuit.

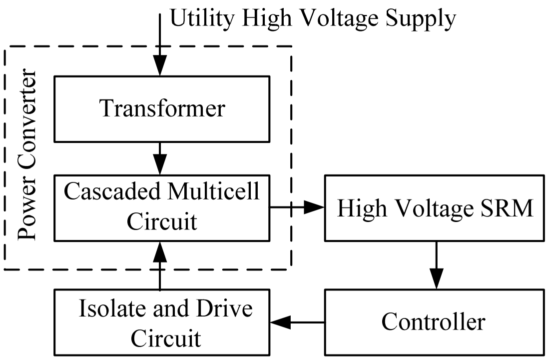


Fig. 1. The system structure of the high voltage SRD.

Different from usual SRD, the power converter of high voltage SRD includes two parts: transformer and cascaded multicell circuit. The main function of transformer is to resolve the input high voltage into multiple low voltage outputs with certain phase difference each other. The number of secondary windings and each winding's voltage value can be flexibly designed according to the rated voltage of SRM. The cascaded multicell circuit is composed of several cells, which are used to convert secondary voltage of transformer into DC voltage, and superpose DC low voltage to DC high voltage and output to the SRM windings.

Taking eight-level converter as an example, the structure of this power converter is shown in Fig. 2. It is the situation of driving three-phase SRM. The transformer includes 24 sets of secondary three-phase windings, whose output voltage is respectively sent to 24 cells of cascaded multicell circuit. The 24 cells will be divided into three groups: A1~A8 corresponding to phase A windings of SRM will be called Cell Group A, B1~B8 called Cell Group B and C1~C8 called Cell Group C similarly. In each Cell Group, a pair of output terminals of each cell is connected in sequence so that the output DC voltage of each cell can be superposed and then be added to the corresponding windings of high voltage SRM respectively.

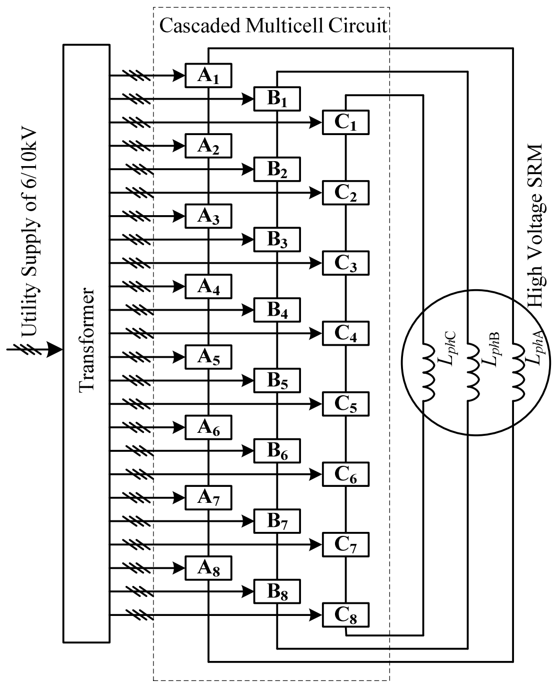


Fig. 2. The converter structure of the high voltage SRD.

In Fig. 2, the 24 power cells are exactly the same. As shown in Fig. 3, each power cell consists of a three-phase rectifier bridge BR_n, a filter capacitor C_n, and an output voltage control bridge made up of two power electronic switches V_{ln}, V_{rn} and two diode VD_{ln}, VD_{rn}. The AC low voltage from each secondary coil of transformer is changed into DC voltage U_{DC} through rectification and filtering. The final output voltage u_{On} of each cell varies according to working mode determined by the states of two switches V_{ln}, V_{rn}.

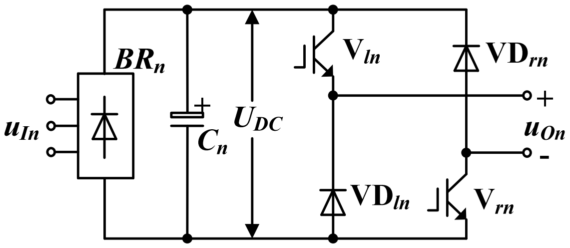


Fig. 3. The power cell circuit.

3. Working Modes of the Power Cell and Voltage Synthesis Law

3.1. Working Modes of the Power Cell

Fig. 4 shows the circuit for one phase leg of a multilevel converter with four power cells in each phase. L_{ph}, R_{ph} stand for the winding inductance and resistance of SRM. In the figure, solid lines indicate turn-on devices or valid current paths and the dashed lines represent turn-off devices or invalid current paths. Fig. 4 illustrates the interconnecting way between power cells as well as the three different working modes of the power cell. According to different states combination of switch devices V_{ln}, V_{rn}, three kinds of working modes of the power cell can be defined as Table 1. The output voltages in every mode were also provided in the table.

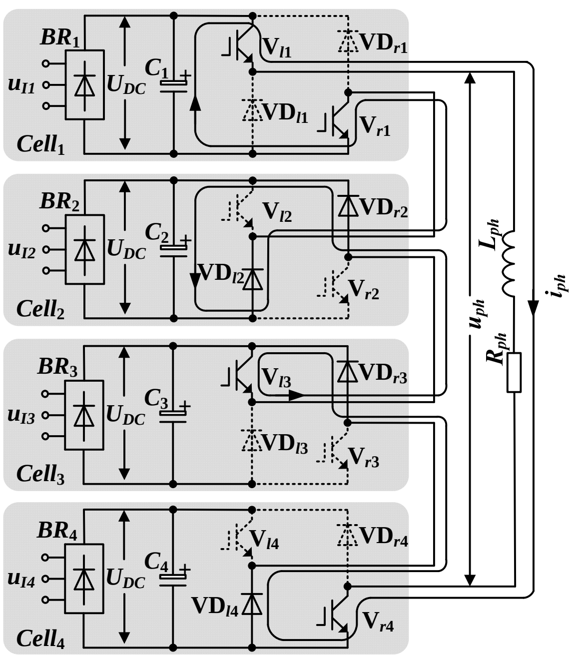


Fig. 4. The illustration of cell's operation modes and interconnecting way between cells.

Positive supply mode is shown in $Cell_1$ of Fig. 4. In this mode, both V_{ln} and V_{rn} are turned on and U_{DC} is output by way of V_{ln} and V_{rn}, and then u_{On} is equal to U_{DC}. At this time, VD_{ln}, VD_{rn} are turned off. The current path in the mode is also shown in $Cell_1$.

In negative supply mode, both V_{ln} and V_{rn} are turned off and the load current freewheels through VD_{ln}, VD_{rn}, as illustrated in $Cell_2$ of Fig. 4. The power source of U_{DC} is output oppositely and u_{On} is equal to $-U_{DC}$, so that the freewheeling time will be shortened.

Table 1. The working modes of the power cell.

Working modes	Switches states		u_{On}
	V_{ln}	V_{rn}	
Positive supply	ON	ON	U_{DC}
Negative supply	OFF	OFF	$-U_{DC}$
Natural Freewheeling	ON	OFF	0
Natural Freewheeling	OFF	ON	0

When one of switches V_{ln} and V_{rn} is turned on, and another is turned off, the current paths are as $Cell_3$ and $Cell_4$ shown in Fig. 4, and they both are called natural freewheeling mode. In this mode, the output of DC voltage U_{DC} is cut off and cannot supply power for SRM windings, and then u_{On} is equal to 0. The cell in this mode only maintains the current path for the corresponding Cell Group.

3.2. Voltage Synthesis Law

From Table 1, it can be seen that the relationship between the number of turn-on switches and each cell's output voltage can be formulated by

$$u_{On} = (x_n - 1) \cdot U_{DC}, \tag{1}$$

where x is the number of turn-on switches which varies among 0, 1, 2 corresponding the three modes: positive supply, negative supply, natural freewheeling. The subscript n is the cell number. Just as shown in Fig. 4, the winding voltage of SRM is the summation of the output voltages of all cascade cells, as given in formula (2).

$$\begin{aligned} u_{ph} &= \sum_{n=1}^{N} u_{On} = (\sum_{n=1}^{N} x_n - N) U_{DC} \\ &= (m - N) U_{DC} \end{aligned}, \tag{2}$$

where N is the sum of cascade cells and m is the number of turn-on switches in each Cell Group. Obviously the value range of m is between 0 to $2N$. Thus it can be seen that the voltage u_{ph} depends only on the number of turn-on switches in each Cell Group, m, provided that N and U_{DC} are constant parameters. The range of u_{ph} is from $-NU_{DC}$ to NU_{DC} with changing at a unit of U_{DC}. Thus the changing rate of winding voltage can be reduced and reduce the threat to winding insulation.

4. Control Strategy and Timing Sequence

According to different purpose, many kinds of control strategies could be adopted and all the strategies have to be implemented through controlling specific power conversion circuit. The same as the existing low voltage SRD, high voltage SRD constructed by proposed cascade multilevel converter can also adopt three control modes, i.e. voltage pulse width modulation (PWM) control, angle position control (APC) and current-chopping control (CCC), to govern the speed of SRM, depending on the rotational speed. The difference is, adjusting every SRM phase winding voltage (or current) through the proposed converter has to be implemented by regulating every cell circuit harmoniously in the corresponding Cell Group. Hence, in the SRD constructed by proposed converter, the control task can be divided into three parts hierarchically: speed control strategy(including feedback loop structure and regulator control algorithm), power circuit control modes and coordination control to cells within each Cell Group, as shown in Fig. 5 and the flow of control logic is pointed out simultaneously. Every level goes about their respective terms of references, that is to say, the outputs of level-3 are given to level-2 and the outputs of level-2 are given to level-1. Finally, at level-1, the states of V_{ln}, V_{rn} in every cell are updated according to commands from their superior level.

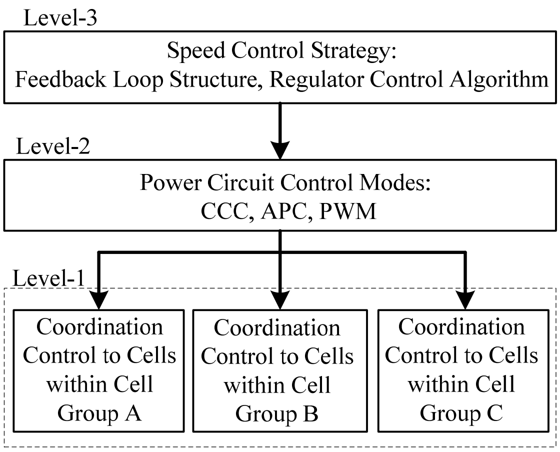


Fig. 5. The layered control map of the Cascaded SRD.

The level-1 is the specific part of the SRD constructed by proposed converter. At level-1, reasonable control sequence for triggering V_{ln}, V_{rn} is the key to guarantee the system performance. In the control timing sequence design, not only the successful implementation of speed control strategy, but also the issues about grid-side harmonic, winding insulation, and the utilization of power devices and so on should be taken into account. In the paper, transformer phase-shifting and multi-pulse rectifier are adopted to suppress harmonic current, so that it is demanded for all cells in each Cell Group to switch at the same time. But in consideration of winding insulation, the switch moment of each cell in every Cell Group expected to be staggered. Here, the control timing sequence of delay trigger in turn between cells was adopted eclectically. Fig. 6 illustrates stagger control sequence for the multilevel converter of 4 cells cascaded. After receiving the on-off signal for phase winding S_{phc}, 4 left arm switches V_{l1}~V_{l4} are firstly triggered successively by signals S_{Vl1}~S_{Vl4}, afterwards, 4 right arm switches V_{r1}~V_{r4} are triggered one after another by signals S_{Vr1}~S_{Vr4}, with equal time delay interval of τ. This kind of control timing sequence is simple and easy to realize, and has following advantages simultaneously:

1) The switch time of each cell is staggered constantly, so that the output waveform becomes a ladder shape, which effectively reduces the du/dt of SRM winding, and significantly alleviates the impact on winding insulation.

2) Each cell has the same turn-on length of time, shares the load power equably, which helps to reduce the power source harmonic and improve power factor cooperating with the phase shifting of transformer.

3) Each device holds the same on-state loss, which helps the device's cooling operation and balancing working life of all devices engaged.

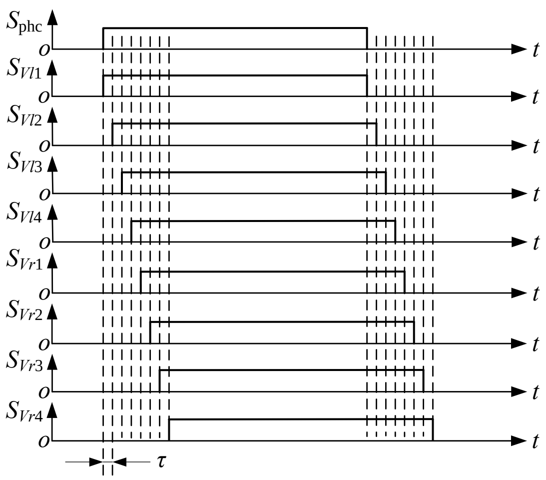
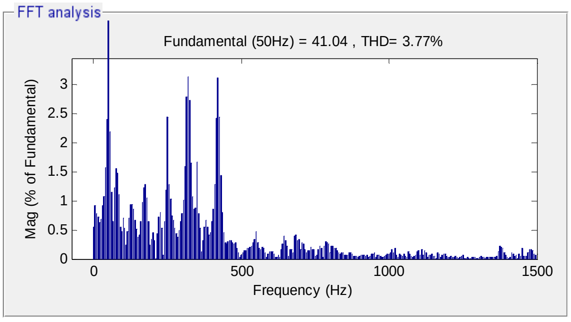
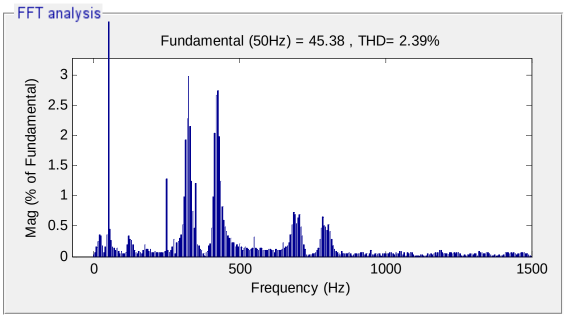


Fig. 6. The control timing sequence of cells.

By the proposed control timing sequence, simulation study on 6 cells and 8 cells cascaded multilevel converters had been conducted with Matlab/Simulink software. Based on normal speed control performance, the spectra of grid-side phase current possessing maximum total harmonic distortion are shown in Fig. 7 and the resulting total harmonic distortions (THDs) are as Table 2. It can be seen that the grid-side harmonic currents were kept at a low level although they cannot be eliminated entirely by use of proposed control timing sequence.



(a)



(b)

Fig. 7. The frequency spectra of grid-side current under two converters: (a) the current spectrum of 6 cells cascaded converter; (b) the grid side current spectrum of 8 cells cascaded converter.

Table 2. The total harmonic distortions of simulation result.

Converter types	THDs (%)		
	Phase A	Phase B	Phase C
6 cells cascaded	3.66	3.77	3.73
8 cells cascaded	2.16	2.01	2.39

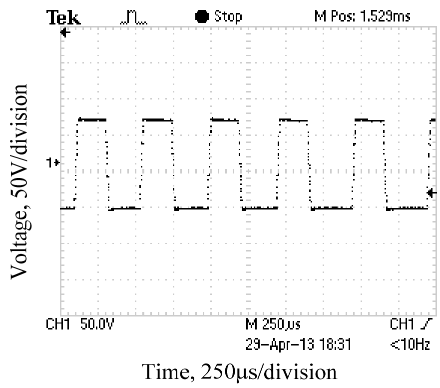
5. Experiment Results

To verify the effectiveness of the cascade multilevel SRD converter and the feasibility of control timing sequence, setting a 3-phase 6/4 SRM of 200 W rated power, 144 V rated voltage for speed regulation goal, build two experimental systems of different converters to be tested, and adopt PWM mode to regulate speed.

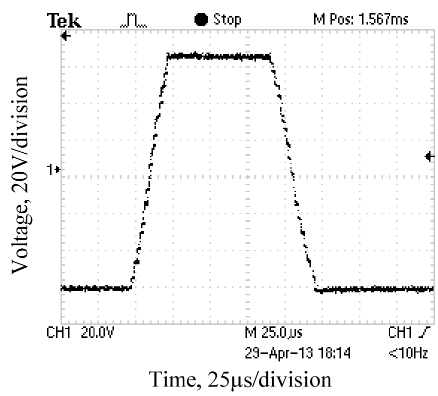
System I: Each phase winding of SRM was driven by a Cell Group including 3 cells in series, a total of 9 cells. The primary winding of the transformer was Y-shape connected. The 9 secondary windings were divided into three groups. In each group, the phase spread with the primary winding is +10°, -10° and -30°. Each winding output voltage is 48 V.

System II: Each phase winding of SRM was driven by a Cell Group including 8 cells in series, a total of 24 cells. The primary winding of the transformer was Y-shape connected. The 24 secondary windings were divided into three groups. In each group, the phase spread between windings is 7.5°. Each winding output voltage is 18 V.

The waveforms of stator winding voltage of SRM had been tested by sampling resistances and oscilloscope. Fig. 8(a) was the PWM voltage waveforms in system II when the motor speed is 700 r/m. It can be seen that the winding voltage of SRM swings from -144 V to 144 V in the process of speed regulation. No matter what the pulse width is, the front and rear edges will have a certain slope. Fig. 8(b) showed a single pulse after zooming in at time axis. Obviously, as the 16 switches in 8 cells turned on in turn, the output voltage increased gradually. Similarly, the output voltage decreased stepwise with the 16 switches turned off in turn. Thus, the rising and falling edges were divided into 8 steps, and the total change rate of output voltage had been reduced effectively.



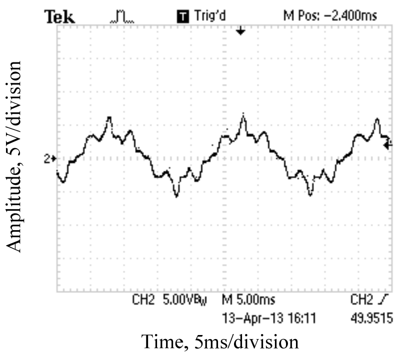
(a)



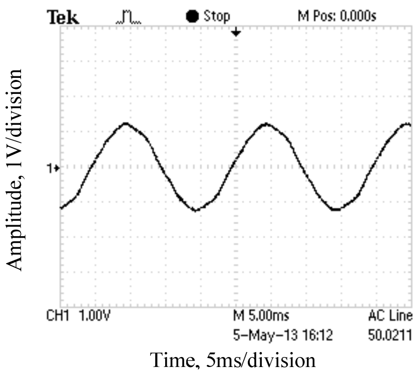
(b)

Fig. 8. The output voltage waveforms of 8 cells experimental system: (a) the PWM waveform under n=700 r/m; (b) the single pulse in PWM waveform.

The grid-side current waveforms of system I, II had been tested by Hall sensors and oscilloscope. They were shown in Fig. 9(a), Fig. 9(b) respectively. The current waveform of system I in Fig. 9(a) approximated to sine wave by and large, but there were still some fluctuations appended, and pulsing was obvious. Fig. 9(b) shows that the current waveform of system II was a better sine wave. It can hardly be seen that the distortion caused by harmonic coming from the running of the SRD. The frequency spectrum corresponding Fig. 9(b) is shown in Fig. 9(c), showing that the value of fundamental frequency amplitude is over 40 dB or so more than other harmonic components, and harmonic pollutions hardly exists.



(a)



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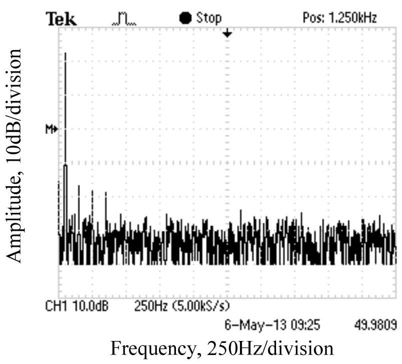

(c)

Fig. 9. The power source current waveforms and frequency spectrum: (a) the grid-side current waveform of system I; (b) the grid-side current waveform of system II; (c) the grid-side current frequency spectrum of system II.

6. Conclusions

For the restriction of the low withstood voltage of present power electronic devices to the development of high voltage and high power SRD, this paper has presented a kind of multilevel power converter made up of cascaded low voltage power cells. The control strategy of SRD formed by proposed converter has been analyzed and corresponding control sequence has been established and simulated by Matlab/Simulink software. Three-level and eight-level configuration experiment systems have been built and tested to verify the circuit scheme and control sequence. Both simulation and experimental results prove that the performance of proposed multilevel SRD converter met the desired output. Firstly, it can superpose the expected high voltage by way of making low voltage cells in series, and the circuit devices of each cell only need to withstand the voltage from its own cell. Secondly, by adopting stagger control sequence cooperated with transformer phase-shifting and multi-pulse rectification, the proposed converter can effectively reduce the change rate of winding voltage and reduce the threat to motor winding insulation as well as significantly eliminate harmonic pollution in grid-side to improve the power factor.

Acknowledgements

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