Control of a Cascaded Permanent Magnet Switched Reluctance Generator for Automobile Generation Application

QIANLONG WANG, XINLIANG LI, XIN JING, WEI JIANG, (Member, IEEE), HONG JIN, MINYAN LI, AND YUNYUN CHEN

College of Electrical, Energy and Power Engineering, Yangzhou University, Yangzhou 225000, China

Corresponding author: Qianlong Wang (wangqianlong@yzu.edu.cn)

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ABSTRACT Aiming at the problems of the low efficiency of electro-magnetic generator, and the difficulty in the regulation of magnetic field intensity for the permanent magnet generator, a new cascaded permanent magnet switched reluctance generator (CPMSRG) is proposed for the automobile generation application. The generator has the advantages of simple structure, wide effective power generation speed, adjustable excitation, high efficiency, and low risk of demagnetization. The structure and basic principles of the CPMSRG are introduced firstly. Secondly, the topology of the power converter, the generation control method and the battery free starting generation control method are studied according to the operation characteristics of the generator, and the CPMSRG sensorless generation control strategy is proposed based on the full conduction generation control method. Finally, the prototype experiment platform is built, and the sensorless power generation experiments of the CPMSRG are completed under the conditions of different speeds, different loads and different battery residual powers. The experimental results show that the new cascaded generator proposed can generate power efficiently and stably in a wide speed range, and can realize the battery free power generation at very low speed, which verifies the effectiveness of the designed system and its control methods.

INDEX TERMS Switched reluctance generator, permanent magnet generator, cascaded generator, sensorless control.

I. INTRODUCTION

The generators used in the automobile can be classified as electro-excitation generators and permanent magnet (PM) generators according to different excitation modes. The electro-excitation generators are widely used in the automobile industry, because of its low manufacturing cost and convenient magnetic field adjustment. Nevertheless its low output power and large excitation loss lead to low efficiency and large electromagnetic noise at medium and low speed [1]–[3]. Compared with the electro-excitation generator, the PM generators have high reliability and excitation efficiency. However, due to the inherent characteristics of the PM, the air gap magnetic field is hard to regulated, and the speed and load of the generator are changing at any time, which makes the output voltages of the generator difficult to be stable [4]–[6]. Considering the shortcomings of electro-excitation generators and PM generators, hybrid excitation (HE) generators are proposed, which combine the advantages of electro-excitation generators and PM generators, and then attracts the interest of many researchers [7].

The basic principle of the HE machine is to add excitation coil in the stator or rotor of the traditional PM machine, and adjust the air gap magnetic field by changing the current in the excitation coil. When there is no current in the excitation winding of the HE machine, the operation principle of the machine is the same as that of the PM machine, and only the PM material provides excitation. When currents are applied to the excitation winding, the magnetic field of the PM and the electro-excitation magnetic field act on the machine together. The PM material in the HE machine is the main excitation source. The electro-excitation only plays the role of magnetic field regulation to maintain the stability of the machine output. This excitation matching method can

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smoothly adjust the machine magnetic field. Many types of HE machines have been developed, but most HE machines have some shortcomings. For example, the PM magnetic circuit and electro-excitation magnetic circuit of some HE machines are in series, which will lead to problems such as large excitation loss and reduction of the efficiency [8], [9]. The magnetic circuits of some HE machines are parallel, and the demagnetization risk of PM is small, but this kind of machines need the brush and slip ring, which will reduce the reliability of the machines [10], [11]. In addition, although some new HE machines without brushes and slip rings can realize parallel magnetic circuit, their structures are complex, which greatly increases the manufacturing cost of the machines [12]–[14]. Therefore, the research on generators with simple structure, reliable operation, independent magnetic circuit and adjustable excitation is of great significance for the automobile generator, wind power generation and other applications.

The CPMSRG proposed in this paper consists of a switched reluctance generator (SRG) and a PM Generator (PM synchronous generator or brushless DC generator, PMG). Compared with other generators, SRG has the advantages of simple structure, low cost and high reliability [15]–[17]. The rotor and stator of the SRG are only made of laminated silicon steel sheets, so it can operate in harsh environment such as high speed, high temperature and strong vibration [18]. The power generation efficiency of a single SRG at low speed is not high. With the increase of the speed, its power generation efficiency will increase, and the excitation and output voltages are controllable [19]. The single PMG has the problems of difficult air gap magnetic field regulation and complex voltage stabilizing control in a wide speed range.

In the proposed CPMSRG system, the excitation power supply voltage of the SRG is provided by the PMG, which can realize battery free power generation. The output voltage in the power generation state is provided by the PMG and SRG together, and the effective power generation speed range is wide. The PMG and SRG in the cascaded generator are coaxial series, the magnetic circuits are completely decoupled, and there is no demagnetization risk caused by large excitation current. The power generation system adopts double machine structure, the overall efficiency of the system is higher than that of the electro-excitation generator, and the manufacturing process is simpler than that of the HE generator. By adjusting the excitation magnetic field of the SRG, the generator output voltage can be regulated without additional voltage stabilizing circuit, which simplifies the hardware circuit of the power generation system.

II. STRUCTURE OF THE CPMSRG POWER GENERATION SYSTEM
A. STRUCTURE OF THE CPMSRG
The CPMSRG is composed of a PMG and a SRG in coaxial cascade, as shown in Figure 1. The PMG is a traditional PM synchronous generator or brushless DC generator. The SRG is also a traditional structure. Because the power generation system designed is for the 36 V batteries and loads in the vehicle, the rated voltage of the generator is 42 V (42 V voltage is the charging voltage of the batteries). In addition, considering the ripple of the output voltage and machine noise in the power generation system, the traditional three-phase 12/8 structure is selected for the SRG in this paper.

![Structure of the CPMSRG power generation system.](image1)

The structure of the CPMSRG power generation system is shown in Figure 2, which is mainly composed of the proposed cascaded generator, the power converter, drive circuits, current sensors, voltage sensors, batteries, loads and the controller. TMS320F28335 DSP of the TI Company is selected as the controller of the generator, which is used to calculate and logically judge the voltages, phase winding currents and output generation voltages collected by the voltage and current sensors, and give the control signals of the SRG. The control signals are amplified by the drive circuits to directly control the power switches, so as to realize the control of the power generation system. In order to facilitate the prototype comparison tests and control parameters optimization, an independent SRG and a PMG are selected for the experiments, which are connected in coaxial series. In the later stage, the two generators can be processed into a single compact structure by removing the coupling. The prime motor is used to simulate the automobile engine to drive the cascaded generator to rotate. The loads of the generator include batteries and resistors with different resistance values.

![Structure of the CPMSRG power generation system.](image2)
the separately excited asymmetric half bridge structure. The SRG has a double salient structure, and its output generation voltages and currents are pulsating [20]. In order to reduce the output voltage ripple and ensure the stable charging of the battery and normal power supply of loads, LC filter circuit is selected in this system.

III. PRINCIPLE AND CONTROL METHODS OF THE CPMSRG

A. PRINCIPLE AND CONTROL STRATEGY OF THE CPMSRG AT NORMAL SPEED

The cascaded generator designed in this paper is mainly used for automobile generator. According to the operation characteristics of the automobile engine, this paper sets the speed range of 1000 r/min - 3000 r/min as the normal operation speed of the generator. The speed below 1000 r/min is set as the low speed range, and the speed is higher than 3000 r/min for high speed range. When the prime motor operates within the normal operating speed range, the working mode of the cascaded generator is that the PMG and the SRG generate power together. The power generation mode of the SRG selects the full conduction chopping control (FCCC) method [21], to realize the sensorless control. The specific control strategies are as follows:

The principle of the FCCC is that the regulator calculates the real-time chopping thresholds of the SRG phase currents according to the differences between the given voltages and the actual output voltages, and the controller completes the current chopping control according to the chopping thresholds to adjust the SRG phase currents. This scheme doesn’t need the values of the turn-on angle and turn-off angle of the SRG, and completely depends on the comparison between the current chopping thresholds and the phase current values, so as to control the on-off state of the switches and then regulate the output voltages of the generator. The FCCC method is shown in Figure 4.

Taking phase A of the SRG as an example, when phase A is at the minimum inductance position, the power switches $S_1$ and $S_2$ are turned on, and the phase current $i_{ph}$ rises rapidly under the excitation of the power supply voltage (i.e. the output voltage $U_{PMG}$ of the PMG in Figure 5). The phase current path in this state is shown in Figure 5 (a). When the phase current $i_{ph}$ reaches the set current chopping threshold $i_{chop}$, the switch $S_2$ is turned off, the switch $S_1$ remains on, and the phase current flows through the diode $D_8$ to the load (the current path is shown in Figure 5 (b)). Under the function of the load voltage, the phase current will decrease, and the switch $S_2$ will be turned on again after a fixed off time $\Delta t$. When the SRG rotor reaches the phase inductance rising zone and the power switches are turned on, the back EMF of the phase winding will hinder the rising trend of the phase current $i_{ph}$, and the amplitude of the phase inductance gradually increases, so it is difficult for the phase current to rise to the phase current chopping threshold $i_{chop}$. In the falling area of phase inductance, the reverse of the back EMF makes the phase current rise rapidly. When the phase current reaches the current chopping limit, the power switch $S_2$ is turned off. Under the combined action of the back EMF and the bus voltage, the phase current will continue to rise, so as to realize effective power generation. When the rotor position of the SRG reaches the minimum inductance position, there is $\partial L/\partial \theta \approx 0$, and the phase inductance $L$ is very small, so the phase current decreases rapidly under the effect of the load voltage until entering the next cycle. The phase current waveform is shown in Figure 6.

The voltage balance equation in the excitation region and the power generation region of the winding A shown in Figure 6 are

$$U_{PMG} = \frac{d\psi}{dt} (i, \theta) + r \cdot i_{ph} (S_1 = S_2 = 1)$$

$$= L(i, \theta) \cdot \frac{di_{ph}}{dt} + i_{ph} \cdot \frac{\partial L(i, \theta)}{\partial \theta} \cdot \omega + r \cdot i_{ph}$$

$$U_{PMG} \approx \frac{d\psi}{dt} (i, \theta) + r \cdot i_{ph} + U_o$$

$$= L(i, \theta) \cdot \frac{di_{ph}}{dt} + i_{ph} \cdot \frac{\partial L(i, \theta)}{\partial \theta} \cdot \omega + r \cdot i_{ph} + U_o$$

where $U_o$ is the output voltage of the system, $U_{PMG}$ is the output DC voltage of PMG module, and $r$ is the phase winding resistance of the SRG.

According to (1), in order to ensure that the phase current in the power generation area can continue to rise after the power switch $S_2$ is turned off, the SRG needs to meet

$$U_{PMG} - i_{ph} \cdot \frac{\partial L(i, \theta)}{\partial \theta} \cdot \omega - r \cdot i_{ph} - U_o > 0.$$  

B. PRINCIPLE AND CONTROL STRATEGY OF THE CPMSRG AT HIGH SPEED

When the automobile engine speed exceeds 3000 r/min, the output voltage of the PMG module will be higher than the charging voltage of batteries. Therefore, in this case, the generator control method at normal speed can’t realize constant voltage control. For high speed conditions, the CPMSRG system theoretically has two control schemes.

Scheme 1: the output voltage $U_{PMG}$ of the PMG is only used as the excitation power supply of the SRG, and the
FIGURE 5. Current paths of the CPMSRG under (a) excitation state, (b) generation state.

FIGURE 6. Phase inductance and phase current of the SRG based on FCCC.

The cascaded power generation system outputs electric energy from the SRG to batteries and loads separately. Taking phase A of the SRG as an example, the excitation process of the SRG in scheme 1 is the same as at normal speed, and the current path is shown in Figure 5 (a). When the phase current of the SRG reaches the set current chopping threshold, the power switches S1 and S2 are turned off at the same time, and the phase winding current will flow to the batteries and loads through freewheeling diodes D7 and D8, as shown in Figure 7. The control block diagram of the scheme is shown in Figure 4. The control process is mainly as follows: firstly the cascaded generator control system obtains the output voltage \( U_0 \) through the voltage sensor, then the controller outputs the current chopping threshold after being calculated by the regulator, and finally the chopping module completes the adjustment of the phase currents, so as to stabilize the output voltage of the control system at the charging voltage required by the batteries (i.e. 42 V).

Scheme 2: still taking phase A of the SRG as an example, the output voltage \( U_{PMG} \) of the PMG module, power switch S1, coil of the phase A, diodes D7 and D8, battery and load unit form a BUCK circuit, as shown in Figure 8. The switch S2 remains off, and the output voltage \( U_0 \) can be controlled to stabilize at the charging voltage of the battery by adjusting the duty cycle of the switch S1 in real time through the voltage closed-loop control. In scheme 1, the SRG generates power independently, each phase needs to control two power switches, and the switching loss is higher than that in scheme 2. The output voltage of the SRG presents a pulsating state, and the output voltage ripple is greater than that in scheme 2. Therefore, the scheme 2 is selected as the control strategy of the CPMSRG in high speed state.

C. BATTERY FREE POWER GENERATION

After the on-board batteries are placed for a long time and physically damaged, the batteries will suffer serious power loss, which will make the automobile unable to start. The automobile in manual gear can be started by sliding, but it must be ensured that the batteries have a certain amount of power to provide voltage to the spark plug. Considering the power density and efficiency of generators, many automobile generators have adopted PMGs. If the PMGs need to realize vehicle starting by sliding when the batteries are damaged, a BOOST circuit must be installed to ensure that the output voltage meets the starting requirements, but adding a BOOST circuit will increase the control difficulty and manufacturing cost. The CPMSRG power generation system can raise the voltage output by the PMG module to the starting voltage by using the existing BOOST circuit in the main circuit when batteries are completely dead or damaged, so as to realize vehicle starting operation. The scheme doesn’t need additional hardware circuit, so the system has low cost and high reliability.

The principle of battery free power generation of the CPMSRG is to control the voltage of the PMG module by...
using the BOOST circuit composed of the SRG phase coil, power switch, diode and PMG output voltage, as shown in Figure 9. Taking phase A as an example, the output voltage $U_{PMG}$ of the PMG module and phase A coil $PhA$ of the SRG, switch $S_2$, diode $D_8$, battery and load module form a BOOST circuit. The switch $S_1$ remains on, and the amplitude of the output voltage $U_o$ can be controlled by adjusting the duty cycle of the switch $S_2$ in real time through the voltage closed-loop control.

![Figure 9. Current path of the CPMSRG battery free power generation.](image)

**IV. EXPERIMENTS AND RESULTS ANALYSIS**

**A. EXPERIMENTAL PLATFORM**

In order to facilitate the characteristic detection and control parameter optimization of the CPMSRG, the PMG and the SRG are placed in series in the casing, and a cascaded generator experimental platform is built, as shown in Figure 10. The platform mainly includes a prime motor, a torque sensor, a cascaded generator and a controller. Among them, the prime motor is a servo motor, which is used to simulate the operation of automobile engine and drive the cascaded generator to rotate. Its rated power is 3 kW and rated speed is 5000 r/min. In order to realize the power matching of the PMG and the SRG, the rated power of these two machines in the CPMSRG is the same, which is nearly 400 W. The dynamic torque sensor is used to detect the torque, speed and power output by the prime motor in real time, and can be connected to the upper computer software to display the prime motor input power, speed, torque and other parameter curves on the upper computer. The hardware platform of the controller includes main controller, drive circuit, power converter, filter circuit, voltage/current sensor, rectifier, and auxiliary power supplies. The main controller takes the TMS320F28335 DSP of the TI Company as the control core, the core chip of the drive circuit is the driving optocoupler HCPL-3120, and the load is three 12 V lead-acid batteries and power resistors with different resistance values. These resistors are used to simulate different power loads in the automobile.

**B. POWER GENERATION EXPERIMENTS AT DIFFERENT SPEEDS**

In order to test the power generation characteristics of the CPMSRG in the normal speed range, the specific settings of the experiments are as follows: the load resistance is 15 Ω; the remaining power of three batteries is high (no-load voltage is 40 V); the chopping delay time $\Delta t$ during the FCCC control is 20 μs. The specific experimental steps are as follows:

1) Adjust the prime motor speed to 1000 r/min, 1500 r/min, 2000 r/min, 2500 r/min and 3000 r/min, respectively.
2) The SRG phase current, output current and output voltage of the cascaded power generation system at different speeds are measured, and the results are shown in Figure 11.
3) The input power, output power and efficiency of the system at each speed are measured by the torque meter, and the results are shown in Table 1.

![Figure 10. Hardware experiment platform of the CPMSRG power generation system.](image)

**TABLE 1. Input power, output power and efficiency of the CPMSRG at different speeds.**

| Speed (r/min) | Input power (W) | Output power (W) | Efficiency |
|--------------|----------------|-----------------|------------|
| 1000         | 343            | 264.6           | 77.40%     |
| 1500         | 309            | 258.3           | 86.40%     |
| 2000         | 285            | 253.26          | 88.90%     |
| 2500         | 275            | 244.02          | 86.40%     |
| 3000         | 265            | 240.24          | 90.70%     |

The results show that under different speeds, the output voltage of the designed CPMSRG power generation system can be stable at 42 V, and the output voltage ripple is small, which can meet the requirements of battery charging and load power supply. Due to the high remaining power of the battery and small load, the output power of the system in this experiment is not high, which is under a light load condition. With the increase of prime motor speed, the output voltage and output power of the PMG module will also increase. In this case, the output power of the SRG will decrease, and the current chopping threshold of the SRG will also decrease with the increase of the speed during the stable operation of the generator. When the speed of the prime motor is 1000 r/min, the vehicle is at idle speed, and the output voltage of the PMG module is low. In this case, the generation voltage and power of the SRG account for a high proportion of the total output voltage and output power, and the current chopping threshold during the stable operation is also high, resulting in large excitation loss of the system. Therefore, the efficiency of the cascaded generator system at low speed is low. The output power of the power generation system is 264.4 W at the speed of 1000 r/min, and the power generation efficiency is only 77.4%. The output voltage and power of
the PMG increase with the speed, and the output voltage and power of the SRG decrease with the increase of the speed. Therefore, the efficiency of the cascaded power generation system will increase with the speed. When the speed reaches 3000 r/min, the output power of the system is 240.24 W, and the power generation efficiency is 90.7%. It can be seen that the power generation of the PMG and SRG is automatically distributed with the change of the speed in the CPMSRG system designed in this paper. At low speed, the power generation of SRG is relatively high, and the power generation of PMG is relatively low. The reverse is true at high speeds.

C. POWER GENERATION EXPERIMENT UNDER DIFFERENT LOADS

For verifying the influence of loads on the output characteristics of the designed power generation system, 4 Ω, 8 Ω, 15 Ω and 80 Ω resistors are selected respectively to complete the power generation experiments under different loads. The experimental settings are as follows: the prime motor speed is 2000 r/min; the remaining power of the three batteries is high (no-load voltage is 40 V); the chopping delay time $\Delta t$ during the FCCC control is 20 $\mu$s. The SRG phase current, system output current and output voltage under each load are measured, as shown in Figure 12. The input power, output power and efficiency of the system under different loads measured in the experiment are shown in Table 2.

According to the results in Figure 12 and Table 2, with the change of the loads, the output voltage of the CPMSRG can always be stable at 42 V required for the battery charging under voltage closed-loop control, and the voltage ripple is small, which meets the requirements of the battery charging and electric loads. The system output current and power of the cascaded generator under constant voltage control will increase with the decrease of the load resistance. When the load resistance is 4 Ω, the output power of the power generation system reaches 562.8 W; when the load resistance is 80 Ω, the output power of the system is only 132.3 W. Because the prime motor speed in the experiment is relatively high, the output voltage of the PMG, that is, the excitation voltage of SRG, is also high, and the efficiency of the system can maintain a high level when the load changes. The average efficiency measured by the designed CPMSRG prototype platform in the variable load tests exceeds 86%.

D. POWER GENERATION EXPERIMENT UNDER DIFFERENT BATTERY RESIDUAL CAPACITIES

In order to explore the influence of different battery residual capacities on the performance of the power generation system, this experiment sets the load resistance as 8 Ω, the speed as 2500 r/min and the load resistance as 15 Ω, the speed as 2000 r/min, respectively, to detect the phase current of the SRG, the output current and output voltage of the power generation system under different residual battery capacities,
and the results are shown in Figure 13. The input power, output power and efficiency results of the power generation system are shown in Table 3.

According to Figure 13 and Table 3, the power generation system can stabilize the voltage amplitude to the battery charging voltage of 42 V under the conditions of different speeds, loads and remaining battery powers, so as to meet the system battery charging and load requirements. When the residual power of the battery is high, the charging current required by the battery is small and the total load is relatively small. When the prime motor speed is 2000 r/min and the load resistance is 15 Ω, the output power of the power generation system is 205.8 W, and the power generation efficiency of the system is 90.27 %. When the speed reaches 2500 r/min and the load resistance is 8 Ω, the system output power is 461.5 W and the power generation efficiency is 88 %. It can be seen that the power generation system can maintain high efficiency when the remaining capacity of the battery is high. In the case of low battery remaining power, the battery needs high charging current, and the equivalent total load is large under the same resistance load. Therefore, the excitation current and excitation loss required by the SRG are also large, and the efficiency of the system will decrease.

**FIGURE 13. Current and voltage waveforms of the CPMSRG under different battery residual capacity.**

| Battery No-load Voltage (V) | Speed (r/min) | Load (Ω) | Input Power (W) | Output Power (W) | Efficiency |
|-----------------------------|---------------|----------|----------------|-----------------|------------|
| 40 V                        | 2500          | 8        | 525            | 461.5           | 88%        |
|                             | 2000          | 15       | 228            | 205.8           | 90.27%     |
|                             | 2500          | 8        | 906            | 730.8           | 80.67%     |
| 37 V                        | 2000          | 15       | 613            | 546             | 89.1%      |

**FIGURE 14. Current and voltage waveforms of the CPMSRG with sudden-added and sudden-decreased loads under the condition of different speeds and loads.**

**FIGURE 15. Current and voltage waveforms of the CPMSRG in the reducing voltage generation experiment.**

**E. SUDDEN-ADDED AND SUDDEN-DECREASED LOAD OPERATION TEST**

In order to verify the influence of load sudden increase and load sudden decrease on the power generation performance of the cascaded power generation system, the experiments of sudden-added and sudden-decreased load (8 Ω, 15 Ω and 80 Ω) operation tests are carried out at different speeds (1500 r/min, 2000 r/min, and 2500 r/min). The phase current of the SRG, the output current and output voltage of the power generation system in the experiment are detected, as shown in Figure 14.

The experimental results show that the output voltage of the system remains constant after the sudden change of the
load, which meets the requirements of battery charging. The output current of the system and the phase current of the SRG have an upward trend when the load is suddenly added at the output terminal of the system. Similarly, when the load of the CPMSRG power generation system is suddenly reduced under the stable operation, the output current and SRG phase current of the system show a downward trend, and the SRG phase current and the output current of the system can recover to a stable state in a short time. According to Figure 14 (e), when the sudden load is large, that is, the sudden load resistance is small, the system output current varies greatly before and after the sudden load change, and the system output voltage fluctuates slightly at the moment of sudden change.

F. EXPERIMENT OF REDUCING VOLTAGE GENERATION UNDER HIGH SPEED CONDITION

As described in Part B of Section III, when the automobile engine runs at high speed, the cascaded power generation system should adopt the control scheme 2, namely, the PMG BUCK power generation control strategy. In this experiment, the speed of prime motor is set as 3500 r/min, and the output voltage of the PMG module is about 46 V. Using the BUCK circuit in the main circuit of the power generation system, the output voltage of the power generation system is stabilized at 42 V by the closed-loop control. The results are shown in Figure 15, which verify the effectiveness of the proposed buck power generation scheme at high speed.

G. BATTERY FREE POWER GENERATION EXPERIMENT

When the battery power of the vehicle is too low, or the battery is completely damaged, the vehicle can drive the generator to rotate by hand, sliding, etc. When running at low speed, the PMG can output low voltage. The CPMSRG system designed in this paper can use the BOOST circuit in the power converter to increase the low voltage output by the PMG module to meet the starting voltage requirements, so as to realize the battery free starting of the automobile.

In this experiment, the prime motor speed is set to 700 r/min, and the PMG output voltage is only 11 V. The voltage is increased to a constant voltage of 42 V by the BOOST circuit, which meets the starting requirements of the vehicle. The results are shown in Figure 16.

V. CONCLUSION

This paper introduces the structure and basic principle of a proposed CPMSRG for the automobile generator application. Combined with the characteristics of generator operation, the power converter topology of the CPMSRG power generation system is proposed. According to the operation characteristics of automobile generator, the operation speed range of the CPMSRG is divided into low speed, normal speed and high speed. When the generator runs at normal speed, a sensorless control method based on the full conduction chopping control is proposed in this paper. Under this control strategy, the PMG module and SRG module always generate power together, and the power generation efficiency of the system is high. For the high speed state, the PMG buck control scheme is compared and designed. In view of the extreme situation of no power or damage of the battery, a battery free power generation scheme is proposed. The scheme uses the BOOST circuit in the main circuit to increase the low voltage output by the PMG, which doesn’t require additional hardware equipment, and has low cost and high reliability. The software and hardware experimental platform of the cascaded power generation system is built, and the power generation experiments of the generator under different speeds, different loads and different battery residual capacities are completed. The load mutation experiment and battery free power generation experiment during the operation of the generator are also completed. The experimental results show that the designed cascaded generator proposed in this paper can generate power efficiently and stably in a wide speed range. When the load changes, the CPMSRG system remains stable and can generate power without battery at low speed.

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XIN JING received the B.S. degree in building electrical and intelligent chemistry from Guanling College, Yangzhou University, Yangzhou, China, in 2018, where he is currently pursuing the M.S. degree. His current research interest includes control and power generation of switched reluctance machines.

WEI JIANG (Member, IEEE) received the B.S. degree from Southwest Jiaotong University, Chengdu, China, in 2003, and the M.S. and Ph.D. degrees in electrical engineering from The University of Texas at Arlington, TX, USA, in 2006 and 2009, respectively. From 2007 to 2008, he worked at EF Technologies LLC as a Senior Design Engineer. In 2010, he joined Yangzhou University as a Lecturer and founded the Smart Energy Laboratory, where he is currently a Professor. He has been a Visiting Professor with Gunma University, Japan, in 2012, the University of Strathclyde, and Aston University, U.K., in 2015. He holds two U.S. patents and 13 Chinese patents. His current research interests include digitalized power conditioning to renewable energy and energy storage devices and microscopic analysis of electromechanical energy conversion.

HONG JIN received the Ph.D. degree in electrical engineering from Southeast University, Nanjing, China, in 2016. She is currently working as a Lecturer with Yangzhou University, Yangzhou, China. Her current research interests include design and control of ultrasonic motor and switched reluctance motor.

MINYAN LI received the B.S. degree in mechatronic engineering from Nanjing University of Science and Technology, Nanjing, China, in 1996, and the M.S. degree in electrical engineering from Southeast University, Nanjing, China, in 1999. She is currently working as a Lecturer with Yangzhou University, Yangzhou, China. Her current research interests include computer control technology and motor control.

YUNYUN CHEN received the B.Sc. and M.Sc. degrees in electrical engineering from Anhui University of Technology, Ma’anshan, China, in 2002 and 2005, respectively, and the Ph.D. degree in electrical engineering from the School of Electrical and Information Engineering, Jiangsu University, Zhenjiang, China, in 2014. Since 2005, she has been with Yangzhou University, where she is currently a Professor of motor and control system with the School of Electrical, Energy and Power Engineering. Her research interest includes design, optimization, and drive control of high performance permanent magnet motor.

QIANLONG WANG received the B.S. and Ph.D. degrees from the School of Information and Electrical Engineering, China University of Mining and Technology, Xuzhou, China, in 2010 and 2016, respectively. He is currently working as a Lecturer with Yangzhou University, Yangzhou, China. His current research interests include design and control of rotary and linear switched reluctance machines.

XINLIANG LI received the B.S. degree from the School of Building Electrical and Intelligent Chemistry, Yangzhou University, Yangzhou, China, in 2020, where he is currently pursuing the M.S. degree in electrical engineering. His research interest includes integrated drive system control of switched reluctance linear motor.