A High Speed Induction Generator Based on Power Integration Techniques

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***Abstract*—A novel high speed induction generator is presented based on the new idea of electric power integration, wherein a stator containing one set of M-phase power winding and another set of 3-phase compensation winding, is combined with an M-phase bridge rectifier, self-excited capacitors, interphase reactors, a static excitation regulator as well as a evaporative cooling system to form an integral whole. The dual-stator winding structure improves the EMC of the system and the multiphase rectifier ensures the high quality of the dc power. A solid iron squirrel-cage rotor satisfies both strength requirements and electrical requirements. The self-excited capacitors and IPR can reduce the capacitance of the SER. A simple stator-voltage-orientation control strategy is presented to regulate the output voltage under variable speed and load. The proposed scheme of high speed induction generator is suitable for larger power integration of distributed generation, which can be applied in electric vehicles, ship propulsion and aircraft generation, etc.**

Keywords-Distributed generation, dual-stator winding, evaporative cooling system, high speed induction generator, interphase reactors, multiphase rectifier, power integration, self-excited capacitors, solid iron squirrel-cage rotor.

I. Introduction

Long distance electric power transportation does not only require high expenditure and complicated control system, but also induces power outages. Distributed generation provides a solution to both the problems created in the aging central power generation infrastructure and the growing demand for energy in the new power generation mode. The realization of the low cost and high efficiency of the generation system is a precondition to the widespread application of the distributed generation. Power integration techniques have been presented in order to utilize the more complicated distributed power system and satisfy the requirements of the increasing need for electric energy. The main purpose of power integration techniques is to realize the integration of the relative dispersed components according to their respective functions by comprehensive integration and optimization, which shows high power density, high integrality and high reliability.

As is well known, improving the speed of electric machine is one of the most effective methods to improve the power density of machines. High speed electric machines have become a popular direction of power integration techniques, [1]-[11], and have been applied to high speed drive, high speed generation and flywheel storage system, etc, of which the rated power is mainly concentrated below 200 kW and between 1~15 MW.

The synchronous generator with a brushless exciter, the permanent generator and the induction generator are the main three machines which are suitable for high speed generation. As the most widespread application generator, synchronous generator with a brushless exciter absolutely dominates in the large generation system, of which the rated power is between 1~1000 MW. However, even for the large synchronous generator, at 1000 MW rating power, its tip speed is around 200 m/s due to mechanical integrity of the exciter diode bridge, [12], and the design of the rotor is very complicated requiring hydrogen-cooling or inner water-cooling. As a result, the synchronous generator is expensive to operate, especially the high speed synchronous generator, of which the rated power is between 1 MW and several tens MW.

The permanent generator has been employed in micropower systems. Because it is made of high-energy rare earth materials such as Neodymium Iron Boron or Samarium Cobalt, the cost is quite high. Also, the processing of the rotor is very complicated. Although connecting a DC-AC inverter in parallel with the generator can improve the flexibility of output-voltage regulation and obtain a constant dc output-voltage, the EMC (Electromagnetic Compatibility) of large power PWM (Pulse-Width Modulation) bridge rectifier is still a problem. So a 1.2 MW permanent generator produced by Turbo Genset Corp. represents the larger power permanent generator.

The induction machine is the most widespread application motor due to the simple rotor structure, the high strength and the low maintenance. The high speed induction motor, of which the rated power is between 2 MW and 15 MW and the rotational speed is between 3800 r/min and 15000 r/min, has been made by ABB Corp. Simultaneously, more and more attentions are paid to the application of the induction generator, and the tip speed reaches 286 m/s, [7]-[8].

Induction generators have been employed to operate as wind-turbine generators and small hydroelectric generators in isolated power systems [13], [14]. With the development of the packaged high speed gas turbine and high speed diesel engine, it becomes more and more clumsy that the prime mover and the generator are connected by a gear reducer. On

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the contrary, the direct connection between the prime mover and the generator will obtain many advantages, such as low noise, high efficiency, and high power density. Undoubtedly, the induction machine is very suitable for high speed generation, although there are many problems to be solved, such as the terminal voltage of a self-excited induction generator is highly dependent on rotor speed, terminal capacitance and load [15]. These disadvantages on the performance of self-excited induction generators limit their widespread application.

With the development of power electronics, many approaches have been proposed to solve the problem above. A static reactive power generator implemented with fixed capacitors and thyristors controlled inductors provides variable compensating capacitance or reactive power to maintain the output voltage [16], but injects harmonics into the load current and induces voltage ripple simultaneously.

Because the voltage frequencies are variable with varying load at a given rotor speed, induction generators have no more advantages for constant frequency and constant voltage (CFCV) than synchronous generators. Therefore, many measures for CFCV generation have more or less shortcomings. Turbine speed control is lack of fast dynamic response [17]. Connecting a DC-AC inverter in series or parallel with the load provides variable reactive power to regulate the load voltage magnitude and frequency [18], [19], which suffers from the worse efficiency standpoint or complexity due to the use of a discharge resistor or battery.

An automotive power generation system with a diode bridge rectifier and a PWM inverter is presented as a high power source [20]. The scheme is not sensitive to varying frequency, but the total necessary reactive power is supplied by means of a voltage-source PWM inverter and sufficient inductance of filter is necessary to reduce the influence of harmonics. So it is only suitable for small power applications.

A novel large power induction generator system is presented in this paper. The high integration of the system is realized according to the characteristic of every component on the basis of the new idea of electric power integration [21]. The two windings are isolated in electric circuit and connected with magnetic field, which will help to improve the EMC of the system. The generator supplies high quality dc power via a 12-phase bridge. The necessary reactive power to maintain dc output-voltage at a set value is by means of a static excitation regulator (SER). The stator design is based on comprehensive factors such as rotor loss, capacitance of SER and power factor. The rotor is made of solid steel and the cage is made of copper bars and copper end rings. The usage of self-excited capacitors and interphase reactors (IPR) can reduce the capacitance of the SER by their corresponding mechanism. The scheme of the proposed high speed induction generator system is suitable for larger power integration generation, which can be applied in electric vehicles, ship propulsion and aircraft generation, etc.

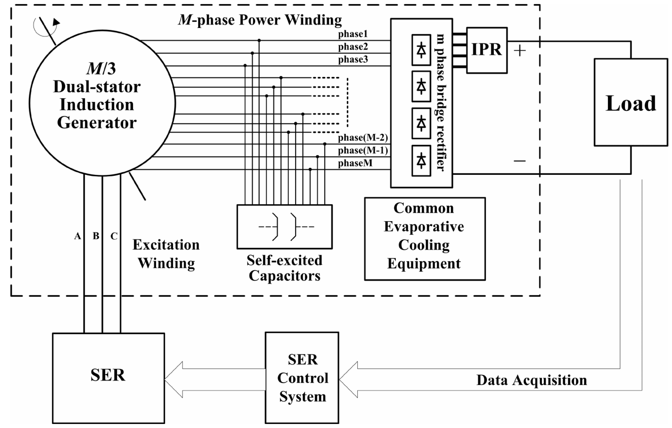

Fig. 1 The system diagram of high speed induction generator.

II. PROPOSED GENERATION SYSTEM

The block diagram of the proposed system is shown in Fig.1. In this generator, two sets of windings are embedded in the stator slots. One set of the M-phase (M=3,6,9,12…) winding, composed of four 3-phase star windings and referred to as the power winding, supplies power to the load via a m-phase bridge rectifier, and another set of 3-phase winding, termed the excitation winding, is connected to a PWM voltage source static excitation regulator (SER). A DC-bus capacitor acts as a voltage source of the SER. The machine supplies active power to the load and the output voltage is rectified by means of m-phase diode bridge rectifier. Interphase reactors in the dc side of m-phase bridge rectifier are used to improve the power factor of bridge rectifier. The necessary reactive power at no load and rated voltage is supplied by self-excited capacitors, and the SER supplies the other varying reactive power with load and rotational speed to the generator and the charging current to the dc-bus capacitor so that it can be maintained at a set voltage level.

The proposed system is made of M/3-phase induction generator, self-excited capacitors, m phase bridge rectifier, SER and cooling equipment. Induction generator, self-excited capacitors, m phase bridge rectifier and cooling equipment are integrated into one part, and SER is a separate part for repair conveniences, and the common cooling equipment is used by both parts.

As is well known, the voltage ripple ratio is one of the most important parameters to evaluate the dc electric energy quality. The DC voltage ripple ratio becomes smaller and smaller with the increasing of the number of the phases, as shown in Table I.

TABLE I. THE RELATION BETWEEN THE NUMBER OF THE PHASES OF RECTIFIER AND THE DC VOLTAGE RIPPLE RATIO UNDER IDEAL CONDITION

The number of the phases of rectifier	The dc voltage ripple ratio (%)
3	5.7
6	1.4
12	0.35
24	0.09

The number of the phases in the power winding is determined by the dc electric energy quality request. The 12-phase rectifier is selected to satisfy the certain quality request in this paper.

III. Design of the High Speed Induction Generator System

A. Stator Design

1) Stator Windings: The dual-stator winding was presented in order to improve the capacitance of single generator by breaking through the capacitance limitation of disconnector [22], [23]. The structure is applied more extensively in multiphase rectifier generator and ac-dc hybrid generator [21], [24]. The dual stator windings are connected to each other by magnetic field, not electrical circuit, which greatly reduces output dc voltage pulsation caused by the excitation winding harmonic currents. This considerably improves the EMC of the system under the usage of the properly designed windings. And the filter inductors can be reduced with the excitation winding leakage inductors.

When the symmetrical currents are injected into the corresponding stator windings, the currents can be decomposed into a series of harmonic currents by FFT analysis. According to the magnetomotive force (MMF) principle of electric machine, [25], the MMF induced by these currents are be obtained by

$$\sum_{\substack{n=6i\mp1\\ n\geq1}}^{\infty} f_{3,n} = \frac{3}{\pi}\frac{I_{c1m}W_c}{p}k_{cdp1}\sin[\omega t-\alpha+\varphi_{c1}] + \sum_{\substack{n=6i\mp1\\ n>1}}^{\infty}\frac{3}{\pi}\frac{I_{cnm}W_c}{p}k_{cdp1}\sin[n\omega t\pm\alpha+\varphi_{cn}] \tag{1}$$

$$\sum_{\substack{n=6i\mp1\\ n\geq1}}^{\infty} f_{12,n} = \frac{12}{\pi}\frac{I_{p1m}W_p}{p}k_{pdp1}\sin[(\omega t-\alpha)+\varphi_{p1}) + \sum_{\substack{n=6i\mp1\\ n>1}}^{\infty}\frac{12}{\pi}\frac{I_{pnm}W_p}{p}\frac{1}{n}k_{pdpn}\sin[n(\omega t-\alpha)+\varphi_{pn}) \tag{2}$$

Equation (1) designates the MMF induced by 3-phase symmetrical currents, and (2) designates the MMF induced by 12-phase 4 star shift 15^0 symmetrical currents.

To simply the analysis, take the 5th and 7th harmonic as an illustration.

From (1), the 5th and 7th harmonic currents of three winding induce the corresponding revolving magnetic fields. The winding factors of the fields are the same with that of the fundamental revolving field, and the revolving speed of the fields is much higher than the rotor speed, which will induce large high frequency loss. From (2), the 5th (or 7th) harmonic currents induce the corresponding space harmonic revolving magnetic fields, such as 5th, 19th and 29th (7th, 17th and 31st). The harmonic revolving magnetic fields can be reduced greatly by distribution winding or short pitch.

Based on the techniques of the multiphase and the usage of properly designed windings, the harmonic revolving magnetic fields induced by fundamental or harmonic currents will be reduced more greatly than those of three winding.

Commonly, the 3-phase induction generator establishes voltage by self-excited capacitors at no load. Once the proper capacitors and certain rotor speed are satisfied, the induction will establish the corresponding voltage with certain magnitude and frequency. The speed of the fundamental revolving magnetic field induced by the fundamental current is nearly equal to rotor speed, so the rotor winding can be approximately thought of as open-circuit. However, the speed of the revolving magnetic field induced by the harmonic current is much higher than the rotor speed, so the rotor winding can be approximately thought of as short-circuit, which cannot establish harmonic voltage in a common three phase induction generator, [26].

As for the 12-phase induction generator, from (2), the 5th (or 7th) harmonic currents can induce the 5th (or 7th) harmonic revolving magnetic field. The speed of these harmonic fields induced is also nearly equal to rotor speed at no load, which means the rotor winding can be approximately thought of as open-circuit. Once the self-excited and machine parameters satisfy the condition of self excitation at certain rotor speed, the harmonic currents will establish the corresponding harmonic voltage. This course should be avoided, and can be avoid it by the usage of properly designed windings. The detailed analysis will be presented in following papers.

2) The number of Pole Pairs: At a certain rotor speed, the synchronization frequency is linear in proportion to the number of poles. When the number of pole pairs is 1, the long coil end winding will induce large end loss and end leakage inductor. Although increasing the frequency can reduce the self-excited capacitors, it increases stator core loss. The switch frequency of IGBT is only several kHz, so the synchronization frequency is less than 500Hz in order to improve the quality. The number of pole pairs is selected according to that principles.

3) Stator Core: The stator core is made of silicon steel lamination. The selection of stator core material should give attention to core loss and magnetism. Commonly, the high frequency loss is direct proportion to the thickness of the silicon steel lamination. The thinner silicon steel lamination is prior [11], with the rectifier load.

The skew which will help reduce tooth-harmonics can be located in stator or rotor, but it is located in the stator core in this generator, considering its convenience and the structure of the solid steel rotor core.

4) Design of winding capacitance: The capacitance of the power winding is determined by the rated output power and the self-excited capacitors. And the capacitance of the excitation winding is determined by the reactive power required to maintain the output dc voltage at a set value at rated load.

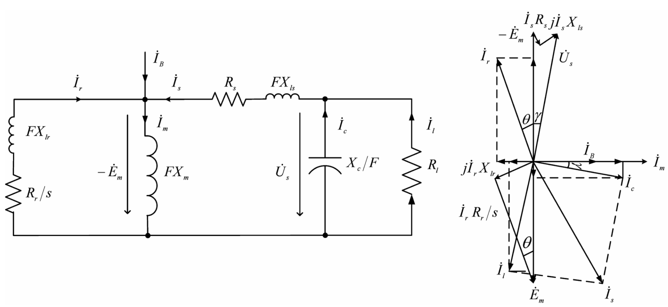

Fig. 2. Equivalent circuit and phasor diagram of the induction generator.

To simplify the process, three assumptions are made.

(1) The rotational speed is constant and its unit value is 1;

(2) The hysteresis loss and eddy current loss can be neglected;

(3) The self-excited capacitors provide all reactive power required at the rated voltage and no load. An ideal compensation current source supplies proper reactive power to maintain the voltage U_s at a constant.

The equivalent circuit at rated load is shown in Fig.2.

The self-excited capacitor and rectifier load can be united as a total load. The phase current $\dot{I}_s$ can be divided into the active component I_c and the reactive component I_l

$$I_c = I_{c1} + I_{l1}\sin\varphi \tag{3}$$

$$I_l = I_{l1}\cos\varphi, \tag{4}$$

where φ is the angle which the fundamental phase voltage $\dot{U}_s$ lags behind the fundamental load current $\dot{I}_{l1}$, $\dot{I}_{c1}$ is the current of the self-excited capacitor.

In order to satisfy the need of the output power at load, the frequency at rated load is lower than that at no load, and the magnetizing reactance X_m at load-supporting is becoming smaller than X_{m0} at no load.

So the EMF can be obtained by

$$\dot{E}_m = \dot{E}_{mo} + \Delta\dot{E}. \tag{5}$$

where

$$\begin{aligned}\Delta E &= E_m - E_{mo} \\ &= \sqrt{[U_s - (FX_{ls}I_c - R_sI_l)]^2 + (FX_{ls}I_l + R_sI_c)^2} - E_{mo}\end{aligned},$$

E_{m0} is the no-load magnetizing voltage at rated voltage.

In order to maintain the voltage U_s at the rated value, the required magnetizing current can be obtained by

$$I_m = \frac{E_m}{FX_m} = \frac{E_{m0} + \Delta E}{FX_m} \approx I_{m0}\frac{1 + \Delta E / E_{m0}}{k(1 - \Delta F)}, \tag{6}$$

where $I_{m0} = \dfrac{E_{m0}}{X_{m0}}$ and $X_m = kX_{m0}$.

Similarly, the current of excited-capacitors can be obtained

$$I_{c1} = \frac{U_s}{X_c / F} \approx (1 - \Delta F)I_{m0}. \tag{7}$$

From Fig. 2, the following equations are obtained

$$I_r\cos\theta = I_c\sin\gamma + I_l\cos\gamma \tag{8}$$

$$I_m = I_c\cos\gamma - I_r\sin\theta - I_l\sin\gamma + I_B, \tag{9}$$

where $\sin\theta = \dfrac{FI_rX_{lr}}{E_m}$, $\cos\theta = \dfrac{-I_rR_r / s}{E_m}$, $\sin\gamma = \dfrac{I_cR_s + I_lFX_{ls}}{E_m}$, and $\cos\gamma = \dfrac{U_s - (I_cFX_{ls} - I_lR_s)}{E_m}$.

Substituting (3)-(8) into (9), the compensation current can be obtained

$$\begin{aligned}I_B &= I_m + I_r\sin\theta + I_l\sin\gamma - I_c\cos\gamma \\ &\approx \Delta I_X + \Delta I_Z + \Delta I_F\end{aligned} \tag{10}$$

where $\Delta I_X = I_{mo}(\dfrac{1 + \Delta E / E_{mo}}{k(1 - \Delta F)} - U_s\dfrac{1 - \Delta F}{\Delta E + E_{mo}})$,

$\Delta I_Z = \dfrac{FX_{lr}I_r^2}{E_m} + \dfrac{FX_{ls}I_s^2}{E_m}$, and $\Delta I_F = -\dfrac{U_s}{E_m}I_{L1}\sin\varphi$.

From (10), it can be seen that the compensation current is decided by ΔI_X and ΔI_Z. ΔI_X is determined by the variant of the magnetizing voltage, the variant of the voltage frequency and the no load excitation current I_{m0}. It will help reduce ΔI_X that the magnetic circuit of the machine is designed to operate at linear range, while the magnetic circuit of the machine should be designed to operate at certain saturation range in order to satisfy the condition of the self excitation at no load [15]. ΔI_Z is determined by the stator leakage and the rotor leakage. Commonly, the ΔI_X is minor and the compensation current I_B is mainly determined by ΔI_Z. The representative unit value of the stator leakage and rotor leakage is 10%, so the unit value of compensation current is about 20% at rated resistive load. As for the rectifier load, I_B is determined by ΔI_F besides ΔI_X and ΔI_Z. ΔI_F is commonly determined by the load, the self-excited capacitors and the machine parameters.

The ratio of I_B to I_s is the ratio of the capacitances of two windings. From (10), it will help reduce the capacitance of the excitation winding that reducing the stator or rotor leakage inductor, the saturation of the magnetic circuit and the no-load excitation current, and improving the self-excited capacitor. But it will incur large short-circuit current that reducing the stator and rotor leakage inductor. So the comprehensive consideration is necessary.

5) Stator Slot: Although the usage of the magnetic slot wedge will help to reduce the magnitude of the tooth harmonic, it is limited on the large power electric machine due to its unstable characteristics.

The reduction of the slot notch will not only help reduce the magnitude of the tooth harmonic, but also reduce the no-load excitation current. Simultaneously, it will increase the stator slot leakage inductor and the capacitance of the SER from (10). So a middle result will be achieved in order to satisfy all requirements.

B. Rotor Design

The design of the rotor is very important to satisfy the requirements on both the mechanical strength and the electromagnetic characteristic for a high speed generator. The integrity of the iron core and the shaft can satisfy the requirement of mechanical strength easily. The structure of squirrel-cage rotor can obtain good electromagnetic performance [27].

The annular slots are laid along the axis of the rotor at the equal intervals to reduce the high frequency loss [28]. The insulation between the squirrel-cage and iron core is used to reduce the transverse loss [27].

The selection of diameter is restricted by the strength of the material, and the length of the generator is restricted by rotor dynamic consideration like bending critical speed [3], [11]. The mechanical bearing is suitable under the permission of the mechanical strength and the rotor dynamic. Active magnet bearing is suitable for higher rotational speed, where mechanical bearing cannot be suitable [8].

C. Airgap Design

The airgap is the most important factor, which has direct influence on the electromagnetic characteristic, the high-frequency loss of the rotor and the rotor cooling. And the electromagnetic characteristic is the no-load excitation current and the power factor. The tooth harmonics can incur high-frequency loss in the solid alloy-steel rotor, and the longer the airgap, the smaller the loss [29]. Although there is a conflict between the two requirements, the latter is prior to the former.

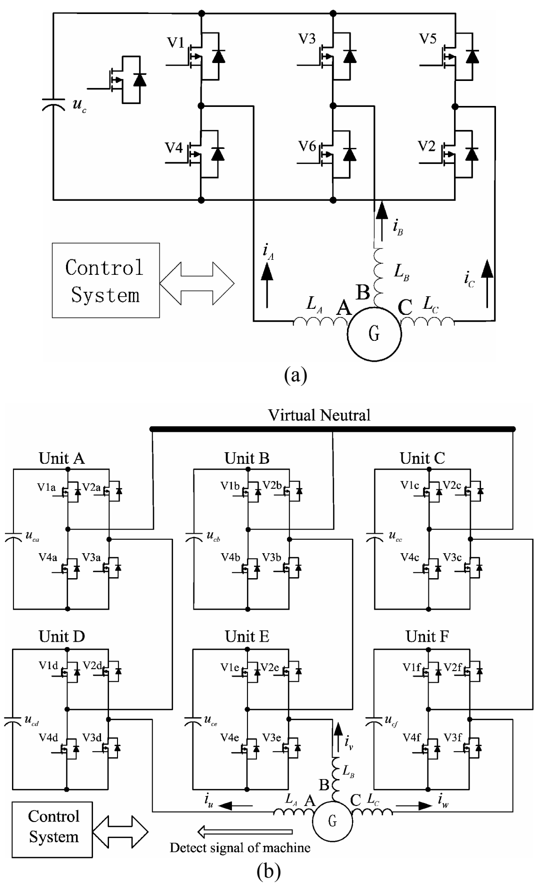

Fig. 3. The diagram of (a) two-level SER and (b) five-level SER.

IV. Static Excitation Regulation

The SER is made of a voltage source PWM inverter. A dc-bus capacitor acts as a voltage source to the inverter. The SER has two types of main circuitry, as shown in Fig. 3.

The two-level circuit is a simple and low cost structure suitable for small power applications [25], [26], [30], as shown in Fig. 3(a). The five-level cascade circuit is suitable for large power applications. The large power circuit is made of small power electronics, which can produce a higher equivalent switch frequency and a lower harmonic current ratio than the two-level circuit [31], as shown in Fig. 3(b). The stator-voltage-oriented control is used. The SER regulates the output voltage of the rectifier-bridge by varying the reactive current and also maintains the dc-bus capacitor voltage by varying the active current [30].

V. Other Components

A. Self-excitation Capacitors

The self-excited capacitors increase the complexity of the system with following advantages:

1) Establishing the voltage at no load by self excitation without auxiliary power source;

2) Providing certain reactive excitation power to reduce the capacitance of the SER;

3) Improving the commutation process of bridge rectifier to increase the power factor and reduce the capacitance of the SER;

4) Connecting with leakage inductors constructs a LC low-pass filter, which improves the EMC of the system.

In sum, the system with self-excited capacitors has more advantages than that without those. The selection of the self-excitation capacitors should satisfy the requirement of the self-excitation. Of course, the capacitance of the SER will be reduced with the increasing of the self-excited capacitors. The optimum design between the capacitors and the capacitance of the SER will be presented in the future papers.

B. Interphase reactor

In order to reduce the capacitance of the SER, the IPR is used in the proposed system. The comparisons between experiments with IPR and without IPR for the principle machine are shown in Fig. 4. The design parameters of the system are shown in the Appendix.

From Fig. 4, it can be seen that the commutation process is improved greatly, from which the waveform of the AC-side current of the bridge rectifier become approximate rectangular waveform from two-peak waveform after the IPR is used. The power factor is increased greatly, and the compensation current is reduced to 6.6 A from 11.9 A at rated load.

VI. Cooling System

Evaporative cooling makes full use of the gasification latent heat much larger than the apparent heat to realize high

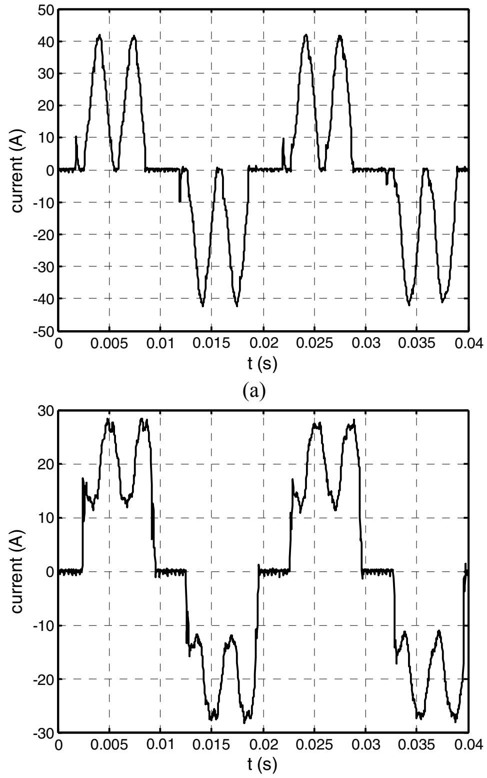

Fig. 4. The experimental waveform of the AC-side current of the bridge rectifier at rated load for principle machine (a) without IPR and (b) with IPR.

efficiency cooling [32]. The coolant is a fluorocarbon which is a green material. The basic operation principle is as follows: when the temperature of the components that require cooling reaches a certain temperature above the boiling point of the coolant, the coolant absorbs heat and becomes gas, and then becomes liquid via a condensator and is used repeatedly. The thermal cycle is similar to a heat engine cycle. The majority of the heat energy is absorbed by the condensator, and a small quantity of heat energy is used to make work, which can make self-circulating evaporative cooling without a circulated pump.

The coolant is a good insulated material, and there is a isolated sleeve between stator and airgap, as shown in Fig.5, so stator core, stator windings, self-excited capacitors and IPR are dipped into the coolant. The temperature of the components is controlled to about the evaporative temperature of the coolant and nearly equable, which dominates obviously over other cooling systems. The wall-hung cooling system is used in the cooling of 12-phase bridge rectifier and the SER, as shown in Fig.6. The junction temperature of 12-phase bridge rectifier and SER is controlled up to 80^{o}C.

According to the advantages of the evaporative cooling, current density can reach 10 A/mm^2 or even higher. So the system has high power density.

Because a series of improvements are applied, the total loss of the rotor is only about 1 percent of the rated power. So the wind cooling is suitable for the cooling of the rotor. Separate cooling fans are located on the machine enclosure instead of

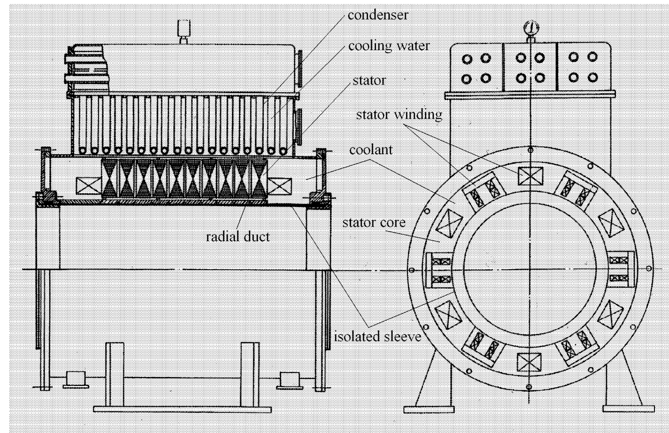

Fig. 5. The structure of evaporative cooling equipment

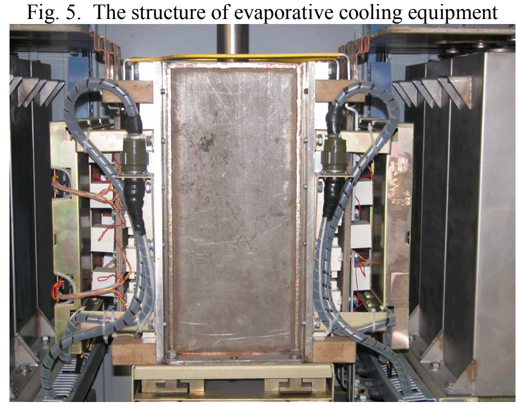

Fig. 6. The wall-hung evaporative cooling equipment.

the shaft-mounted fans. With the improvements of the techniques for revolving-airproof, the spray evaporative cooling will be applied in the cooling of the rotor, because it is a more efficient cooling system.

VII. Experimental results

In order to verify the characteristic of the proposed system, many experiments have been carried out at a 400 kW principle generator with the five-level SER.

A. *Static performance*

To demonstrate the performance, the rated load experiment is taken as an example.

The experimental waveforms of the output voltage u_{dc} and the output current i_{dc} are shown in Fig. 7. The corresponding excitation winding current i_A is shown in Fig. 8.

The FFT analyses of the output voltage u_{dc} and the excitation current i_A are shown in Fig. 9 and Fig. 10.

As shown in Fig. 9 and Fig.10, when the five-level cascade circuit are adopted in SER, the THD of the excitation current is about 2% and the ripple ratio of the output voltage udc is less than 0.7%. This shows the system is a high quality power supply source.

B. *Dynamic performance*

Fig. 11 gives the experimental waveforms of the output voltage and current of the 12-phase bridge rectifier when a half load is loaded suddenly at half load. The waveforms of

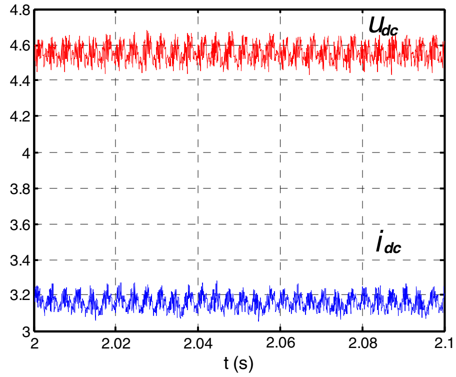

Fig. 7. The experimental waveforms of u_{dc} and i_{dc}.

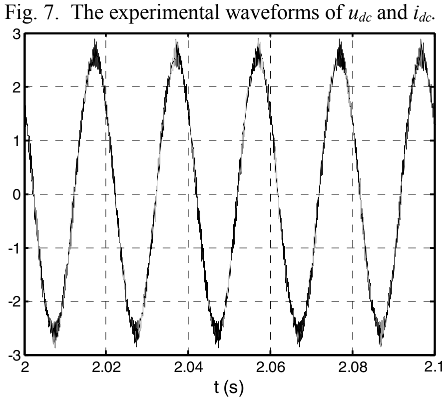

Fig. 8. The experimental waveform of the excitation current i_A.

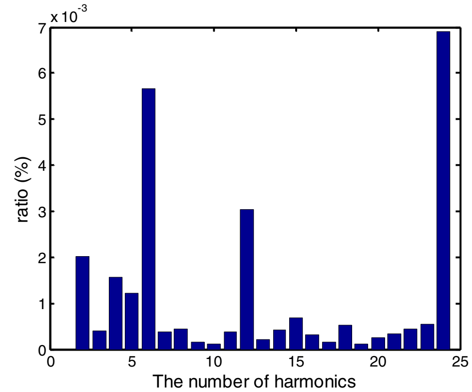

Fig. 9. The FFT analysis of the output voltage u_{dc}.

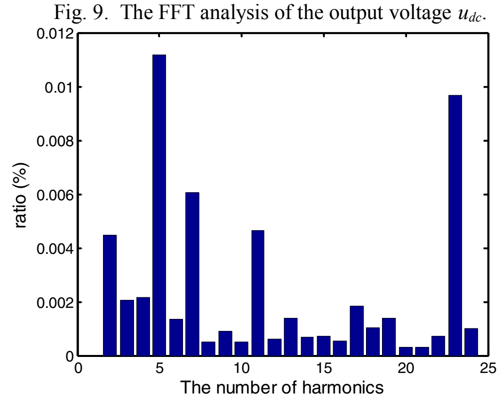

Fig. 10. The FFT analysis of the excitation current i_A.

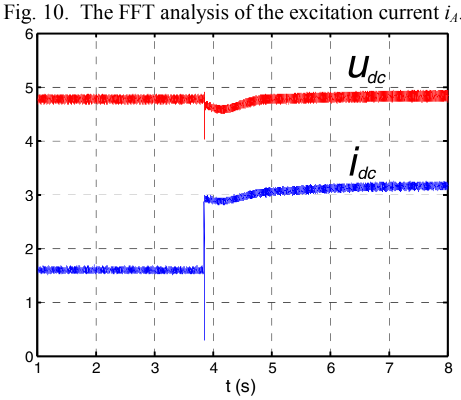

Fig. 11. The experimental waveforms of the output voltage u_{dc} and the output current i_{dc} when a half load is loaded suddenly at half load.

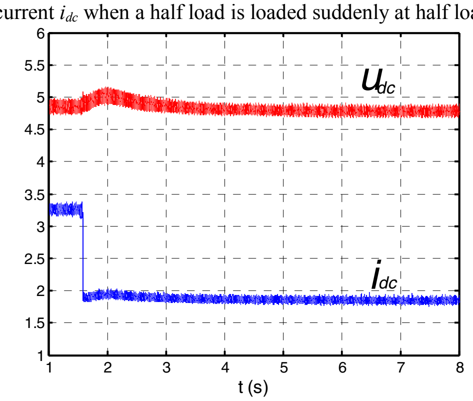

Fig. 12. The experimental waveforms of the output voltage u_{dc} and the output current i_{dc} when a half load is unloaded suddenly at rated load.

Fig. 11 and Fig.12 go through a filter of which cut-off frequency is about 10 kHz to eliminate high frequency components. The rotor speed is maintained at 1500 r/min before sudden-unloading. The total time of the process from the beginning of the sudden-loading to stabilization is less than 1 s from Fig. 8, and the fluctuation ratio of u_c is less than 6%.

Similarly, Fig. 12 gives the experimental waveforms of the output voltage and current of the 12-phase bridge rectifier when a half load is unloaded suddenly at half load. The total time of the process from the beginning of the sudden-loading to stabilization is less than 1 s from Fig. 12, the fluctuation ratio of u_c is also less than 6%.

This shows the system has fast dynamic response.

VIII. CONCLUSION

A novel large power induction generator has been proposed based on the new idea of electric power integration, of which the high integration is realized according to the characteristics of every component. The basic principle of machine design is presented. The structure of dual-stator winding improves the EMC of the system due to complete electrical separation of the two sets of windings and the usage of the properly designed windings. The techniques of multiphase rectifier ensure the high quality DC power. The solid iron squirrel-cage rotor satisfies both strength requirements of high speed generation and electrical requirements of high efficiency. The usage of self-excited capacitors can reduce the capacitance of SER by their capacitance and weaken the inductive of rectifier load. The usage of IPR can obtain high power factor and reduce the capacitance of the SER by improving the commutation process. The experimental results show that the system has a high quality power supply and a fast response. The scheme of the proposed high speed induction generator is suitable for higher power integration of distributed generation, which can be applied in electric vehicles, ship propulsion and aircraft generation, etc.

IX. APPENDIX

12/3-Phase Induction Generator System Design Data:

Number of poles	4;
stator slots	48;
rotor slots	44;
stator diameter	350 mm;
rotor diameter	248.8 mm;
stack length	150 mm;
airgap	0.6 mm;
filter inductance	3× 3 mH;
dc-bus capacitor	1650μF/900V;
rotor speed	1500 r/min;
self-excited capacitor	192 μF;
rated power	18.4 kW;
rated dc voltage	230V;
interphase reactor	3.6 mH.

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