Switched Reluctance Generators with Hybrid Magnetic Paths for Wind Power Generation

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The novel switched reluctance generator (SRG) with hybrid magnetic paths is developed for wind power generation in this paper. For the proposed SRG, there is no mutual coupling between phase windings. The proposed SRG has the longitudinal magnetic structure at the completely aligned position. However, it has the transverse and longitudinal magnetic structure at the unaligned position. Thus, three-dimensional finite element computation is needed in the design. The computed results based on three-dimensional finite-element analysis (FEA) are shown in the paper. Furthermore, the experimental results of the prototype demonstrate that the proposed SRG is feasible and effective.

***Index Terms*—Generators, magnetic paths, switched reluctance, wind power.**

I. Introduction

WIND energy with free-emission or free-pollution can be converted to electric energy. Electric generators for wind power generation may be selected as DC generators, permanent magnet generators, asynchronous generators, doubly-fed generators, and switched reluctance generators (SRGs). SRGs match demand of wind power generation [1] due to the following inherent features: 1) the simple and robust configuration supports operation under terrible ambient; 2) the absence of windings on the rotor results in the majority of the losses within the stator, making SRGs relatively easy to be cooled; 3) the rotor with low weight is beneficial for start of wind turbine; and 4) the switched nature of SRGs is suitable for variable-speed operation of wind turbine. Thus, SRGs are an attractive candidate for electric generators in wind power generation.

Some investigation and development of SRGs were reported [1]–[6]. Energy conversion in the SRG controller and the structure of the SRG controller for speed-control and power-control applications were discussed in [1]. In [2], the results of the simulation studies were presented to determine the effect of faults on the operation of SRGs and on excitation requirements. A novel control system for the operation of an SRG driven by a variable speed wind turbine was proposed in [3], where the SRG is controlled in order that a wind energy conversion system operates at the point of maximum aerodynamic efficiency. In [4], the optimal efficiency operation of SRGs at single-pulse mode was investigated. Furthermore, the new method based on the optimal control of the flux-linkage was proposed according to electrical power requirements of the load. The three-phase autonomous switched reluctance generator was presented in [5]. The suitable power circuit design and dynamic voltage control for the SRG system were proposed in [6]. Different from previously reported SRGs [1]–[6], this paper presents a novel SRG with hybrid magnetic paths, which has the lower weight of rotor and in which there is no mutual coupling between phase windings.

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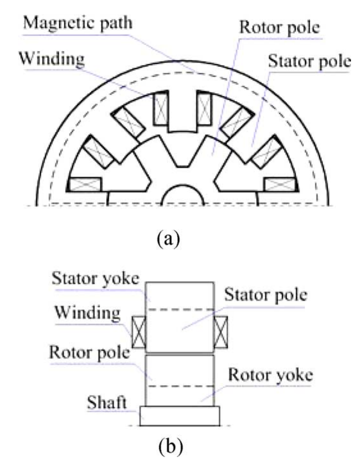


Fig. 1. Typical structure of conventional SRGs. (a) Transverse structure. (b) Longitudinal structure at the completely aligned position.

II. Proposed SRG With Hybrid Magnetic Paths

Typical structure of conventional SRGs is illustrated in Fig. 1. Clearly, it can be seen that there is only the transverse magnetic paths and there is mutual coupling between phase windings. Furthermore, the rotor consists of the rotor poles, the rotor yokes, and the shaft.

The structure of the proposed SRG with hybrid magnetic paths is shown in Fig. 2. It can be observed that: 1) the rotor only includes the rotor poles, the shaft, and the mechanical support parts; 2) there is no mutual coupling between phase windings because each phase has independent magnetic paths (independent stator core); 3) there are the longitudinal magnetic paths at the completely aligned position; and 4) there are both transverse and longitudinal magnetic paths at the unaligned position.

SRGs have the following features: 1) the current is unipolar to produce unidirectional torque; 2) the direction of the torque only depends on the slope of the inductance versus rotor position; 3) the motoring mode $(\text{torque} > 0)$ is active due to its operation on the positive slope of the inductance versus rotor position; and 4) the generating mode $(\text{torque} < 0)$ is active due to its

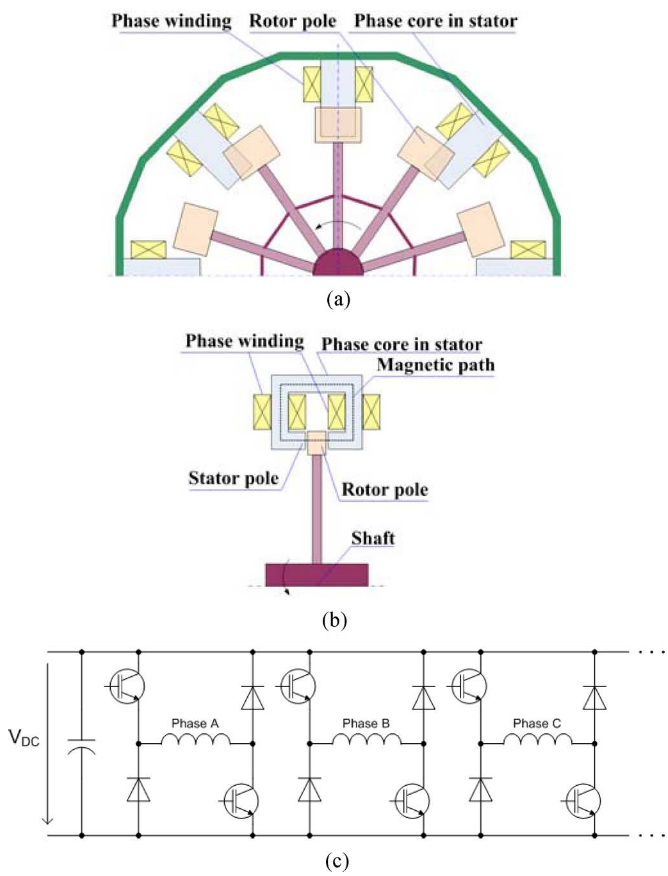


Fig. 2. Structure of the proposed SRG. (a) Transverse structure. (b) Longitudinal structure at the completely aligned position. (c) Electric connection schematic of phase windings.

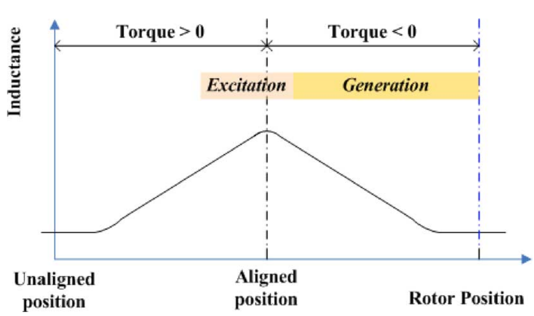


Fig. 3. Operation schematic diagram of SRGs.

operation on the negative slope of the inductance versus rotor position, as shown in Fig. 3. The operation of the proposed SRG can be described schematically as follows. Generally, the phase is turned on if a phase is closed to the fully aligned position, in order that the phase draws the electric energy from the DC bus for the phase excitation. The excitation is necessary because the SRG is a singly excited machine. The phase excitation may be switched off and the SRG operates under generation mode after the rotor pole passes the fully aligned position. The work done by the mechanical system (such as wind turbine) to pull the rotor poles away from the fully aligned position is converted into the electric energy returned to the DC bus. It should be pointed out that the output electric energy must be much more than the input excitation energy in SRGs.

In comparison with conventional SRGs, it can be seen from the above discussion that the proposed SRG with hybrid magnetic paths has the following advantages: 1) it has the better controllability due to absence of mutual coupling between phases; 2) it has the better redundancy features due to independent magnetic structure; and 3) it is easier to be started due to the lower weight of rotor.

III. Key Design Equations

The flux linkage at the completely aligned position is computed as

$$\psi_a(i) = L_a(i)i \tag{1}$$

where i represents the current, and L_a the phase inductance at the completely aligned position.

The computation of the flux linkage at the fully unaligned position is given as

$$\psi_{\rm ua}(i) = L_{\rm ua}(i)i \tag{2}$$

where $L_{\rm ua}$ represents the phase inductance at the fully unaligned position.

The co-energy at the completely aligned and fully unaligned positions is expressed as

$$W_a' = \int_0^{I_p} \psi_a di \tag{3}$$

$$W_{\rm ua}' = \int_0^{I_p} \psi_{\rm ua} di. \tag{4}$$

The average torque from the fully unaligned position to the completely aligned position is computed as

$$T_{\rm em} = N_{\rm ph}\frac{(W_a' - W_{\rm ua}')N_r}{2\pi} \tag{5}$$

where $N_{\rm ph}$ denotes the number of the phases and N_r the number of the rotor poles.

The computation of the average electromagnetic power is given as

$$P_{\rm em} = T_{\rm em}\omega_r \tag{6}$$

where ω_r denotes the angular velocity of the rotor.

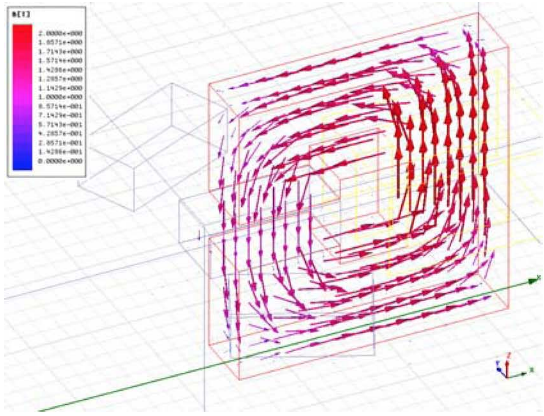
The copper loss is computed as

$$P_{\rm cu} = N_{\rm ph}I_{\rm rms}^2 R_{\rm ph} \tag{7}$$

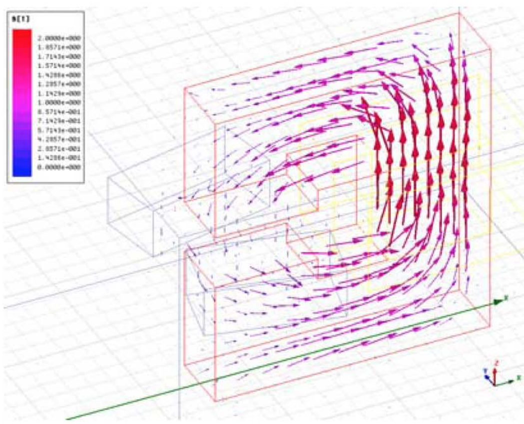
where $I_{\rm rms}$ is the rms value of the phase current and $R_{\rm ph}$ is the phase resistance.

The computation of the core loss is expressed as [7]

$$P_c = \sum_{k=1}^{N_{\rm Fe}} P_{ck}W_k \tag{8}$$



(a)



(b)

Fig. 4. Distributions of flux density vector computed by using FEA. (a) Completely aligned position. (b) Fully unaligned position.

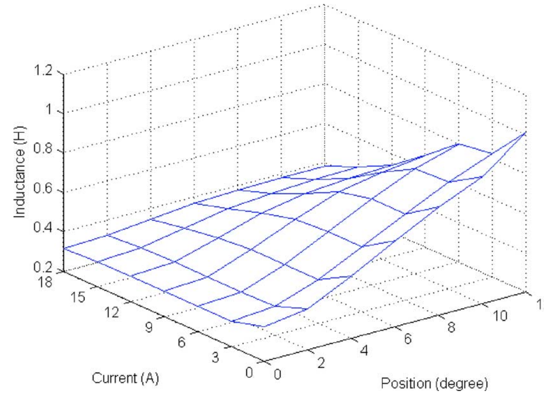


Fig. 5. Inductance characteristics computed by using FEA.

Fig. 6. Photo of the inner structure of the prototype.

Fig. 7. Photo of the developed SRG controller.

where N_{Fe} is the number of the iron segments, W_k is the weights of the iron segments, and P_{ck} is the loss coefficients. The selection of the iron segments depends on the flux densities in the iron. In an iron segment, the flux density is the same.

The electric power output by the SRG can be computed as

$$P_{\mathrm{out}} = P_{\mathrm{em}} - P_{\mathrm{cu}} - P_c. \quad (9)$$

To be suitable for low-speed operation and direct-drive wind turbine, the number of the rotor poles can be selected as [8]

$$N_r = 2N_s - 2 \quad (10)$$

where N_s represents the number of the stator poles $(N_s > 4)$.

IV. Three-Dimensional Field Analysis

It can be seen from the last section that the computation of the completely aligned and fully unaligned inductance is required in the SRG design. The hybrid magnetic paths result in the 3-D field distribution in the proposed SRG. Thus, three-dimensional FEA has to be used to compute the completely aligned and fully unaligned inductance in the design.

Due to the independent magnetic structure of each phase, the magnetic structure of a phase is selected as the solved domain. The completely aligned position means that the stator pole is completely aligned with the rotor pole and the fully unaligned position means that the stator pole is fully unaligned with two adjacent rotor poles. The distributions of the computed flux density vector are shown in Fig. 4. The computed inductance characteristics are depicted in Fig. 5. It can be observed from Fig. 5 that the fully unaligned inductance is almost a constant due to large air gap and the completely aligned inductance reduces with increase in the current due to magnetic saturation.

V. Application

Based on the presented key design equations and the completely aligned and fully unaligned inductance characteristics computed by using FEA, the prototype of the proposed SRG with the hybrid magnetic paths was designed and fabricated. The design objective of the prototype is: number of phases = 8, maximum power = 10 kW, rated voltage = 300 V, and rated speed = 100 rpm. Fig. 6 shows the inner structure of the prototype and the developed SRG controller is illustrated in Fig. 7.

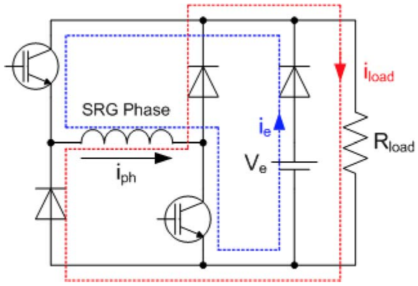


Fig. 8. Schematic diagram to test a phase.

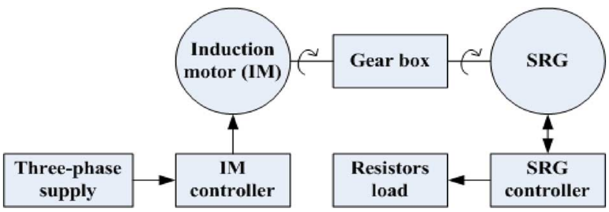


Fig. 9. Block diagram of the experimental system.

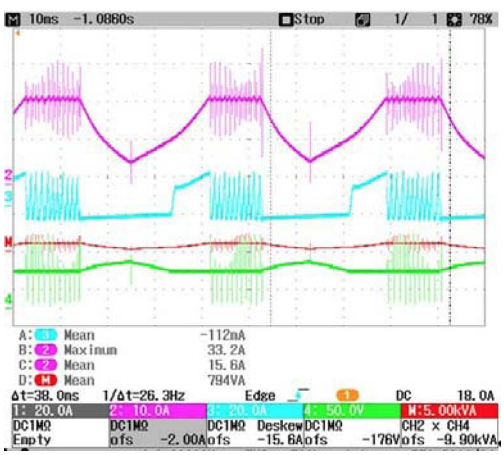


Fig. 10. Measured waveforms (Channel 2: phase current, 20 A/div; Channel 3: excitation current, 10 A/div; Channel 4: Vdc, 100 V/div; Channel M: phase current*Vdc; Horizontal scale: 10 ms/div).

The elementary test on the prototype was done. The schematic diagram of the test is illustrated in Fig. 8, where i_{ph} denotes the phase current, i_e denotes the excitation current, and i_{load} denotes the output load current. The block diagram of the experimental system is illustrated in Fig. 9. The measured output power is expressed as

$$P_{ph} = P_{phg} - P_{phe} \tag{11}$$

$$P_{out} = N_{ph} P_{ph} \tag{12}$$

where P_{phg} represents the average generation power of a phase, P_{phe} the average excitation power of a phase, and P_{out} the SRG output power.

The measured waveforms of a phase are given in Fig. 10, where the excitation voltage is 100 V, the rotor speed is 100 rpm, and the measured output power of a phase is 355.47 W. Therefore, the fabricated SRG prototype and the experimental results demonstrate the operation of the developed SRG with the hybrid magnetic paths. The test at the rated voltage will be done in the future work.

VI. Conclusion

The novel SRGs with the hybrid magnetic paths are proposed in this paper. Due to the 3-D hybrid magnetic paths, the design of the proposed SRGs requires 3-D FEA for inductance computation. The main design equations and the results computed by using FEA are given in the paper. The experimental results of the prototype have demonstrated that the developed SRG is feasible and effective. In comparison with conventional SRGs, the proposed SRG has the better controllability, better redundancy features, and lower weight of rotor.

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