A Novel Variable Flux Reluctance Generator for Vehicles

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Abstract. The general vehicle generators are claw-pole synchronous generators, which have the problems such as complicated processing technology of claw poles, low reliability of brushes and low operating efficiency. In this paper, a novel variable flux reluctance generator (VFRG) for vehicles is introduced and it is different from common reluctance machines. It has field coils on each stator pole and forms sinusoidal flux-linkage at each phase’s winding. Compared with general vehicle generators, it has the advantages of simple structure, strong robustness and high efficiency. The structure and operating principle are illustrated at first. Then a VFRG vehicle generator of 28V output voltage for 24V power systems is designed and optimized, which has low cogging torque as well as sinusoidal back-EMF waveforms. In addition, the characteristics and voltage ripple are obtained by simulation. And the technical specifications meet the requirements for a vehicle generator to work in a wide speed range. The results validate the applicability and superiority of VFRG to be a novel generator for vehicles.

1. Introduction

In the 1990s, the doubly salient permanent magnet (DSPM) machine was proposed by Professor Thomas A. Lipo in the University of Wisconsin [1]. Due to its simple and reliable structure, it has some application value in aerospace, wind power and other fields. However, DSPM has the inherent problem of uncontrollable magnetic field and expensive permanent magnets (PMs) [2].

By replacing PMs with DC field windings, the doubly salient electro-magnetic (DSEM) machine was manufactured [3]. When used as a generator, DSEM can generate constant rectified voltage by adjusting the field current [4]. However, every three adjacent stator poles of DSEM share a set of field winding, which makes the magnetic circuit asymmetric and increases the output voltage ripple [5].

The variable flux reluctance generator (VFRG) was developed on the basis of DSEM [6]. It has field coils on each stator pole. Its symmetrical magnetic circuits are beneficial to reduce the ripple of the rectified voltage. And the flux-linkage and back-EMF of each phase are close to sinusoidal waves. These factors enable VFRG to achieve high power quality and power density [7]-[8].

At present, some researches have been taken on the control and drive of VFRG [9]. While there are few researches for it to be applied in vehicle power generation systems till now. Therefore, this paper studies the rationality and superiority of VFRG as a new type of automobile generator.

2. Structure and operating principle

2.1. Structure of VFRG
The VFRG under study possesses 12 stator poles and 10 rotor poles, and the stator poles and rotor poles are all radial salient poles. The DC field windings and AC armature windings are wound on the stator, and they are non-overlapping concentrated windings. Also, no winding or permanent magnet
exists on the stator of VFRG. Generally, the two-dimensional (2-D) and three-dimensional (3-D) structure of VFRG is very simple, which is shown in figure 1.

In VFRG, when DC field current is applied on each pole of the stator, the magnetic polarity of two adjacent stator poles is exactly opposite. And the open-circuit magnetic circuit is composed of the paths in two adjacent stator poles, the stator yoke and the rotor. Compared with a switched reluctance machine or a doubly salient machine with 12 stator poles and 8 rotor poles, VFRG of 12/10 structure has a shorter magnetic circuit [8]. Hence, VFRG has smaller core loss than common reluctance machines under the same condition. In addition, the lengths at the end of these non-overlapping concentrated windings are relatively short. Thus, the copper loss of VFRG is also small.

2.2. Operating principle of VFRG
VFRG is a kind of reluctance machine with periodically changing flux. It follows the principle of minimum magnetoresistance, i.e., the magnetic circuit follows the path of the smallest magnetic resistance. As the field winding is excited by a direct current, a magnetic field is generated in the air gap. Owing to the structure of salient stator and rotor, when the reluctance rotor rotates, the magnetoresistance in the airgap changes, and the magnetic field also rotates. Hence, the flux in the armature winding shows a rule of periodic change, and the periodic back-EMF is induced in the armature winding.

In figure 1, the rotor pole is aligned with the A1 and A3 stator poles, and the electrical angle of the rotor is taken as 0 degree at this moment. Each phase winding of VFRG consists of four coils in series. When the two opposite stator poles are aligned with the rotor poles, the other two stator poles are exactly aligned with the rotor slots, such as A1, A3 coils and A2, A4 coils in phase A. Although the flux-linkage of single coil in phase A is unipolar, the synthesized flux-linkage of phase A is bipolar and very close to a sinusoidal wave. As the field current is 15A, the synthesis of Phase A flux-linkage is shown in figure 2. And the syntheses of other phases’ flux-linkage are similar to the flux-linkage of phase A.

3. Design of VFRG and rectifier circuit
When VFRG is operating as a vehicle generator, it follows the continuous operation system. Under normal driving circumstances, VFRG obtains mechanical energy from the engine and converts it into electrical energy. The energy can be used to supply the electrical appliance and recharge secondary batteries. In order to guarantee the stable and continuous working of VFRG, it is essential to determine the basic size of it and optimize its structural parameters.

3.1. Design of VFRG
As a vehicle generator, VFRG must satisfy the assembly space requirements in the vehicle. Thus, the shaft-diameter ratio, i.e., the ratio of core length to stator outer diameter, should be considered during the designing phase.
In order to create good ventilation and cooling conditions, improve the rotor’s rigidity, and reduce the rotor’s vibration, VFRG with small shaft-diameter ratio is considered. From the processing point of view, this machine reduces the punching time of silicon steel sheet, which improves the efficiency of mass production. In this way, the outer diameter of the stator is set to 210 mm, the core length is set to 140 mm, and the shaft-diameter ratio is 2/3.

According to simulation, the output power of VFRG is easily influenced by the stator yoke height and the stator tooth height. After optimization of the output power, the stator yoke height is set to be 9.3 mm, and the stator teeth height is set to be 31.5 mm.

Among other parameters of VFRG, the rotor pole arc is also a sensitive parameter, it has an obvious influence on the back-EMF and cogging torque of VFRG. The above cogging torque is defined as the static torque as the field windings are excited and the armature windings are unexcited [10]. After optimization of back-EMF and cogging torque, the rotor pole arc is set to be 17°. At this time, the back-EMF of armature windings is highly sinusoidal, and the cogging torque is small. When the field current is set at 15 A, the cogging torque of VFRG is shown in figure 3.

The current density in the coil has effects on the output power and copper loss of the generator. High current density will result in high output power and high copper loss. To balance the output power and copper loss, the current density of the field winding coils and armature winding coils are both set to approximately 6 A/mm². The field winding is wound by 50 turns, and it takes use of enameled wires with sectional area of 2.5 mm². While each of the armature windings is wound by 2 turns, and it takes use of enameled wires with sectional area of 4.0 mm². The armature windings are also composed of 15 coils in parallel to share the large current in them. The enameled wires are chosen as polyamide imide (PAI) enameled wires to ensure the stability at high temperature. By calculation, the slot-fill factor is 63.65%, which is reasonable for actual winding requirements. The major topological parameters of VFRG are shown in table 1.

| Structural Parameters       | Value | Structural Parameters       | Value |
|-----------------------------|-------|-----------------------------|-------|
| Stator outer diameter /mm   | 210   | Rotor tooth height /mm      | 10.9  |
| Stator yoke height /mm      | 9.3   | Rotor pole arc /deg         | 17    |
| Stator tooth height /mm     | 31.5  | Core length /mm             | 140   |
| Stator pole arc /deg        | 15    | Air gap length /mm          | 0.4   |
| Rotor outer diameter /mm    | 127.6 | Armature winding turns       | 2     |
| Rotor yoke height /mm       | 23.2  | Field winding turns          | 50    |

Table 1. Topological parameters of VFRG

3.2. Design of rectifier circuit

The schematic diagram of the eight-diode three-phase bridge rectifier circuit of the vehicle system is shown in figure 4. The connection method of armature windings is Y-type, which provides the
possibility for the composition of the rectifier circuit. When the generator works, the rectifier circuit converts the three-phase alternating current in the armature winding into direct current.

Each two diodes on the right side of the circuit are connected to each output terminal of the armature windings so as to form a six diode three-phase bridge rectifier circuit, which outputs the voltage of the three-phase armature windings. In addition, two diodes on the left side of the circuit are connected to the neutral point of the three-phase armature windings so as to output the rectified voltage of the neutral point.

The voltage of the neutral point belongs to the third harmonic. As the speed of VFRG increases, the voltage of neutral point increases too. As the amplitude of the neutral point voltage is greater than the maximum instantaneous voltage of the armature winding, the neutral point’s output current flows out. That makes the output power of the generator increases, especially under heavy loads.

4. Performance analysis

4.1. Open circuit flux-linkage and back-EMF of VFRG

The flux-linkage of the three-phase armature windings is shown in figure 5, and their back-EMF is shown in figure 6. The back-EMF of each phase lags 90 degrees behind the flux-linkage of each phase, which is consistent with the Faraday’s Law of Electromagnetic Induction.

Harmonic analysis of the back-EMF of the armature winding is performed using the fast Fourier transform (FFT) method. The harmonic content of back-EMF in the armature winding is shown in figure 7. It refers to the ratio of each harmonic to the fundamental. As shown in the figure, the harmonic content of each order is not high. Among different harmonic orders, the fifth harmonic is the highest, which reaches 2.60%. It is still lower than the 4% requirement of ordinary machines. This means that VFRG is able to produce electricity of high quality.
The indicator of total harmonic distortion (THD) is defined to further describe the distortion of back-EMF in the armature winding. The formula of THD can be calculated by:

\[
\text{THD} = \left[ \sum_{n=2}^{N} \left( \frac{E_n}{E_1} \right)^2 \right]^{1/2}
\]

where \( E_n \) and \( E_1 \) are the harmonic component and the fundamental component, \( N \) is the order. The result of the THD value comes out to be 3.38% when the order is up to 30. Compared with the goal of 5%, this calculated value is lower, so it meets the requirement.

4.2. Operating characteristics of VFRG

Through the 2-D transient finite element analysis (FEA) of VFRG, various operating characteristics of VFRG can be obtained, including the open-circuit characteristic, the external characteristic and the output characteristic.

The open-circuit characteristic of VFRG is shown in figure 8, which reflects the saturation of the magnetic circuit. On the one hand, as the field current goes from small to large, the magnetomotive force (MMF) generated by the field current grows gradually. At this time, the magnetic circuit becomes saturated, and the curves in the figure bend by degrees. While the value of rated field current is the value when the magnetic circuit has just entered saturation, which is at 15A. On the other hand, when the field current keeps unchanged, the open-circuit voltage of VFRG enlarges with the increase of rotor’s speed, which is obvious for the machine.

The external characteristic of VFRG at the speed of 2000rpm is shown in figure 9. When the field current is constant, the output voltage decreases as the output current increases, and this downward trend gradually increases. The reason is that, as the output current increases, the demagnetization effect of the armature reaction is enhanced, and the overlapping commutation phenomenon of the rectifier circuit becomes obvious. In addition, when the field current is gradually increasing, the output voltage also shows an increasing trend. What is special is that, as the load is small, the armature reaction is weak and the magnetic circuit is easy to be saturated. Thus, the former part of the curve at the field current of 20A is lower.

The output characteristic curve of the designed VFRG is shown in figure 10, it describes the relationship between output current and speed when the output voltage is at the rated value of 28V and the field current is at the rated value of 15A. According to the output characteristic curve, when the generator is working without load, the speed should be up to 1400rpm for the output voltage to reach the rated value of 28V. That is to say, the minimum speed for VFRG to reach the output voltage of 28V and start outputting current is 1400rpm.

On the output characteristic curve, the point where the ratio of the output current to the speed reaches maximum is taken as the rated operating point. When VFRG reaches the rated operating point, the rated current is 200A, the rated speed is 2000rpm, and the corresponding output power reaches
5.6kW. In addition, the maximum value of the output current reaches more than 300A. When the speed continues to increase, the output current of the generator essentially no longer increases.

Figure 10. Output characteristic curve.  
Figure 11. Rectified output voltage ripple.

4.3. Voltage ripple of VFRG
Due to the use of three-phase bridge rectifier circuit, the output voltage fluctuates six times within the range of an electrical cycle. When the speed is 2000rpm, field current is 15A and loading resistance is 0.14Ω, the rectified output voltage ripple of VFRG using the three-phase bridge rectifier circuit is shown in figure 11.

The output voltage ripple coefficient $K_r$ can be defined as a key indicator to measure the magnitude of the VFRG output voltage ripple. It is defined as:

$$K_r = \frac{U_{\text{max}} - U_{\text{min}}}{U_{\text{avg}}}$$  \hspace{1cm} (2)

where $U_{\text{max}}$ and $U_{\text{min}}$ stand for the maximum and minimum voltage at rated operation state, $U_{\text{avg}}$ stands for the average voltage at rated operation state. The calculated voltage ripple coefficient $K_r$ is equal to 17.86%, which is smaller than reluctance machines like DSPMs and DSEMs.

4.4. Technical specifications of VFRG
To be applied to the DC power generation system, VFRG needs to meet the performance requirements of vehicle generators. When the vehicle is running, the engine works in a wide speed range, so the generator it drives should also work normally within the certain speed range. By FEA simulation, the technical specifications of VFRG are obtained in table 2.

| Technical specifications | Value |
|-------------------------|-------|
| Number of phases        | 3     |
| Stator poles            | 12    |
| Rotor poles             | 10    |
| Generating speed /rpm   | 1400-3000 |
| Rated speed /rpm        | 2000  |
| Rated power /kW         | 5.6   |
| Rated voltage /V        | 28    |
| Rated current /A        | 200   |
| Overload power /kW      | 7.0   |
| Overload current /A     | 250   |

the range of generating speed for this machine is 1400-3000rpm, where the rated speed is 2000rpm. At the rated speed, the rated DC current is up to 200A, and the rated power is up to 5.6kW. At this moment, the efficiency of VFRG reaches 92.72%. In addition, the designed VFRG is able to withstand
the overload DC current of 250A and the overload power of 7.0kW for a few minutes. That is equivalent to 125% of the rated load.

5. Summary
In this paper, a novel vehicle generator called VFRG is introduced. Structurally, VFRG is a special type of reluctance machine. Both the field winding and armature windings are non-overlapping concentrated windings. Due to the short length of magnetic circuit and windings, the iron and copper losses are low. The flux-linkage in a single coil is unipolar, while the flux-linkage and back-EMF in each phase’s winding are bipolar and close to sinusoidal waves. By optimizing the main structural parameters, high power density and low cogging torque can be achieved. Then the characteristics and technical specifications of VFRG are obtained by FEA simulation. The rated output power reaches 5.6kW, the operation efficiency reaches 92.72%, and the output voltage ripple is also acceptable. In summary, the research has verified the applicability and superiority of VFRG as a new type of vehicle generator.

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