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A flux-mnemonic permanent magnet brushless machine for wind power generation

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In this paper, the concept of flux mnemonics is newly extended to the wind power generator. By incorporating a small magnetizing winding into an outer-rotor doubly salient AlNiCo permanent magnet (PM) machine, a new flux-mnemonic PM brushless wind power generator is proposed and implemented. This generator can offer effective and efficient air-gap flux control. First, the characteristics of the proposed generator are analyzed by using the finite element method. Second, the closed-loop flux control is devised to achieve a constant generated voltage under time-varying wind speeds. Finally, the experimental results are given to verify the validity of the proposed generator and control system. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3072377]

I. INTRODUCTION

Due to its inherent high efficiency and high power density, the permanent magnet (PM) brushless (PMBL) machine is widely studied.[1,2] However, it suffers from the problem of uncontrollable flux, thus limiting its application to wind power generation. By incorporating hybrid-field excitation into the doubly salient PM (DSPM) machine,[3] the resulting PMBL hybrid generator can perform effective flux control.[4] However, its efficiency is deteriorated due to the continuous dc field winding loss. Recently, based on the concept of memory motor,[5] the flux-mnemonic motor[6] which can offer effective flux control has been proposed for electric vehicles.

The purpose of this paper is to newly extend the concept of flux mnemonics to the wind power generator. Hence, the resulting flux-mnemonic PMBL generator can offer effective and efficient air-gap flux control. Based on the finite element method (FEM), the static characteristics of the proposed generator are analyzed. The prototype and the microcontroller-based flux controller are then built for verification.

II. DESIGN AND ANALYSIS

The configuration of the proposed flux-mnemonic PMBL generator is shown in Fig. 1, in which a five-phase outer-rotor doubly salient topology is adopted. First, the solid outer rotor is simply composed of salient poles with no PMs or windings, which is very robust for direct coupling with wind blades. Second, the inner stator space is fully utilized to accommodate all the windings and PMs, hence achieving a compact structure. Such structure can also facilitate the PMs immune from demagnetization by armature reaction. Third, a small magnetizing winding is specially wound around the AlNiCo PMs so that it can offer effective and efficient air-gap flux control. The high effectiveness is due to the use of magnetizing winding for direct PM magnetization, while the high efficiency is due to the use of temporary current pulse for magnetization.

Applying the FEM, the static characteristics of the proposed generator are analyzed. By temporarily tuning the magnetizing current, the PM magnetization level can be flexibly adjusted from the full level using a magnetizing mmf 2000 A turn, then the half level using a demagnetizing mmf 360 A turn, to the weak level using a demagnetizing mmf 500 A turn. The corresponding air-gap flux density distributions are shown in Fig. 2. It can be seen that the air-gap flux density can be flexibly controlled over a wide range of about four times. Consequently, the back emf waveform amplitudes at different rotor speeds can be maintained constant by properly tuning the air-gap flux density.

III. FLUX CONTROL

Similar to the DSPM machine,[3] the back emf of the proposed generator can be derived as

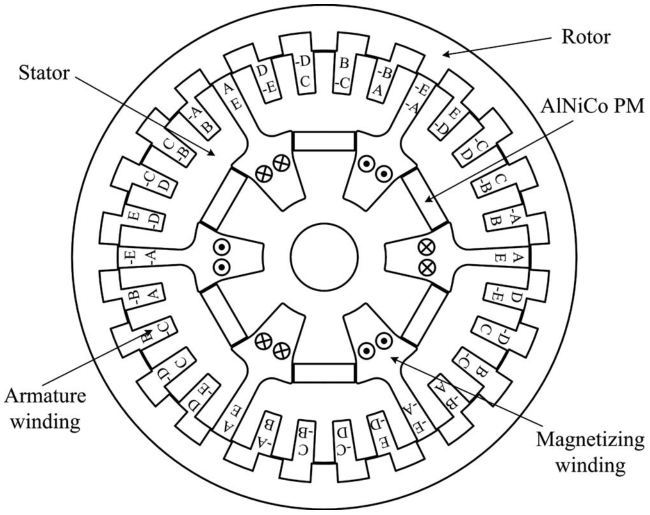

FIG. 1. Proposed generator configuration.

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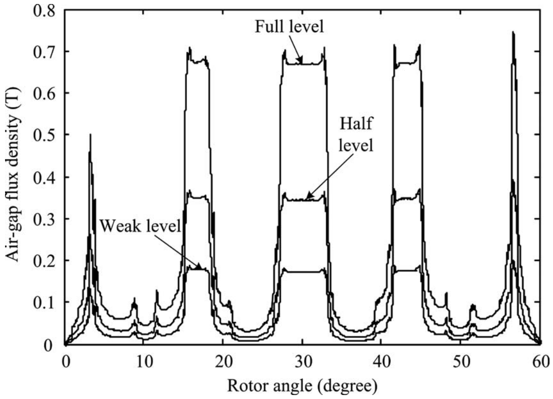

FIG. 2. Air-gap flux density distributions at different levels.

$$E = \frac{\pi^2}{60}\frac{N}{N_s\theta_p}k_\Phi k_d DLB_\delta n = CB_\delta n, \tag{1}$$

where N is the number of turns in series per phase, N_s is the number of stator poles, θ_p is the rotor angle difference between the maximum and minimum flux linkages, k_Φ is the flux linkage factor, k_d is the flux leakage factor, DL is the dimension of the generator, B_δ is the air-gap flux density, n is the rotor speed, and C is the voltage coefficient. From this equation, in order to maintain a constant-voltage output under various speeds, B_δ needs to be online regulated.

Rather than using the dc field winding to regulate the air-gap flux density as in the PMBL hybrid machine,[4] the PM magnetization level of the proposed machine is online tuned by temporarily exciting the magnetizing winding. Due to the nonlinearity of both the magnetization and demagnetization curves of the AlNiCo PMs, the relationship between the magnetizing current and the PM magnetization level has been experimentally determined and stored as a look-up table for online control.

Figure 3 shows the proposed wind power generation system, which consists of wind blades for energy capture, the proposed generator for energy conversion, the bridge rectifier for ac-dc conversion, the flux controller for online air-gap flux density regulation, as well as the encoder and sensor for speed and voltage feedback. So, based on the rectified output voltage and rotor speed, the flux controller will feed a temporary current pulse, controllable in both magnitude and direction, into the magnetizing winding to magnetize or demagnetize the AlNiCo PMs.

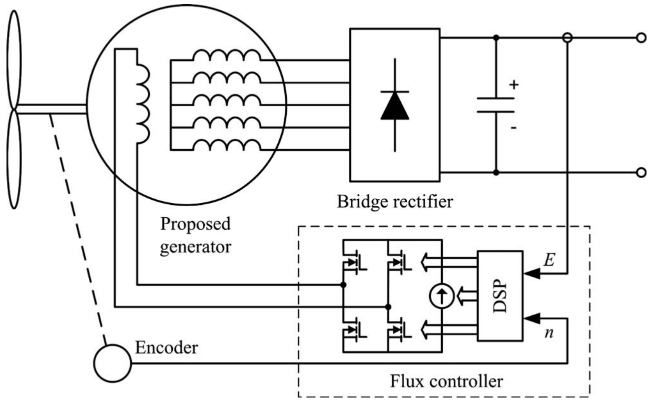

FIG. 3. Proposed wind power generation system.

In this wind power generation system, the cut-in wind speed and hence the rotor speed is set at 100 rpm. During operation, the flux controller online demagnetizes or magnetizes the PMs in such a way that the generated voltage can be kept constant.

This constant-voltage output property can eliminate the dc-dc converter and simply use a diode rectifier to charge the batteries for energy storage. Also, the flux controller can inherently offer overvoltage protection when the wind speed exceeding the threshold. Additionally, the controller can simultaneously regulate the output voltage under different loads. Therefore, the proposed system is particularly suitable for remote and standalone wind power generation which incorporates a battery storage system.

IV. EXPERIMENT

The proposed wind power generation system is prototyped for experimentation. With the proposed flux control, the measured waveforms at 200 and 400 rpm are shown in Fig. 4. It can be seen that the proposed flux controller can maintain a constant generated voltage.

The flux controller is digitally implemented. As shown in Fig. 5, the rotor speed initially runs at 100 rpm, then increases to 200 rpm, and finally settles at 140 rpm. The

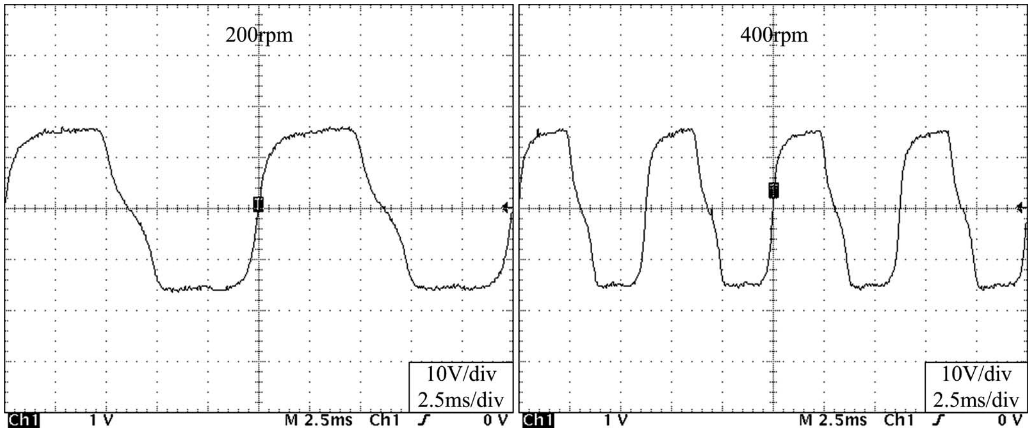

FIG. 4. Measured back emf waveforms with flux control.

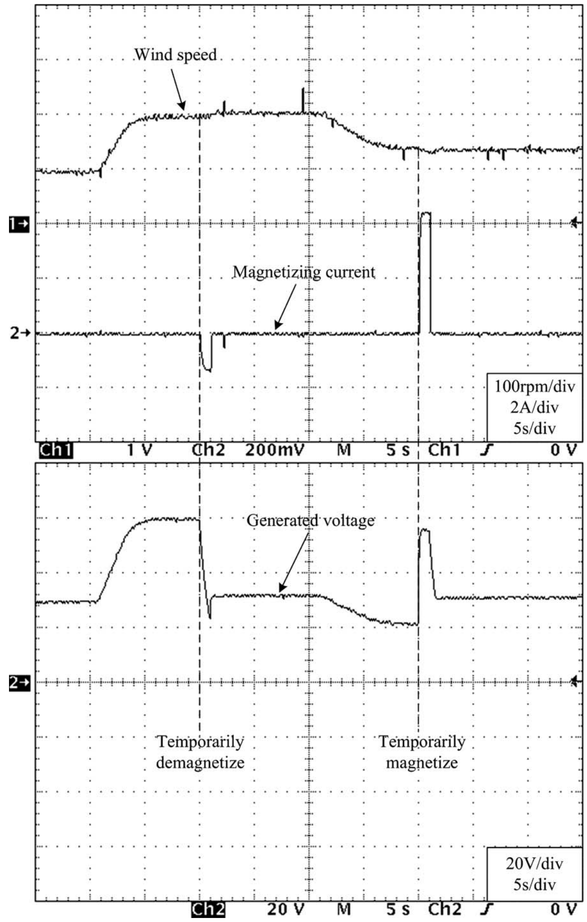

FIG. 5. Measured transient responses with closed-loop flux control.

corresponding magnetizing current pulses, negative and then positive, are activated to decrease the magnetization level and then to increase the level so that the generated voltage can be maintained constant. In order to assess the proposed wind power generation for prolonged operation, the wind speed is emulated to make the rotor speed swinging between 100 and 500 rpm. As shown in Fig. 6, the resulting rectified voltage response is measured, which can be maintained constant over the whole speed range.

Finally, the proposed system is assessed under different load currents and wind speeds. As shown in Fig. 7, both the simulated and experimental results confirm that the system can offer a very good voltage regulation with flux control.

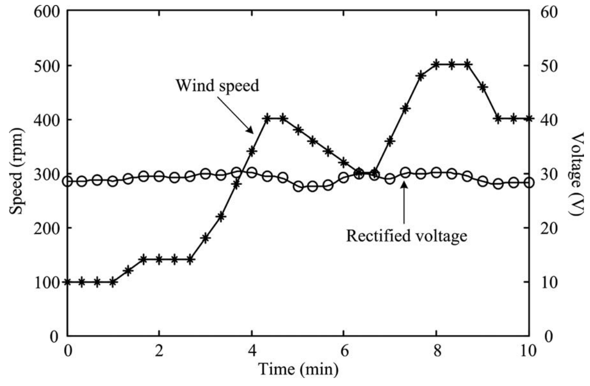

FIG. 6. Measured rectified voltage under time-varying wind speed.

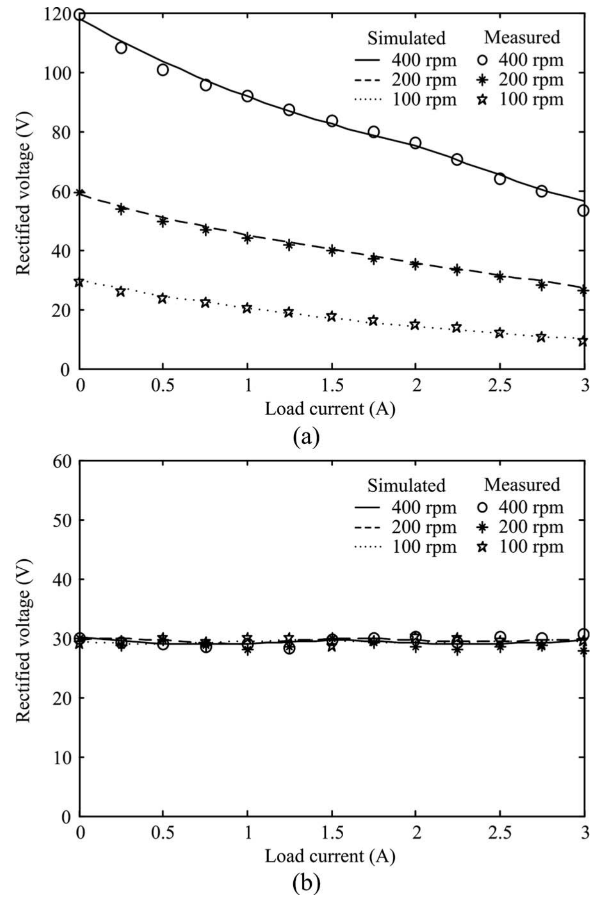

FIG. 7. Simulated and measured rectified voltages under different load currents and wind speeds. (a) Without flux control. (b) With flux control.

V. CONCLUSION

In this paper, a new flux-mnemonic PMBL wind power generator has been designed and implemented, which offers effective and efficient air-gap flux control. Also, the flux controller has been devised and implemented, which can provide a constant generated voltage under time-varying wind speeds. Both the computer simulation and experimental results have been given to confirm the validity of the proposed flux-mnemonic PMBL generator for wind power application.

ACKNOWLEDGMENT

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