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Stand-Alone Pico-Hydro Generation System using a High-Efficiency IPM Synchronous Generator

Kazumi Kurihara * and Tomotsugu Kubota **

Abstract – This paper presents a successful stand-alone pico-hydro generation system using a high-efficiency interior permanent-magnet (IPM) synchronous generator. A 1-kW 4-pole V-type IPM generator with low voltage regulation is used for laboratory test in stand-alone hydro energy conversion system. It has been found from experimental results that the constant output voltage is supplied stably by the proposed system under wide speed range.

Keywords: Hydro generation system, IPM generator, Automatic voltage regulation

1. Introduction

Recently, global warming has become an important problem. In Japan, there has been a power-shortage problem because of the shutdown of the nuclear power reaction by the Great East Japan Earthquake on March 11, 2011. In such situation, the territorially distributed energy generation using wind or water power attracts attention.

The development of permanent-magnet (PM) synchronous generators has progressed rapidly due in part to emergence of the high energy rare-earth magnets like neodymium-iron-boron (Nd-Fe-B) and many designs of PM rotors have been presented in recent years [1]-[6]. However, rare-earth materials such as neodymium and dysprosium are expensive and depend on China for 90% or more of the world share [7]. Therefore, the research for the substitution of Nd-Fe-B to Ferrite magnets has been reported [8]. However, it is considered that the downsizing of the generator needs the high energy rare-earth magnets in stand-alone small power generation system still now. Small wind or water power generation systems have been presented in recent years, for example, [9]-[12].

This paper presents a successful automatic voltage regulation of high-efficiency IPM synchronous generators for stand-alone pico-hydro power generation system. A 1-kW 4-pole V-type IPM generator with low voltage regulation [13] is used for laboratory test in hydro energy conversion system.

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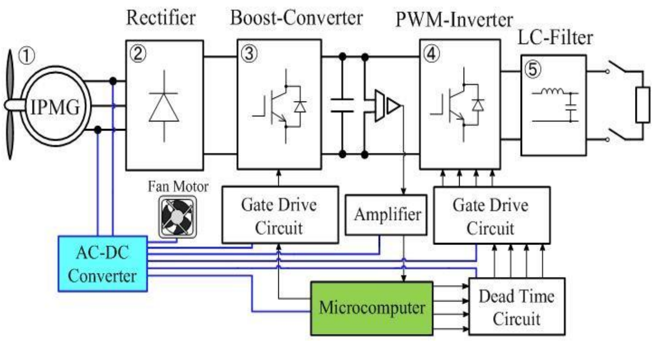


Fig. 1. Hydro energy conversion system using the IPM generator

2. Stand-Alone Pico-Hydro Generation System

Fig. 1 shows the schematic of a pico-hydro energy conversion system using the IPM generator. The proposed stand-alone hydro power system supplies single-phase consumers at 100 V/50Hz. It consists of a hydro turbine, a direct-driven IPM generator, an ac/dc converter (full bridge diode rectifier + boost converter), a dc filter, a single-phase voltage source pulse width modulated (PWM) inverter, and an ac output filter connected to the load. Further, dc power sources for a microcomputer and switching devices are built by an ac-dc converter. The hydro power is converted into the mechanical rotational energy of the hydro turbine rotor. The hydro turbine rotor is connected to the hydro generator, and the mechanical energy is converted into electrical energy. The ac voltage of the IPM generator is converted into dc voltage through the ac/dc converter. The rectifier is matching the ac voltage to the dc voltage, while the boost converter provides the required level of constant dc voltage. The dc output voltage is fed a PWM inverter through the dc filter. The voltage should stay constant for various water flow velocities. We determined the maximum

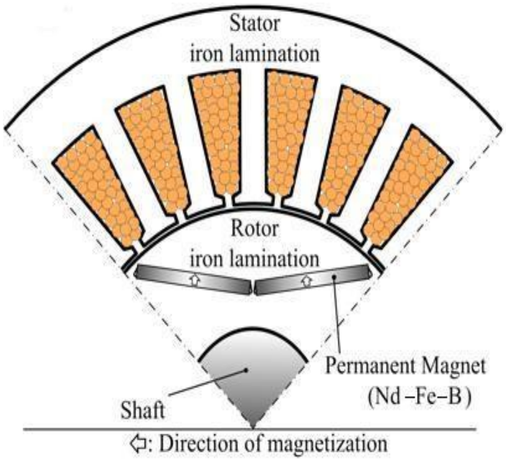


Fig. 2. Configuration of an IPM generator

rotational speed of the IPM generator and used the boost converter to keep the voltage constant at low water flow velocities.

Fig. 2 shows the configuration of a three-phase V-type IPM generator [13]. The designed maximum output was about 2 kW at 1000 rpm. The rated current is designed at 4.7 A. The stator is skewed by one slot pitch to eliminate cogging torque resulting from the PMs. The generator has the distinctive feature that it does not need the voltage control by the field DC winding to reduce the voltage regulation [14]. This is the reason why the width of stator tooth and the configuration of the PMs have been determined from the simulation results to reduce the magnetic saturation of iron core and the leakage flux in the rotor, respectively [13]. As a result, the voltage regulation of the IPM generator itself was designed very small at rated speed of 1000 rpm.

3. Steady-State Synchronous Performance

This paper contains the steady-state synchronous performance characteristics for the IPM generator itself and the power generation system, respectively.

Fig. 3 shows the experimental setup for measuring the load performance characteristics of the generator. A three-phase 50-Hz 200-V squirrel-cage induction motor and a torque detector were used. The generator has been driven at constant speed by the PWM inverter-driven induction motor, where a V/F control is used.

3.1 EMF and Load Performance of IPM Generator

Fig.4 shows the flux distribution caused by PMs. In simulation, the time-stepping finite element analysis is used [6], [13]. The width of stator tooth and the configuration of PMs have been designed from the simulation results to reduce the magnetic saturation and the leakage flux in the rotor, respectively.

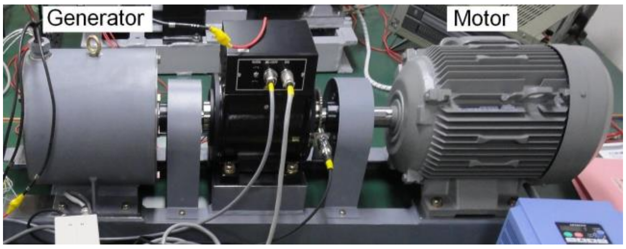


Fig. 3. Experimental setup

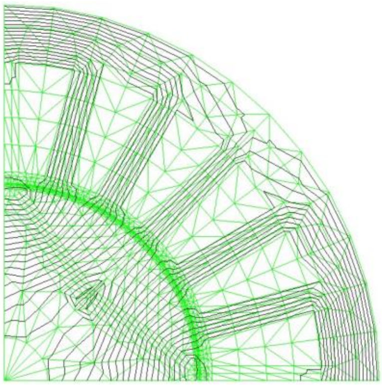


Fig. 4. Flux distribution caused by PMs

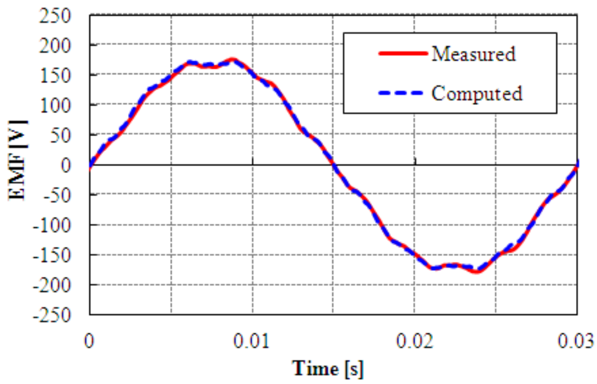


Fig. 5. EMF generated by PMs

Table 1. EMF

	Computed value	Measured value
EMF (V)	124.1	124.1

Fig.5 shows the terminal voltage waveform (EMF) generated by PMs in driving the IPM generator at 1000 rpm [13]. It is shown that the agreement between the computed and measured values of the EMF is good.

Table 1 shows the computed and measured values of no-load EMF. It is shown that the agreement between the computed and measured values is excellent.

Fig. 6 shows the comparison between the computed and measured values of the terminal voltage of the IPM generator, where it is directly connected to a balanced three-phase resistance load. It is shown that the agreement between the computed and measured values is good.

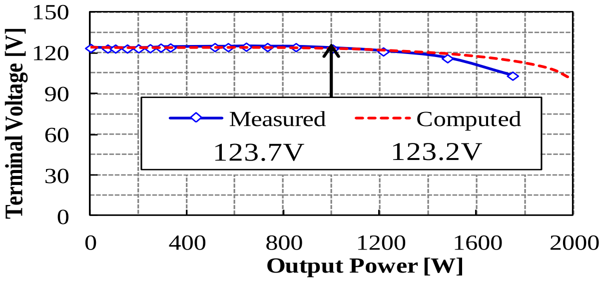
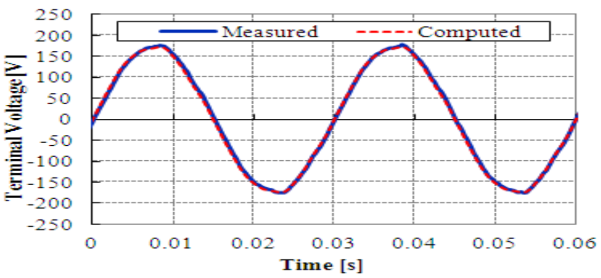


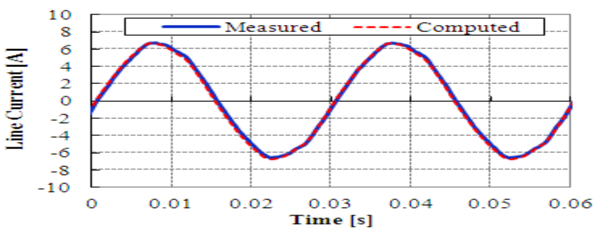
Fig. 6. Terminal voltage versus output power at 1000 rpm

Table 2. Terminal voltage at rated output power

	Computed value	Measured value
EMF (V)	123.2	123.7



(a)



(b)

Fig. 7. Terminal voltage and line current at rated output
(a) Measured and computed results of terminal voltage
(b) Measured and computed results of line current

There is a drop at the end of the measured curve. This is due to the increase of the voltage drop by the increase of the stator winding resistance because there is comparatively high temperature rise in the experiment.

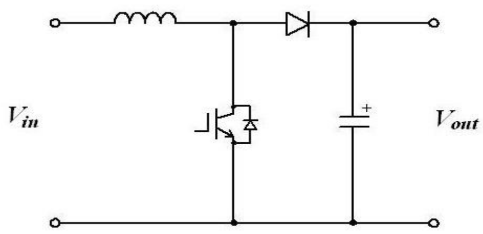


Fig. 8. Boost converter

Table 2 shows the computed and measured values of the terminal voltage at the rated output power of 1 kW. It is shown that the agreement between the computed and measured values is good. In addition, it has been found from Tables 1 and 2 that the voltage regulation has been extremely low and its value was 0.32% from the experimental results. Further, the efficiency of the IPM generator was 93%.

Fig. 7 shows the steady-state terminal voltage and line current at rated output of 1 kW, respectively. It is seen that the good agreement exists between the measured and computed results of the terminal voltage and the line current.

3.2 Output Performance of Power Generation System

The RMS and frequency of the EMF of the IPM generator vary by the rotor speed. Therefore, we kept the ac output voltage constant by using the boost converter

Fig. 8 shows the boost converter. The voltage equation between the input and output sides of the boost converter is given by

$$V_{out} = \frac{V_{in}}{1-\alpha} \tag{1}$$

where α is the duty cycle, V_{in} and V_{out} are the input and output voltages corresponding to the boost converter, respectively.

The target value of the ac output voltage is 100 V/50 Hz. Now, the value of the modulation factor of the PWM inverter is set at 0.95. Therefore, the target value of the dc output voltage of the boost converter is determined at 150 V. We detected the voltage across the capacitor, and changed the α to keep the dc output voltage constant, where a switching frequency was 40 kHz.

Fig. 9 shows the ac output voltage waveform of the single-phase PWM inverter at no load. The fundamental and carrier frequencies are 50 Hz and 2 kHz, respectively.

Fig. 10 shows the measured results of the terminal voltage versus the output power under the resistance load when the rotor speed changes from 400 to 1000 rpm.

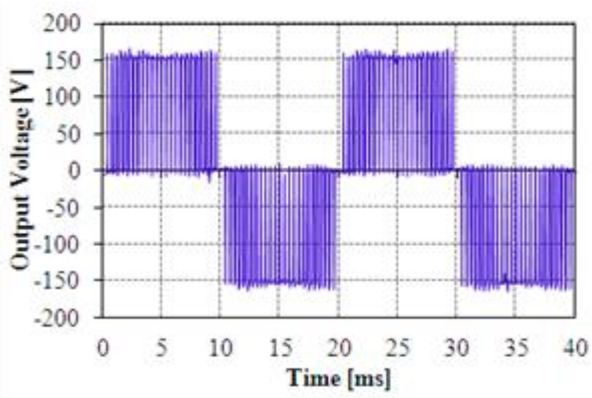


Fig. 9. Output voltage waveform of PWM inverter

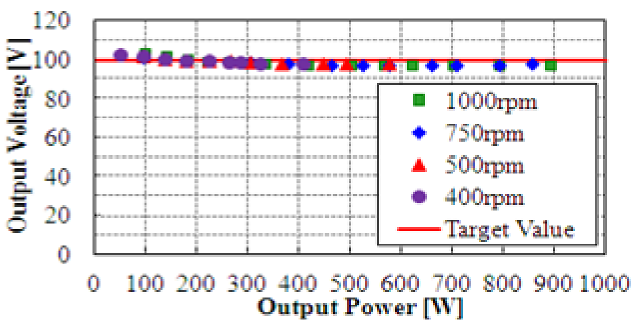


Fig. 10. Measured terminal voltage versus output power

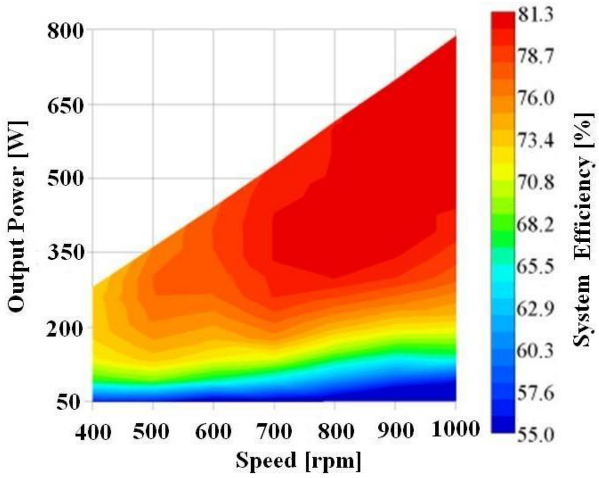


Fig. 11. Measured output power and total efficiency

The target value of the ac output voltage is 100V (RMS). It can be seen that the measured values of the voltage agree well with the target value. It was found from the experimental results that the constant output voltage is supplied stably by the proposed system under wide speed range.

Fig. 11 shows the measured output power and the system efficiency including the IPM generator, control devices and dc power sources versus rotor speed, where the maximum rotational speed is 1000 rpm and the maximum line current of the IPM generator is set at the rated one (4.7A).

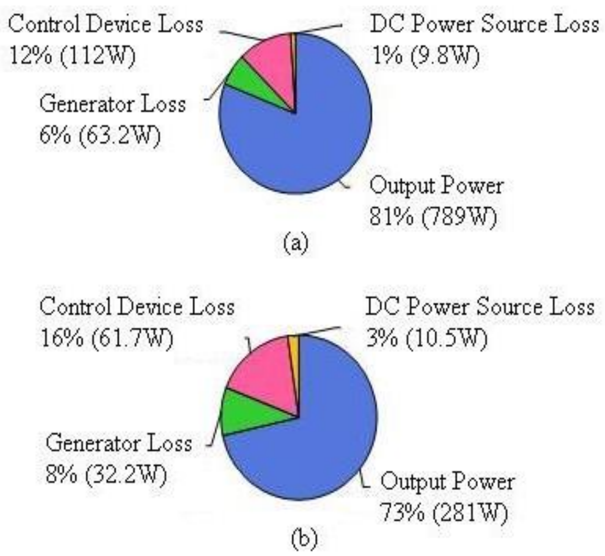


Fig. 12. Output power and loss at rated current (a) at 1000rpm, (b) at 400rpm

It can be seen from Fig. 11 that as the speed is higher, the system efficiency is higher.

Fig. 12 shows the experimental results of the output power and loss at the rated current of the IPM generator. Fig. 12(a) shows those at the rated speed (1000 rpm) and Fig. 12(b) shows those at the minimum speed (400 rpm). The loss of the control device is mainly due to switching.

4. Conclusion

The stand-alone pico-hydro power generation system using the high-efficiency V-type IPM generator is proposed. A 1-kW 4-pole V-type IPM generator with low voltage regulation is used for laboratory test in stand-alone hydro energy conversion system. It has been found from experimental results that the constant output voltage is supplied stably by the proposed system under wide speed range A 1-kW 4-pole V-type IPM generator with low voltage regulation is used for laboratory test in stand-alone hydro energy conversion system. It has been found from experimental results that the constant output voltage is supplied stably by the proposed system under wide speed range.

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