Application of Magnetic Energy Recovery Switch (MERS) to Improve Output Power of Wind Turbine Generators

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Keywords: magnetic energy recovery switch, power conversion system, synchronous generator, wind turbine system

A permanent type synchronous generator is widely used for wind turbine systems. However, an output voltage of synchronous generator for wind turbine system decreases with increasing output power because of large synchronous reactance. Since the overload capacity of generator is small, an instantaneous strong wind power energy cannot be taken out and it is not efficient.

Fig. 1 is a wind power conversion system with magnetic energy recovery switch (MERS) that we are proposing in this paper. The MERS can control of the phase of current and improve a power factor regardless of the impedance and power frequency of the load, and it generates voltage and compensates for the synchronous reactance voltage. Therefore, the output voltage of the generator increases, and it becomes possible to improve limited output power and efficiency of the wind power system, and the efficiency improvement of the power conversion system and the miniaturization of wind turbine generator can be expected. Moreover, the MERS can be used as an AC breaker.

A series of experiments were carried out to verify the remarkable effect of the MERS in a small-scale experimental system of wind power generation with a permanent magnet synchronous generator. Fig. 2 shows a schematic diagram of the experimental system of wind power generation system with MERS. the 3.7-kW induction machine is driven by an inverter to simulate fluctuations of the actual wind, and the 1.5-kW permanent synchronous generator is used as a wind turbine generator. MERSs are inserted in series between the synchronous generator and the diode rectifier.

Fig. 3 shows experimental results of DC output power as a function of output current I_u. The maximum output is 1.2 kW in the system without MERS, while the maximum output is 2 kW or more in the system with MERS because the voltage reduction by synchronous reactance was recovered. These data indicate that an instantaneous strong wind power energy can be caught from a generator with the MERS system. Moreover, even when the same output power is kept constant, the output current can be decreased in the MERS system because the output voltage increases. As a result, a copper loss and an amount of produced heat of the generator can be suppressed, and a miniaturization of the generator can be expected by applying MERS.

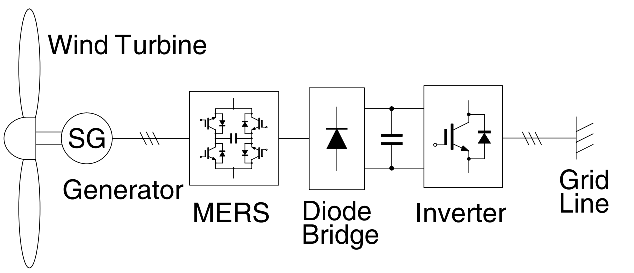

Fig. 1. Wind turbine power conversion system with MERS

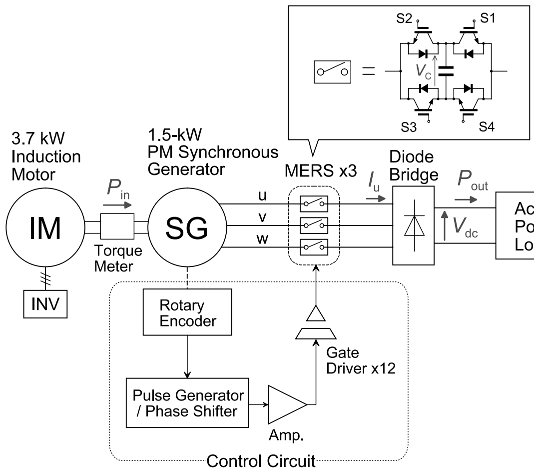

Fig. 2. Experimental configuration of a power conversion system with MERS

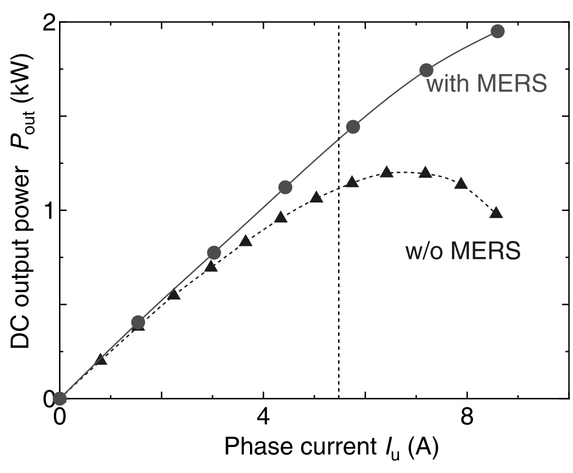

Fig. 3. Comparison between output power of PMSG with and without MERS

Paper

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The experimental results of an innovative power conversion technology using magnetic energy recovery switch (MERS) in a wind turbine system with a synchronous generator to improve the output power and the efficiency are presented. The MERS can compensate for the reactance voltage of the generator. The output voltage of the system increases and the excitation power of the generator can be significantly reduced. The data indicate a great potential of the new power conversion technology to make the actual wind turbine system compact and to improve the efficiency.

Keywords: magnetic energy recovery switch, power conversion system, synchronous generator, wind turbine system

1. Introduction

The wind turbine system is rapidly developing as one of the most promising renewable energy resources over the world. The penetration of this system is very important to solve the global warming and the exhaustion of fossil fuel. In order to optimize the wind turbine system, many kinds of power conversion systems to connect between the generator and the grid line have been proposed and utilized. We do believe that there is still a room to improve the power conversion system to obtain more economical systems.

We have proposed a bi-directional magnetic energy recovery switch (MERS) [(1)]. This switch absorbs magnetic energy which has been stored in the inductance of the load, and it generates itself the high voltage which compensate for the inductance voltage. Also, MERS can control the phase of the current. A power factor correction is possible regardless of the impedance and power frequency of the load by the automatic synchronized switching [(2)]. We are intending to apply the MERS to the power conversion of wind turbine system for improving the system performance. As the first step of this project this paper presents, for the first time, a significant advantage of MERS in a small scale experimental set-up of wind power generation with a permanent magnet type synchronous generator.

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2. Magnetic Energy Recovery Switch

2.1 Circuit Configuration The basic configuration of MERS is shown in Fig. 1. Four IGBTs (or MOSFETs) are connected in two parallel arms. Each arm consists of two IGBTs connected in series. Four IGBTs are connected in reverse direction each other both in series and parallel connection. The middle points of series are connected to a capacitor. Although it is the same composition as a single phase full bridge, it is a new point that the usage differs.

The MERS is inserted in series between the AC power source and load. This switch absorbs magnetic energy which has been stored in the inductance of the circuit and recovers it to the load. MERS itself generates voltage and compensates for the inductance voltage unlike a conventional series

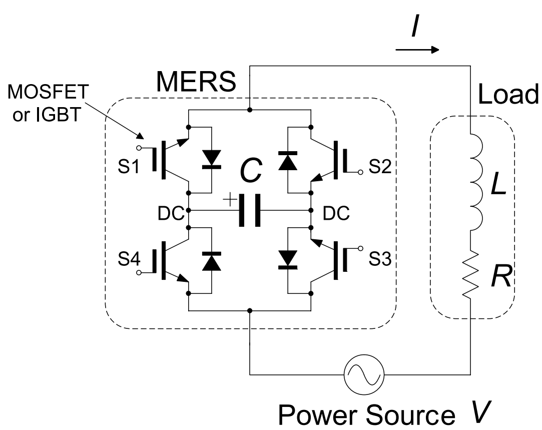


Fig. 1. Circuit diagram of bi-directional magnetic energy recovery current switch (MERS)

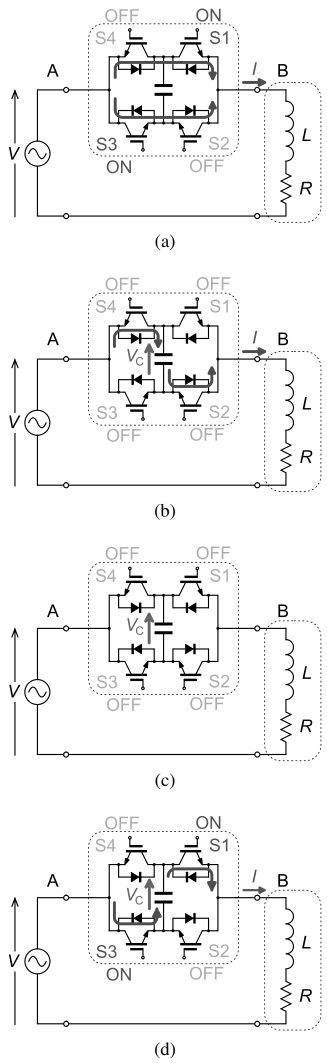


Fig. 2. Operation of the bi-directional magnetic energy recovery current switch (MERS). (a) Current flowing in parallel. (b) Magnetic energy of load is absorbed by the capacitor. (c) Off condition. (d) Capacitor energy discharges to the load

capacitor, so that another DC power supply is not needed.

2.2 Operation Principle Fig. 2 shows a case when the electric current flows from power source A to load B. In this case, on/off control only of S1 and S3 is done, S2 and S4 are kept turned off. When S1 and S3 are turned on, current flows in parallel. Next, when S1 and S3 are turned off, the magnetic energy of the load is absorbed by the capacitor through diodes, and the capacitor voltage is increased gradually. When the capacitor is completely charged, the switch is blocked. After this time, S1 and S3 are turned on, the capacitor discharges the electrostatic energy to the load, and the capacitor voltage gradually decreases. When the capacitor voltage becomes zero, current flows in parallel again. The magnetic energy is recovered from the electrostatic energy.

Also, in the case that a current flows from B to A, the switch is controlled by turning on or off S2 and S4. The polarization of the capacitor remains the same regardless of the direction of current.

The current raised after the switch is turned on is equivalent to the current which was flowing just before turned off.

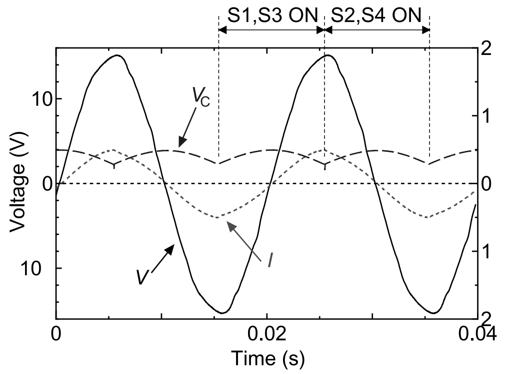


Fig. 3. Example waveforms of automatic power factor correction. $V = 10\,(\text{V})$, $L = 36\,(\text{mH})$, $R = 31\,(\Omega)$, $C = 820\,(\mu\text{F})$. The reactance voltage is compensated by the capacitor voltage V_C

In steady state, the current is determined by the resistance and the voltage of the circuit.

2.3 Power Factor Correction MERS can control the phase of the current by controlling the switching phase of MERS. To improve the power factor, the switching phase of MERS leads power source voltage by $\pi/2$ as shown in Fig. 3. The capacitor of MERS is automatically charged by forced LC resonance and recovers the magnetic energy of load inductance. The capacitor voltage V_C depends on the value of the load reactance. Therefore, when the switching phase angle of MERS is always adjusted to $\pi/2$, the power factor of the power supply automatically becomes unity by the change of V_C even if the impedance of the load changes.

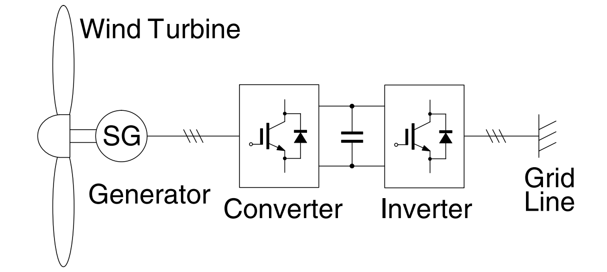
3. Basic Idea for Applying MERS to Wind Turbine Systems

Fig. 4(a) is a conventional wind power system widely used. A variable speed synchronous generator with many poles is connected to a grid through an AC-DC converter and a DC-AC inverter. A permanent magnet type or DC excitation type synchronous generator is used for the generator [3]. Gearless is possible for this system, and it is more efficient than a induction generator. However, the wind power changes always greatly, and the maximum power far exceeds the rated value. The disadvantage of this system is that an output voltage of the synchronous generator decreases with the increase of current because of synchronous reactance. Since the overload capacity of generator is small, an instantaneous strong wind power energy cannot be taken out and it is not efficient. To maintain the output voltage, an excitation current of the generator has to be increased and a volume of the generator is enlarged. This may decline the system efficiency.

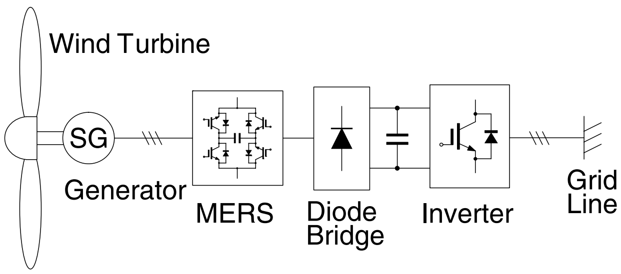
Fig. 4(b) is a wind power conversion system with MERS that we are proposing in this paper. The MERS can improve the power factor regardless of the impedance and power frequency of the load, and it generates voltage and compensates for the synchronous reactance voltage. So, the output voltage of the generator increases, and it becomes possible to improve overload capability and efficiency of the wind power system. Therefore, the efficiency improvement of the power conversion system and the miniaturization of wind turbine generator will be achieved. Moreover, the MERS can be used as an AC breaker.

Fig. 5 is an equivalent circuit of a synchronous generator together with MERS inserted in series. The equivalent circuit of synchronous generator is represented by a series circuit of induced electromotive force $\dot{E}$ and synchronous reactance x_s and armature winding resistance r_a. In a system without MERS, when power factor of the load is assumed 1, the voltage of output terminal $\dot{V}_0$ is shown by the following equation.

$$\dot{V}_0 = \dot{E} - (r_a + jx_s)\dot{I} \cdots\cdots (1)$$



(a) Conventional back-to-back system



(b) Newly proposed MERS system

Fig. 4. Wind turbine power conversion system with synchronous generator

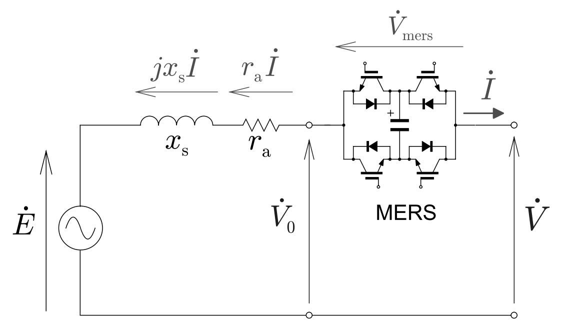


Fig. 5. Equivalent circuit of synchronous generator with MERS

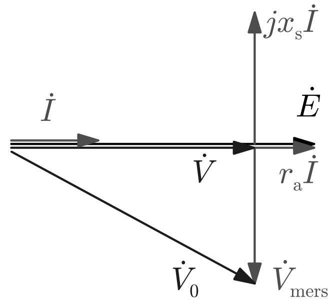


Fig. 6. Phasor diagram of synchronous generator with MERS

$\dot{V}_0$ decreases as the output current $\dot{I}$ increases, and the phase of $\dot{I}$ lags behind $\dot{E}$. MERS can control the phase of the current by an easy control, and correct the power factor of the induced emf $\dot{E}$.

Fig. 6 shows the phase diagram of synchronous generator with MERS. The phase of induced electromotive force $\dot{E}$ is equal to the phase of output current $\dot{I}$. The output voltage $\dot{V}_0$ is increased compared with a system without MERS because the leading current flows to the generator. Therefore, the voltage descent of output voltage $\dot{V}$ is only the voltage of winding resistance $r_a\dot{I}$, and the output voltage $\dot{V}$ in a system with MERS is increased compared with a system without MERS. In other words, the output voltage of a generator is recovered by controlling the phase of output current and compensating the synchronous reactance voltage.

4. Experiments

Before comparing the MERS system with the conventional back-to-back system, we will experimentally investigate effects of MERS in the newly proposed system shown in Fig. 4(b). We will compare the output of the newly proposed system between with MERS and without MERS.

4.1 Experimental Setup Fig. 7 shows a schematic diagram of our small-scale experimental system of wind power generation with a synchronous generator. This system consists of a M-G set and an active power load. MERSs are inserted in series between the generator and the active power load.

The M-G set consists of a 1.5-kW interior permanent magnet synchronous generator coupled with a 3.7-kW squirrel cage induction motor. The generator simulates a wind turbine generator and the induction machine is driven by an inverter, and fluctuations of a wind can be simulated. A rotary encoder detects the mechanical angle of the rotor, and the electrical angle is calculated from it, and gate pulse for MERS is generated. Overviews of the M-G set and MERS modules used in this experimental system are shown in Fig. 8 and Fig. 9. A mechanical input power of the generator is measured with a torque meter. The losses of the system is calculated from the mechanical input power and the output electric power.

The active power load is used instead of a grid connected

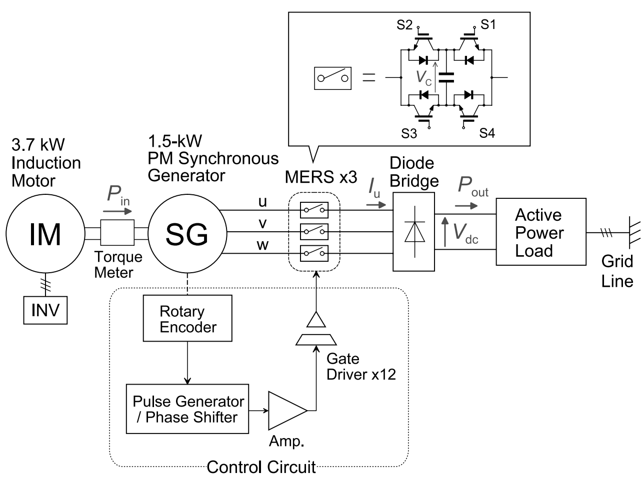


Fig. 7. Experimental configuration of a power conversion system with MERS for wind turbine system

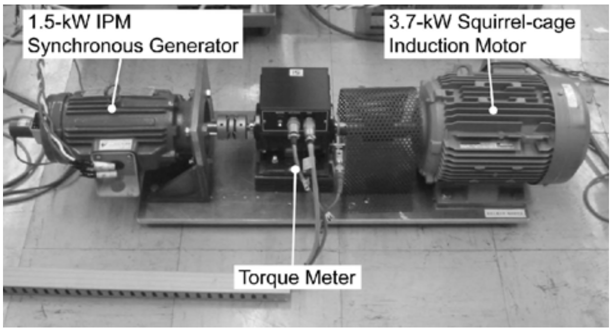


Fig. 8. 1.5-kW IPM synchronous generator and 3.7-kW induction motor (M-G set). The mechanical input of the generator is measured with a torque meter

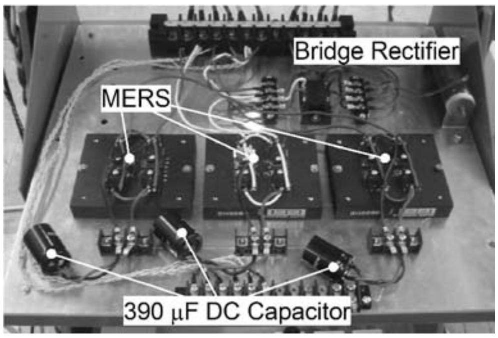
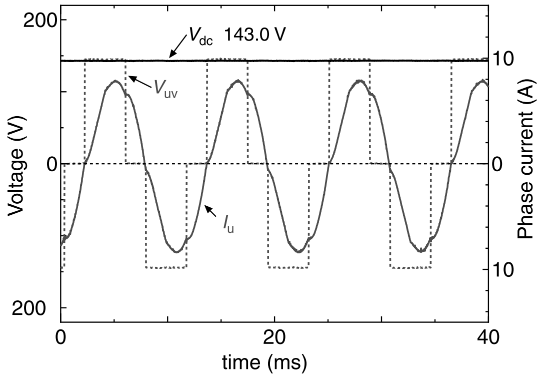


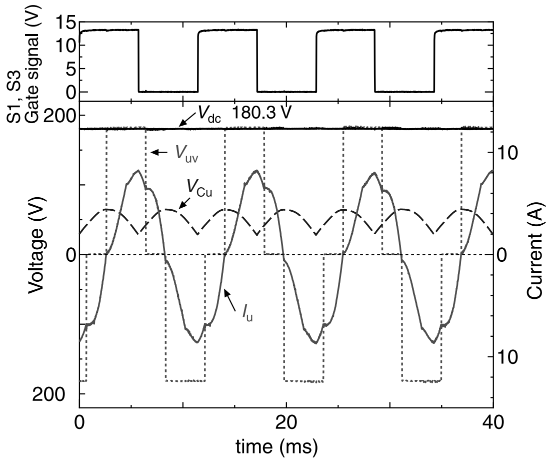
Fig. 9. 3-phase MERS modules

Table 1. Specifications of the permanent magnet type synchronous generator (87.5 Hz)

Rated voltage V_n	130.6 V
Rated current I_n	5.5 A
Pole	6
Rated speed	1750 rpm
resistance r_a	1.55 Ω (0.11 p.u.)
Synchronous reactance x_s	8.12 Ω (0.59 p.u.)
Synchronous impedance Z_s	8.26 Ω (0.60 p.u.)
Short circuit ratio K	1.66



(a) Without MERS



(b) With MERS

Fig. 10. Voltage and current waveforms of experimental results. V_{uv}: line to line voltage, V_{dc}: DC output voltage, V_{Cu}: capacitor voltage of MERS, I_u: phase current

inverter. If the output voltage decreases, a transformer or a boost chopper should be used in order to keep a grid connection.

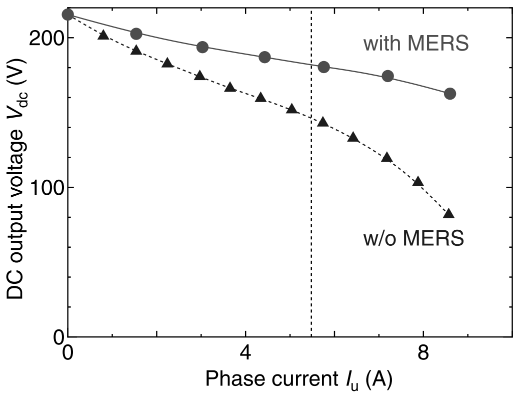
Table 1 shows the specification of the synchronous generator used for this experiment. The synchronous reactance x_s is 8.12 Ω, 0.59 p.u..

The MERS is composed of four IGBTs (1MB20D-060) and 390 μF DC electrolytic capacitor. 3-phase MERS module is shown in Fig. 9. The phase of MARSs' gate signals are made to advance 90 electrical degrees from an induced electromotive force E. The phase angle of the rotor is detected by a rotary encoder installed in the generator. And gate signals are given to each IGBT element through amplifiers and gate drive circuits. Switching loss of IGBT is so small that it can be disregarded, because the switching frequency of MERS is the same as the armature voltage frequency.

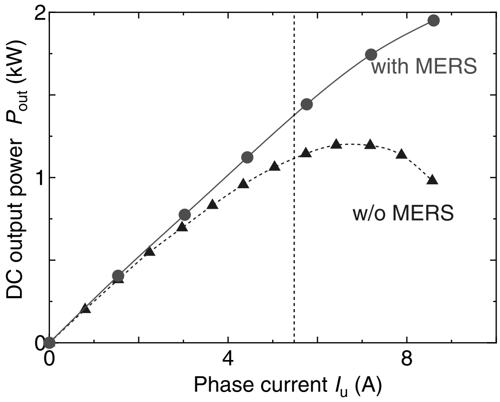
4.2 Experimental Results The measured voltage and current waveforms are shown in Fig. 10. Though the same output current I_u of 5.7 A is observed for with and w/o MERS, the higher DC output voltage V_{dc} of 180.3 V is obtained in the system with MERS, while V_{dc} is 143.0 V in the system w/o MERS. The distortion of the current waveform is not so large. The reactance voltage is compensated by MERS, and the output voltage is increased.

Fig. 11(a) shows the comparison of the DC output voltage of the experimental system with MERS and without MERS. The output voltage V_{dc} decreased with an increase of output current I_u in both system. However, the voltage reduction by the synchronous reactance was recovered by MERS and the output voltage increased in the system with MERS. It becomes only a voltage drop by the resistance, and the characteristic of the synchronous generator is the same as a direct current generator.

Fig. 11(b) shows experimental results of DC output power as a function of output current I_u. The maximum output is 1.2 kW in the system without MERS, while the maximum output is 2 kW or more in the system with MERS. These data indicate that an instantaneous strong wind power energy can be caught from a generator with the MERS system. Moreover, even when the same output power is kept constant, the output current can be decreased in the MERS system because the output voltage increases. As a result, a copper loss and an amount of produced heat of the generator can be suppressed, and a miniaturization of the generator can be expected by applying the MERS to the power conversion system.



(a) DC output voltage (Experiment)



(b) DC output power (Experiment)

Fig. 11. Comparison between (a) DC output voltage and (b) output power of PMSG with and without MERS as a function of phase current I_u

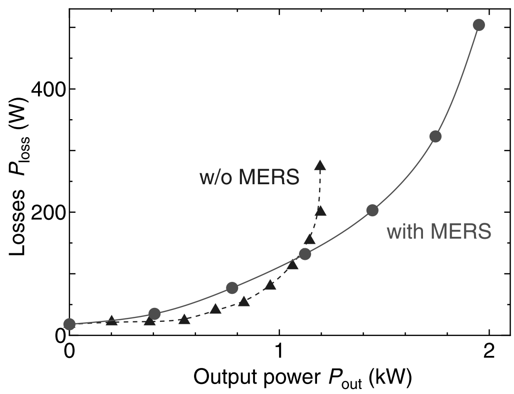


Fig. 12. Total losses (Experiment)

Fig. 12 shows the losses of the experimental power conversion system with and w/o MERS as a function of P_{out}. The loss consists of mechanical loss, iron loss and copper loss of the generator and conduction power losses of IGBTs and the diode bridge. In the area below the rated output power of the generator, the loss of the conversion system with MERS was little bit larger. However crucial advantage in P_{out} and efficiency is attained for the MERS system beyond the rated output power of the generator as shown in Fig. 12.

The experimental results indicate that the newly proposed power conversion system with MERS has a great potential to improve the performance compared with the conventional system. The remarkable advantage of this new system is a big improvement in the output voltage and the overload output capacity of the generator. The latter advantage suggests that the wind turbine generator can be designed much smaller than in the conventional system, which would be much cost effective.

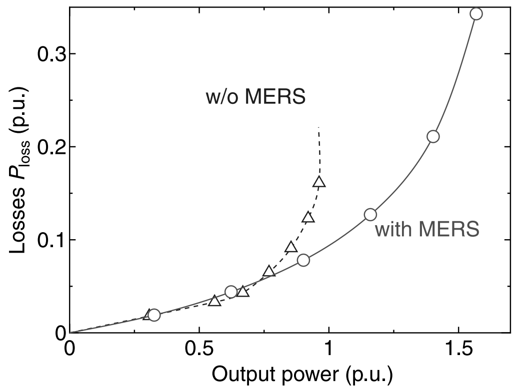


Fig. 13. Total losses in 500-kW power conversion system (Estimating)

It looks like that the efficiency of the MERS system is lower due to the conduction loss in the MERS as shown in Fig. 12. However the loss becomes negligibly small in the large scale systems for commercial use as shown in Fig. 13. This graph shows the estimated total loss of 690 V, 500 kVA power conversion system with MERS. In this graph, maximum ratings of IGBT used for MERS assumed 1700 V, 450 A, and forward on voltage $V_f = 2.0$ V and the loss of the generator was calculated from p.u. value. There is almost no difference in loss also in the area below the rated output power of the generator. Moreover, in the area beyond it, it is expectable that total loss can be reduced greatly.

5. Conclusion

We are intending to realize more economical wind turbine systems by applying the MERS to the power conversion circuit. As the first step of this intension we have shown the remarkable effect of the MERS to improve the output voltage and the overload capacity of a permanent magnet turbine generator. And the characteristic of the SG becomes the same as a DC generator.

The proposed MERS system consists of 12 IGBT's. However, the switching losses of MERS are so small that that it can be desregarded because switching frequency of MERS is the same as a frequency of the generator. The MERS system has advantages in performances, efficiency, and manufacturing costs, including generator.

This suggests us its great potential toward an economical solution to make possible the generator much smaller than the conventional system. As the next steps we will perform the comparison of the MERS system with the conventional back-to-back converter for permanent magnet type as well as excitation type synchronous generators.

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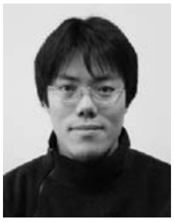

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