Development of Permanent Magnet Generator (PMG) for Small-Scale Hydropower Generation

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Abstract

The demand for renewable energy resources is increasing yearly and hydropower generation is one of them. Among hydropower generation facilities, demand for small-scale hydropower generation facilities has been increasing in recent years because they can generate electricity without the need for dams or large-scale water sources.

As a small-scale hydropower generation facility, variable speed operation of a Permanent Magnet Generator (PMG) combined with a power converter panel results in higher efficiency and a wider operating range than conventional fixed speed generators, allowing for annual power generation with an increase in volume.

With the demand for carbon neutrality and decarbonization, we believe that hydro turbine generators that can utilize renewable energy resource with high efficiency, such as variable-speed PMG, are one of the technologies that should continue to be utilized in the future.

1 Preface

Compared to other systems that use natural energy resources such as wind and solar power, small-scale hydropower generation facilities have a longer service life and can supply stable power installed in various places such as dams, rivers, and agricultural water. Conventionally, induction generators with a robust structure have often been used in small-scale hydropower generation facilities, but they have the drawback of not being able to make an isolated operation, nor realize high efficiency.

A Permanent Magnet Generator (PMG) is a generator that can overcome these drawbacks. Because PMG is expensive, it has not been used in generators that generate modest power, such as small-scale hydropower generation, but it is the perfect generator for prioritizing isolated operation. In addition, when combined with a power converter panel, the generator can be operated at variable speeds and can handle variable head and flow rates, making maximum use of hydro energy possible. This paper introduces a variable-speed submersible PMG developed for small-scale hydropower generation.

2 Overview of Variable-Speed Submersible PMG

Small-scale hydropower stations often use induction generators, which have a simple robust structure and are easy to maintain. Induction generators, however, have poor power factor and secondary copper loss, making them inefficient. Conversely, since PMG does not generate secondary copper loss, it is in principle a highly efficient generator when compared as a generator.

In addition, because induction generators generate electricity by operating at a leading power factor relative to the grid frequency, they cannot make an isolated operation as a generator during a power outage. Variable-speed submersible PMGs can be operated at a constant voltage and frequency using a power converter panel, so they can make an isolated operation if there is a control power source. Hydropower plants are also generally equipped with a DC power supply to ensure safe shutdown, and a power supply to control the power converter panel is secured. Since the system described above can make an isolated operation, it can supply power during power outages and even in non-electrified areas overseas. Fig. 1 shows a comparison of the

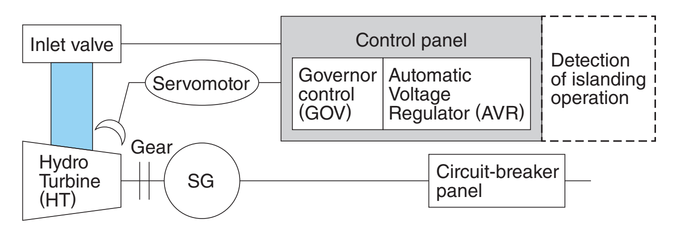
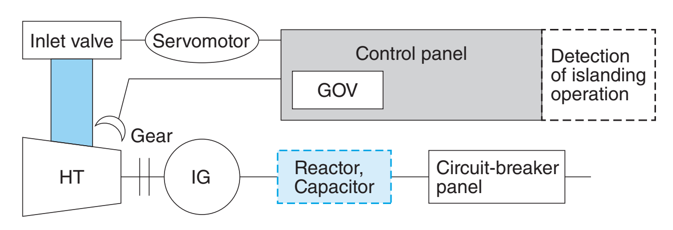
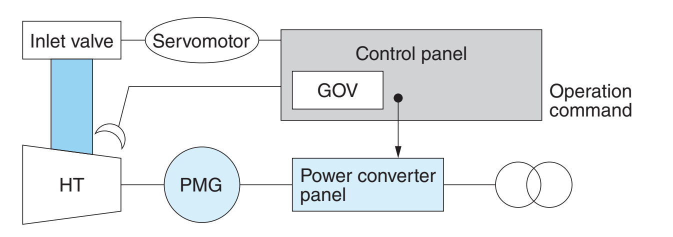
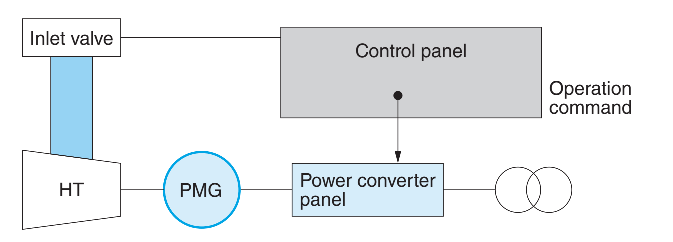
Hydro turbine	Generator	Operating system	System configuration	Applicable product
Francis crossflow pump reversed	Synchronous Generator (SG)	Constant speed		[Conventional product]
	Induction Generator (IG)			[Conventional product]
	PMG	Variable-speed		[Variable-speed system] ・Control panel ・Power converter panel ・PMG
Submersible turbine, pump reversed				[Variable-speed system] ・Control panel ・Power converter panel ・Submersible PMG

Fig. 1 Comparison of System Configurations

The system configuration of the variable-speed submersible PNG and other system configurations are shown.

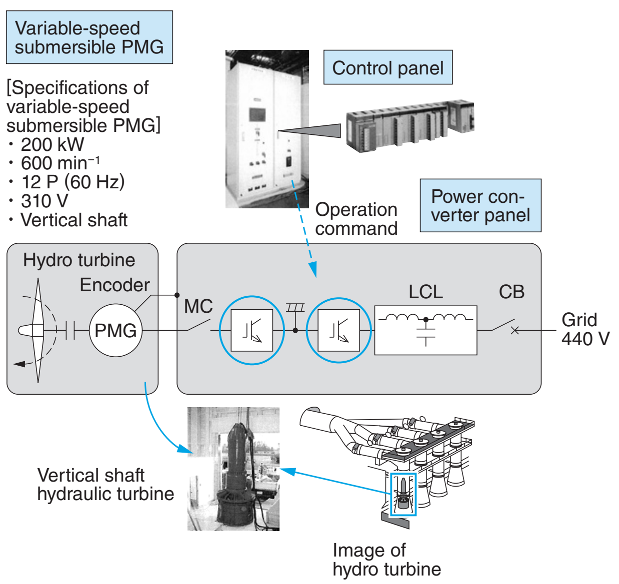


Fig. 2 Details of System

Details of the system configuration for the variable-speed submersible PMG are shown.

system configurations, and **Fig. 2** shows the details of the system.

The developed PMG is combined with a submersible hydro turbine, and the hydro turbine and generator are installed inside the penstock, making it a submersible PMG, which increases the water tightness of the generator. Additionally, since it is installed underwater, there is no need for a separate cooling structure, simplifying the structure of the generator. **Fig. 3** shows a comparison of installations.

3 Specifications and Construction of Variable-Speed Submersible PMG

3.1 Specifications

Table 1 shows the specifications of the developed variable-speed submersible PMG.

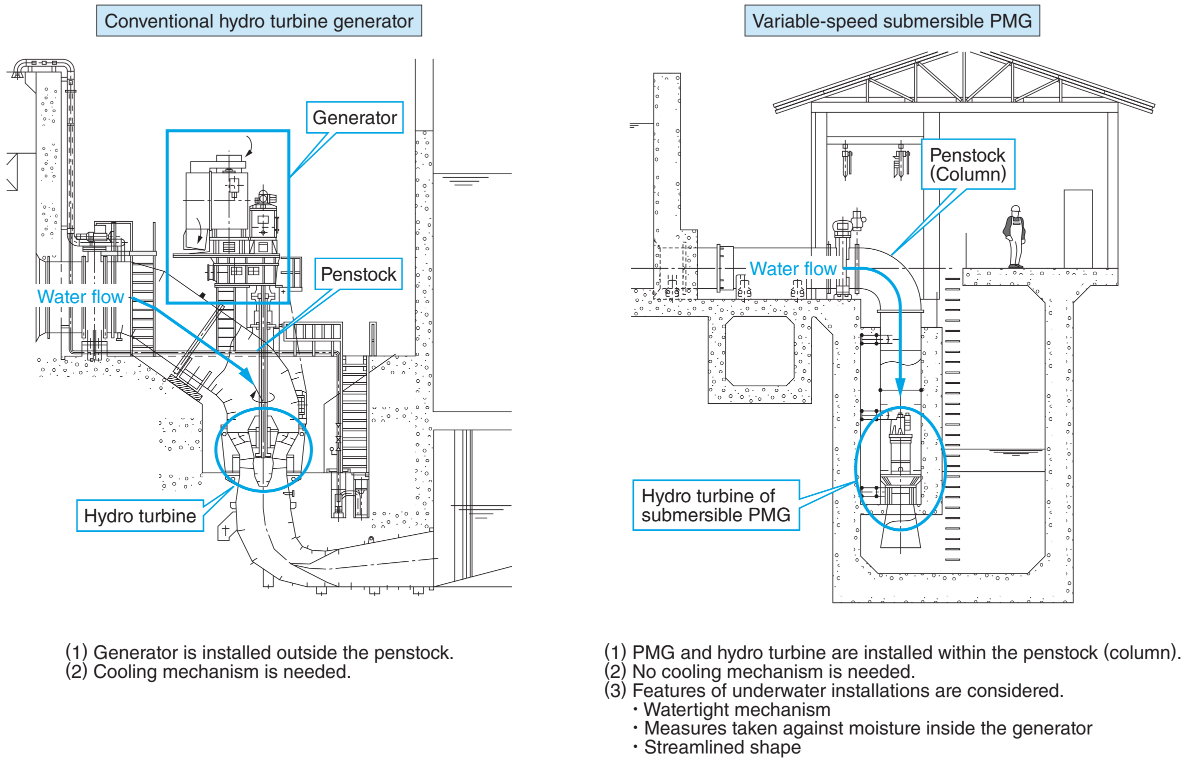


Fig. 3 Comparison of Installations

An example of installations shows conventional hydro turbine generators and the variable-speed submersible PMG.

Table 1 Specifications of Developed Variable-Speed Submersible PMG

Specifications of the developed variable-speed submersible PMG are shown.

Item	Specifications
Type	Vertical-shaft totally-enclosed casing water-cooled
Applicable standard	JEC-2130 (IEC60034-1)
Ambient temperature	0～30℃
Output	215 kVA
Voltage	310 V
Current	400 A
Frequency	60 Hz
Rotational speed	600 min^{-1}
No. of poles	12
Power factor	93%
Heat-resistant class	155(F)
Efficiency	94.5%

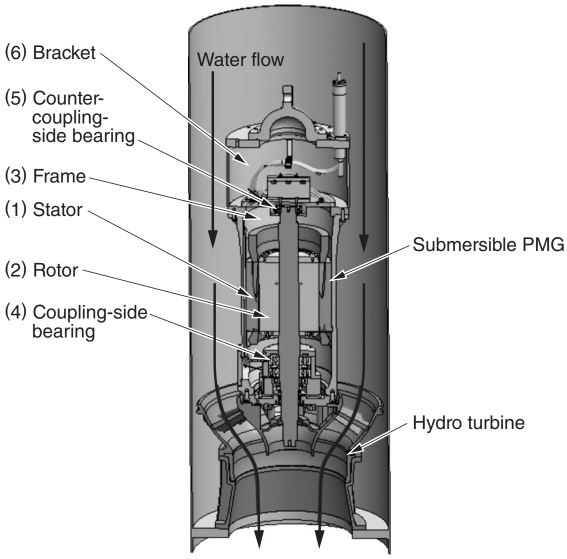


Fig. 4 Structure of Variable-Speed Submersible PMG

Major components of the variable-speed submersible PMG are shown.

3.2 Main Components

Fig. 4 shows the structure of the variable-speed submersible PMG. Broadly classified, it consists of the following components.

(1) Stator

It consists of an iron core laminated with windings and high-grade electromagnetic steel sheets that take measures against switching surges in the connected power converter.

(2) Rotor

It is equipped with permanent magnets and layered iron cores by high-grade electromagnetic steel sheets.

(3) Frame

The joint surfaces and welded parts should be watertight.

(4) Direct-coupling side bearing:

It has an angular contact ball bearing that receives thrust loads, and a cylindrical roller bearing that receives sudden loads in the radial direction from driftwood and debris.

(5) Non-directly connecting side bearing

The rolling elements are deep groove ball bearings are made of ceramics for the purpose of shaft insulation to prevent electrolytic corrosion of the bearings.

(6) Bracket

The joint surface and welded part have a watertight structure, and not only holds the bearing on the side opposite to the direct connection, but also houses the terminal block and cable.

3.3 Characteristic Structure

3.3.1 Variable-Speed: Surge Voltage Protection

This machine performs variable-speed operation using inverter control. There is, therefore, a risk that the switching surge voltage generated from the power converter panel will have an adverse effect on the insulation system. Switching surges from connected power converters tend to have the highest voltage applied to the first coil connected to the power converter panel and then ease toward the neutral point. To prevent insulation breakdown, we have adopted anti-surge wires and strengthened the insulation between the turns of the first coil, where the surge voltage is highest. Fig. 5 shows surge voltage protection measures.

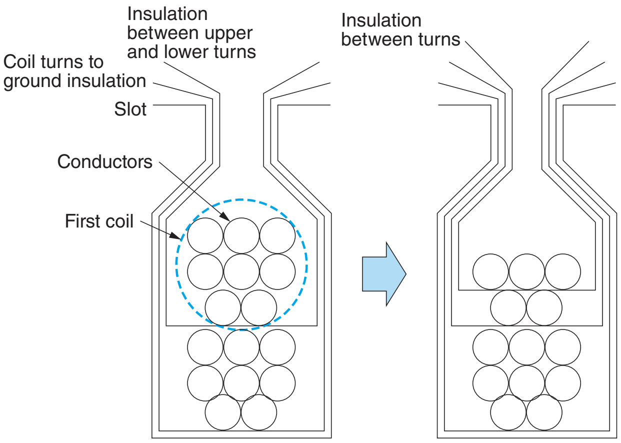


Fig. 5 Surge Voltage Protection Measures

To take measures against surge voltage from the power converter panel, insulation paper is inserted among the turns of the first coil. The state of insulation paper insertion is shown.

3.3.2 Watertight Structure

This machine is intended for use underwater. The joints, welds, and cable pull-outs between each part have a watertight structure. Special treatment is applied to prevent moisture from entering through the gaps in the cable. Fig. 6 shows the watertight structure of the cable head.

3.3.3 Test Simulating Underwater Conditions

Fig. 7 shows the prototype test, and Table 2 shows the test items. For the prototype test, we conducted a rotation test in our factory by directly con-

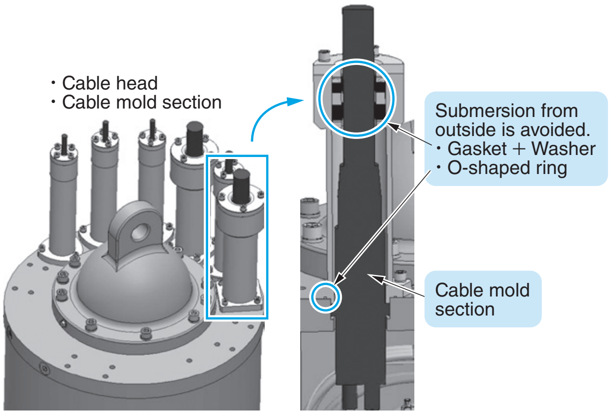


Fig. 6 Watertight Structure of Cable Head

The watertight structure of the cable head is shown. It is made watertight by pressing the cables with gaskets.

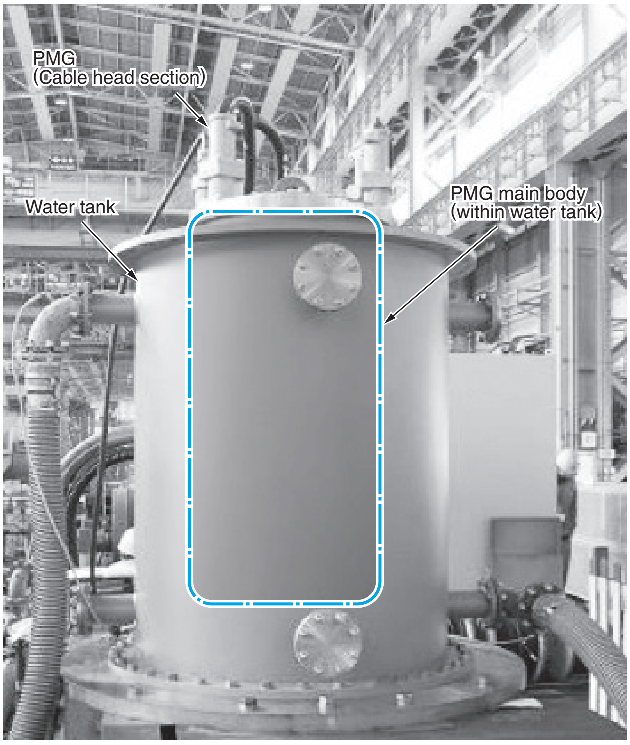


Fig. 7 View of Prototype Test

A view of prototype test in submersion simulation is shown.

Table 2 **Test Items**

Test items are shown relating to the PMG unit test, the regular loading test, and the regular loading test underwater.

Test items	PMG unit	Driver connected (on the ground)	Driver connected (submerged)
Watertight test	○		
External appearance, construction, and dimensional inspection	○		
Winding resistance measurement	○		
Phase rotation		○	○
Impedance measurement (Lq・Ld measurement)		○	
No-load induced voltage measurement		○	
THD and distortion factor		○	
3-phase short-circuit characteristics			○
Torque ripples measurement			○
Stray loss calculation			○
Efficiency calculation			○
Over-speed test		○	
Shaft voltage measurement	○		
Temperature measurement (no load, actual load)			○
3-phase sudden short circuit test (Xd'・Td')			○
Withstand voltage test	○		
Frame's natural frequency measurement		○	
Bearing temperature measurement			○
Noise measurement		○	○

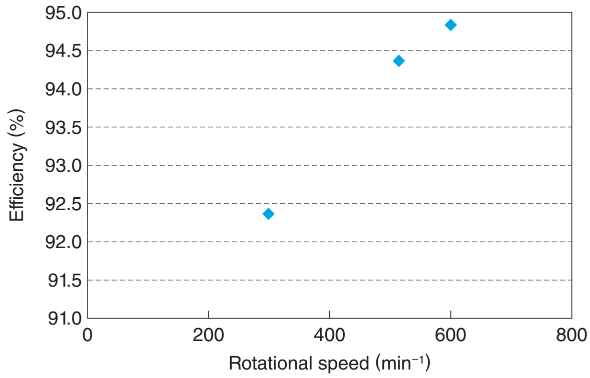


Fig. 8 **Relationship between Rotational Speed and Efficiency**

The efficiency changes with the rotational speed are shown.

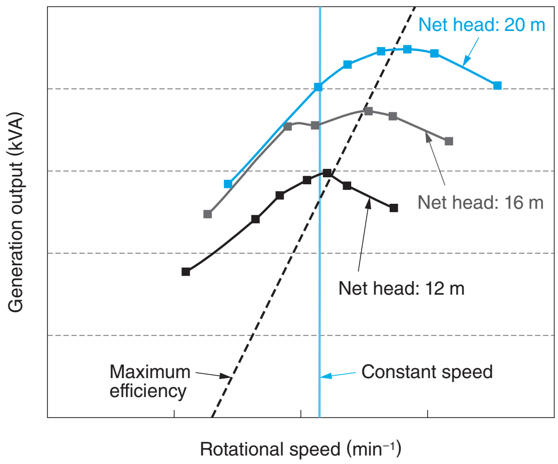


Fig. 9 **Relationship between Efficiency and Rotational Speed Relating to Different Heads**

The relationship is shown between efficiency and rotational speed when the flow rate is kept constant, and the water head is changed.

necting a DC motor. Some performance tests were conducted underwater using a water tank.

4 Efficiency Characteristics of Variable-speed Submersible PMG

Fig. 8 shows the relationship between rotational speed and efficiency obtained from test results for a single PMG. The efficiency at the rated rotational speed and rated output was 94.8%, achieving the development specification of 94.5%.

It is also clear that the efficiency changes depending on the rotation speed. **Fig. 9** shows the relationship between efficiency and rotational speeds for different heads. The maximum efficiency rotation speed of a hydro turbine generator varies depending on the head. By using the newly developed variable-speed submersible PMG, it can be operated at a rotational speed appropriate to the head, allowing for maximum efficiency.

5 Postscript

After completing tests using a prototype, we realized the development of a highly efficient variable-speed submersible PMG suitable for small-scale hydropower generation. There are still many undeveloped and reusable small-scale hydropower plants in Japan. Going forward, we would like to continue providing high-performance products.

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