Heat-to-Electricity With High-Speed Magnetic Bearing/Generator System

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Keywords
ORC, coproduced geothermal, active magnetic bearings, permanent magnet generator, high speed, waste heat recovery, low temperature, oil/gas, R245fa, 125 kW generator, Calnetix, Access Energy

ABSTRACT

The development, testing, and application of a high speed permanent magnet generator in conjunction with a centrifugal expansion turbine supported on magnetic bearings for the production of electricity from waste heat recovery is described. This integrated power module (IPM) can recover waste heat from a number of heat sources including geothermal. The IPM operates between 15,000 rpm and 26,500 rpm depending on the energy available from the heat source. The varying frequency voltage supplied by the generator is connected to the grid using an active/active power electronics package that can deliver power at 400-480 Vac (50 Hz or 60 Hz). Active magnetic bearings that were chosen for the application can operate directly in the working fluid of the ORC system, have low losses, and provide high reliability and remote monitoring capabilities. The shop testing procedure for quality control is described. The first field test unit was installed in April 2009, and since then some 100 units have been distributed worldwide for waste heat-to-electric production. This includes a commercial site for coproduced geothermal energy at a natural gas well in Louisiana.

Introduction

Improving upon ways to efficiently capture low-temperature geothermal resources and generate electricity is a challenging technological problem. It is an important problem because as DiPippo (2008) points out, plotting geothermal resources worldwide in a histogram according to temperature would show the data heavily skewed toward low-temperature resources. Binary ORC systems have been able to convert heat-to-electric at temperatures of 150°C (300°F) and lower. Many of these systems require a physical bearing/lubrication system as part of the generator/rotor combination, which can be a point of failure or long term maintenance for proper equipment function. Thus developing technologies to improve upon binary ORC systems is an important endeavor for expanding geothermal electrical production within low-temperature environments.

Using innovations involving permanent magnet motor generators, magnetic bearing systems, and power electronics, Calnetix Technologies, LLC applied its proprietary technology to the ORC binary system approach to develop a 125 kW integrated power module (IPM) for a wide range of heat-to-electric recovery processes (Hawkins et al., 2011). The Calnetix design has been licensed to GE Energy, Heat Recovery Solutions for their Clean Cycle™ product line and to Calnetix subsidiary, Access Energy, for their Procore™ product line. The Procore™ product is designed specifically for geothermal energy production, especially from heat captured from brine and natural gas, gas compression facilities, amine gas treatment, and heat captured from flared gas.

General Operation

The Integrated Power Module (IPM) 125 is the main component of the 125 kW (net) waste heat recovery system that utilizes a heat input of at least 835 kW and temperature of +82°C (+180°F) or higher to generate electricity to the grid. The closed loop system uses HFC-R245fa refrigerant as a working fluid, allowing a lower boiling point than water and heat recovery from low temperature sources. The system, referred to as a waste heat generator (WHG), is factory built on a module (Figure 1) that is delivered to a site where waste heat is available. The module is then connected to a heat source (evaporator), to a condensing source (condenser), and to the electrical grid (Figure 2). The working fluid navigates through the unit in a seven-step process not uncommon to most ORC power generation systems:

- Starting at the receiver, the working fluid is in liquid form at the condensing pressure and temperature.
- The working fluid enters the pump where the pressure is raised to the evaporating pressure.
The working fluid passes through a heat exchanger (economizer) where it receives heat from fluid leaving the IPM125 expander module, thus improving overall system efficiency.

The working fluid is now a warmer, high pressure liquid. The fluid then enters the evaporator, where it is exposed to the waste heat via a heat exchanger, evaporating the fluid to a high pressure vapor.

The working fluid (now a vapor) enters the turbine of the IPM125. Driven by the pressure, the IPM125 generator and associated power electronics convert the energy to electrical power that can be directly connected to the grid at 50 or 60 Hz.

The working fluid still has considerable heat, some of which is transferred to the pumped liquid via the economizer. Preheating the liquid phase of the working fluid results in less heat being required to vaporize the working fluid prior to entering the IPM125. This also cools the fluid on its way to the condenser requiring less energy for heat extraction rejection.

The working fluid (still a vapor) then enters the condenser where heat is removed, returning the fluid to a liquid. Either air-cooled or liquid-cooled condensers can be used. The low pressure, liquid working fluid drains back to the receiver to complete the cycle.

Due to the modular design of the module, the heat input can be configured for a variety of direct and indirect heat sources. Direct heat sources provide heat directly to the refrigerant using a single facility heat exchanger. A waste gas burner or a geothermal fluid with a heat exchanger carrying the working fluid would be examples of a direct heat source. Heat sources can also be indirect where a secondary fluid is required to carry heat to the refrigerant. This configuration requires more than one facility heat exchangers.

**Carefree™ Integrated Power Module**

The IPM is the heart of the WHG system (Figure 3), combining a high speed permanent magnet (PM) generator with a high pressure vapor. The fact that the IPM is hermetically sealed, with no gearbox or external seals, and supported by non-contact magnetic bearings that require no lubrication has resulted in this being called the Carefree™ IPM.

The generator is connected to a power electronics (PE) package that converts the variable frequency and voltage IPM output power for grid connectivity with 50 Hz and 400 V or 60 Hz and 480 V. The IPM produces full power typically at operating speed of 26,500 rpm but can output a reduced power level down to 15,000 rpm. This is important because the energy available from many waste heat sources can vary considerably throughout the day or on a day to day basis. This is especially true in the case of coproduced geothermal energy where fluid production volume from a well can vary dramatically. The rotordynamics and magnetic bearing controls are sufficiently robust to allow stable and smooth operation at any speed from 0 rpm up to the 25% overspeed of 33,125 rpm.

The IPM is a flow-through design, which means it can be installed in the middle of a straight run of pipe. Superheated refrigerant enters the IPM (Figure 3) and is directed into an annular space by the diverter cone. A typical inlet condition might be 121°C (250°F) and 1.72 MPa (250 psi). The gas then flows radially inward through a nozzle into the turbine. Expansion across the turbine results in a temperature drop and an 8:1 pressure drop. The exhaust then passes through the generator rotor/stator air gap and around the outside of the generator stator to provide cooling for the generator. The system can produce 125 kW gross electrical output with an overall efficiency of heat-to-electric grid power of approximately 12-16%, depending on the temperature of the waste heat stream and the condensing wet bulb temperature. A typical example for a waste heat gas stream of 980 kW (3.34 MBtu/h), evaporating temperature of 121°C (250°F), and condensing temperature of 21°C (70°F), the system will deliver a gross power of 125 kW to the grid.

**Permanent Magnet Generator**

PM generators consist of two basic parts (Figure 4). A stator coil, powered by an alternating current, creates an electric field. Then a rotor made of high energy magnetic material rotates within that field. PM generators employ the latest technology in high strength rare earth magnetic materials to achieve high power density and efficiency. The former leads directly to minimum physical size at all power levels when compare with other motor types, and the latter leads to significant improvement in overall system efficiency.
Calnetix uses two primary types of rotor construction to provide high speed rotating assemblies in mass production. Containment is provided by either a high strength metal sleeve or a proprietary advanced graphite-composite sleeve for tip speeds in excess of 366 meter (1,200 feet) per second. Both offer unique advantages to the system and generator performance, and selection is made according to system performance goals. Other rotor design criteria that are important for the final application or working environment include operating temperatures, type of bearings employed, stiffness required, operating bending modes, and operating gases or liquids.

The generator uses a two-pole, radially polarized PM generator. The magnets are constrained by a nonmagnetic retaining sleeve, which also provides the structural connection between the generator and the rest of the system. PM machines use permanent magnets to provide field excitation, providing high efficiency and reduced size for an equivalent power when compared with induction and variable reluctance machines. They also have lower rotor losses and lower winding inductances, which make them suitable for the rapid energy transfer in expander applications. The three-phase stator is conventionally wound, allowing a simple, low cost construction.

Calnetix uses the latest PM and insulation materials, and continues to work with leading magnet and insulation manufacturers to increase the temperature capabilities and other performance characteristics in its PM machines. Depending on the rare earth magnets utilized, temperatures up to 288°C (550°F) can be achieved. Calnetix uses class H and above insulation systems for its high performance stator windings to push the rated temperatures to be less than 35 W at operating speed. Other benefits are these bearings do not require their own cooling system, they have remote

Magnetic Bearings

Active magnetic bearings are a non-contact rotor support system that replaces conventional mechanical bearings that physically interface with the shaft and require some form of lubrication. Electromagnets provided attractive forces in five of the six degrees of freedom of a rigid body, these being translation in three perpendicular axes and rotation about the two orthogonal transverse axes (the motor/generator operates on the sixth degree of freedom – the spin axis). In active magnetic bearings, non-contact position sensors monitor shaft position and feed this information to a control system, which regulates current to an actuator to adjust rotor position or provide damping. Active bearing systems, while more complex than passive types, provide much higher support stiffness and are tunable for optimizing system response. Also, the existence of requisite position sensors, current sensors and speed sensors, provide a great deal of information for monitoring and diagnostics.

The radial magnetic bearing (Brg1) is a two-axis radial bearing (Figure 4) while the combo magnetic bearing (Brg2) is a three-axis combination (combo) radial/thrust bearing. The radial bearing produces magnetic forces in radial (lateral) directions that maintain the shaft centered about the rotational axis of the machine. The combo magnetic bearing design includes a thrust magnetic bearing that produces magnetic forces in an axial (longitudinal) direction to maintain the shaft’s axial position in the machine. The basic operation of these two bearing topologies is described elsewhere (McMullen et al., 2000; Filatov et al., 2004). The combination bearing is more compact axially than separate radial and axial magnetic bearings, reducing the overall rotor length. This increases the frequency of the rotor bending modes, making the magnetic bearing control design less difficult and allowing for smooth operation even at the 25% overspeed. Three separate pairs of control coils allow individual control of each axis (two radial and one axial). Some characteristics of the magnetic bearings are given in Table 1. Figure 5 shows the generator permanent magnet rotor, the expander, the combo magnetic bearing housing, and end bell.

Magnetic bearings do not require lubrication and allow for near frictionless operation and no wear, thereby optimizing the efficiency and reliability of the system; there is no contact between the rotating assembly and the bearing. The rotor power loss from eddy currents and windage at the bearing journals was estimated to be less than 35 W at operating speed. Other benefits are these bearings do not require their own cooling system, they have remote
monitoring and diagnostic capability, and there is no need to isolate the working fluid from the generator and bearings. This last feature allows the entire module to be hermetically sealed, minimizing the potential for working fluid leakage outside of the system.

**Power Electronics**

The output of the expander/generator is connected to an active/active PE package. The power electronics package uses an insulated gate bipolar transistor (IGBT) rectifier to convert the variable frequency, high voltage output from the expander-generator to DC. It then converts the DC to 400 Vac/480 Vac at 50 Hz/60 Hz for power delivery to the grid. Flexibility and adaptability are provided by digital control software that implements the control algorithms that have been proven through system modeling and simulation.

This is a big advantage of the IPM over the conventional generator. In a conventional generator the speed of the prime mover is dictated by the voltage and frequency determined by selection of the generator at the time of manufacturing. Speed of the prime mover determines frequency of the electrical output with 1,500 rpm for 50 Hz output or 1,800 rpm for 60 Hz output. Matching to the grid is done through a costly synchronizing switch gear. By contrast in the high-speed generator the speed of the prime mover does not determine the frequency or voltage of the electrical output. Matching the grid is accomplished by sampling grid voltage and frequency by the PE, which then changes output voltage/frequency of the inverter system.

### Integrated Power Module Testing

A series of in-house tests are conducted prior to each IPM unit being shipped for installation in a WHG to verify performance of the magnetic bearing system. The four main parts of the testing are the initial setup test, spin test, axial load test, and post-seal verification.

In the initial setup test, resistance and inductance measurements are made for all the actuator and sensor coils. Insulation between all coils and the machine chassis and coil-to-coil insulation of adjacent radial actuator coils are checked to verify coil integrity. A mechanical check is made to confirm the rotor axial travel in the backup bearings, followed by verification of the sensor to rotor target gaps for both the axial sensor and the speed sensor. All radial and axial position sensors are calibrated using an automatic routine that is initiated through a LABVIEW based magnetic bearing graphical user interface (GUI). Finally, with the rotor levitated, five transfer functions—plant, compensator, open loop, closed-loop, and sensitivity—are measured for each of the five active control axes. The transfer functions (Figure 6) are measured using an internal feature of the magnetic bearing control program. A stepped sine excitation is applied to the controller output of the axis of interest. Simultaneously, the input and output signals from the controller are demodulated synchronously with the excitation signal. A complex division produces the gain and phase of the transfer function of interest one frequency at a time.

The motoring spin test uses the generator as a motor and is driven using the motoring mode of the PE. During the full speed spin, rotor position and coil current data are collected at a 5 kHz sample rate using the GUI. These high frequency data are reviewed to make sure no abnormal conditions appear during the test. Transfer functions for each of the five control axes are measured again at full speed to verify the performance of the control algorithms. Synchronous vibration data are also collected at every 250 rpm increment of spin speed. Synchronous displacement, current, and cancellation amplitude and phase are continuously calculated by the controller and are available through the GUI.

At the initial stage of the production of the IPM125 machine, each machine was installed on a special load test platform that facilitates applying and measuring static axial or radial loads. The radial bearing load capacity is measured only on selected units because the dynamic radial load is small due to the use of
synchronous cancellation, the static radial load is expected to be near constant over time, and the radial axes on IPM125 unit do not take heavy load. The axial load capacity was checked on all early production units because it is anticipated but not yet observed in field testing that future long term seal wear may result in an axial load that increases over long time periods. Having an accurate axial load versus current characteristic for all units will assist in drawing better conclusions from future field data. The axial bearing is loaded in 0.25 A steps until the axial coil current reaches 5.0 A. Both the axial coil current and the applied force are recorded and plotted (Figure 7) for measured and calculated values.

After the load test, the IPM is disassembled and the inboard (impeller exhaust) and outboard (back plane) brush seals are installed. With the seals installed, selected tests are repeated that were performed without the seals. These tests include the sensor calibration verification, 0 rpm transfer function measurements, recording of levitation currents, and low speed spin test. Measured data are then reviewed, and if nothing unusual is found, the unit is shipped for installation in a WHG for final acceptance testing.

Waste Heat Generator Installation

After shop testing, the IPM is assembled into the WHG module. The complete module is tested in a test cell with a controllable heat source (a boiler), providing the waste heat. A comparison of 15 tested systems, for example, shows that the maximum thrust load, generally occurring at the maximum inlet pressure, has varied from negligible to just under 335 N (75 lbf).

Beta units were installed in 2008 and the first production installation was in June 2009 with the heat source being the exhaust from a digester at a waste water treatment plant in Lakeland, Florida. This is a containerized unit running on a direct methane flare. Availability has been +98% and as of August 31, 2011 operating hours were 4,449.

Since then over 100 units have been delivered to locations worldwide (Figure 8) by Calnetix, GE Energy Heat Recovery Solutions, and now Access Energy. These units are functioning from several heat sources that include biomass, landfill gas, biodiesel, flue gas, solar thermal, and coproduced geothermal energy. In particular the coproduced pilot unit was purchased by Cleco Corporation and installed at a well operated by Hilcorp Energy Corporation in St. Mary’s Parish in Louisiana (Figure 9). The well produces natural gas along with about 5,000 bbls (110 gpm) of brine per day at a temperature of 115 – 127°C (240 – 260°F). The unit was commissioned in February 2011, and as of August 31 had operated for 2,271 hours. During the time of Mississippi flooding the unit was down and had to be renovated due to unexpected difficulties caused by the flooding.

Figure 6. A) Plant transfer function measurement at 0 rpm. Correlation between calculated and measured results are quite good. B) Sensitivity transfer function data compared with the predicted model at 0 rpm.

Figure 7. Measured axial load versus current for several machine measurement versus the theoretical calculation. Measured slope, or actuator gain, falls within 385 N/A (64 lbf/A) ±10%, agreeing well with the predicted value of 385 N/A (64 lbf/A).

Figure 8. Location of the countries and number of WHG units that have been shipped since the first unit in 2009.
Conclusions

The development of the IPM as described for waste heat recovery is a step forward in improving the mechanical workings of conventional ORC systems. Better control of delivered electrical power can be maintained regardless of the variability of heat input.

The use of PM generator and PM biased magnetic bearings improves efficiency and decreases equipment wear, maintenance, and cost for heat-to-electric production. With over 100 units in active waste heat recovery, including coproduced geothermal energy, this approach has proven to be robust, versatile, and dependable. Its introduction into geothermal energy in a modular fashion can initiate cash flow earlier in heat-to-electric recovery.

References


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Figure 9. Images of the external arrangement of cooling system (air), the shell and tube heat exchange system, and the container housing the waste heat generator (left). The WHG 125 module is seen within the container (right) hooked to the external piping for the hot water delivery and return.