Generators and Controllers for Micro Power Based Distributed Power Systems

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ABSTRACT

Micro turbine based generator systems are becoming popular for providing electric power and heat in a cogeneration environment. The reason for this is the fact that the high-speed turbo-generator sets are very compact in size and are competitive in the cogeneration environment. The electric generator is directly coupled to the high-speed turbine and must be capable of operating at the high speed. The typical micro and mini turbine speeds are in the range of 30,000 rpm to 120,000 rpm. The higher the power, lower is the speed. Thus a 40-kW micro turbine-generator may operate at 120,000 rpm, while a 500-kW mini-turbine may operate at 30,000 rpm.

This article addresses a 200 kW, 60,000 rpm generator and controller suitable for direct coupling to a turbine. Many of the micropower units available in the market use permanent magnet generators. In the design presented here, induction generator technology is applied. It is believed that induction generators offer benefits such as lower cost, higher cycle efficiency, and safety of operation.

TURBO GENERATOR SYSTEM UNDER CONSIDERATION

One specific technology does not necessarily provide the best answer under all situations. Therefore it is important to approach each specific situation carefully and select the right technology for that situation. In this article we narrow our focus to the range of electric power as described below.

i) The generator and the turbine are directly coupled. Figure 1 shows the components in a block diagram.

ii) Constant speed of operation is considered. However, certain operating speed range such as + 0 to –5% may be required in specific applications.

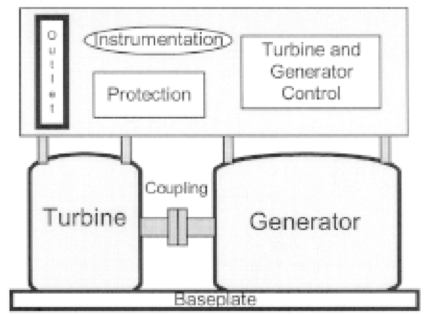


Figure 1.
Turbo-generator Block Diagram

iii) The generator must be designed for a cooling system that is compatible with the system requirements. Typically either air, or lubricant oil, or water glycol mixture is used.

iv) The integrated power system is located close to the user such as in a factory building, hospital, department store, or office complex. Alternatively, vehicle mounted applications in airborne, land based or marine situations are also considered. In either case the length of the feeders to the control unit is short

v) The electrical power output is typically 3-phase ac with single or multiple voltage lines. Alternatively, DC output may be required. In case of AC power systems, 50/60 Hz frequency is common for commercial applications, and 400 Hz frequency is used in military/aerospace applications.

vi) Compatibility with utility power systems may or may not be required. In some situations standalone capability in isolation from a utility system is required. In some other situations, power transfer from utility to the turbo-generator and vice versa may be necessary.

vii) The generator must also provide electric start capability during the initial start up of the turbine.

viii) The system must provide protection against hazards. Safety of operation is an important consideration.

In approaching various issues, we have considered the following parameters to define relative merits:

i) Cost
ii) Reliability and safety, and
iii) Size, power density.

CONTENDING GENERATOR TECHNOLOGIES

We plan to review three different generator technologies that are suitable for high-speed operation. These are: permanent magnet (PM), induction, and switched reluctance (SR). There are other technologies such as synchronous reluctance and homopolar that are also suitable for high-speed operation but are not considered in this article. These technologies result in large electromagnetics, particularly for the ratings under consideration.

Permanent Magnet (PM)

Micropower systems currently in the market use the generator designs based on the permanent magnet technology. The generator itself has two electromagnetic components: the rotating magnetic field constructed using permanent magnets and the stationary armature constructed using electrical windings located in a slotted iron core. Figure 2 shows the construction of typical electromagnetics for a permanent magnet generator in a cross sectional view.

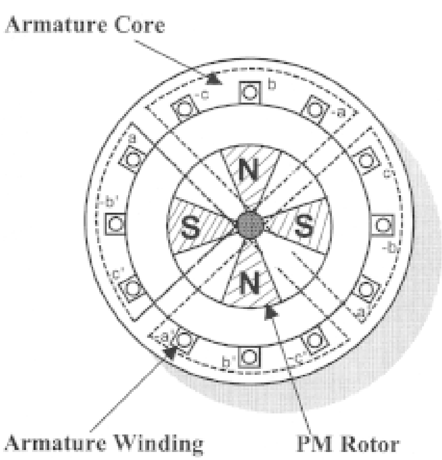


Figure 2. Permanent Magnet Generator Cross-sectional View

The permanent magnets are made using high-energy rare earth materials such as neodymium iron boron or samarium cobalt. High-strength metallic or composite containment ring provides retention of the permanent magnets on the shaft. The stationary iron core is made of laminated electrical grade steel. Electrical windings are made from high purity copper conductors insulated from one another and from the iron core. The entire armature assembly is impregnated using high temperature resin or epoxy.

The voltage output from the generator is unregulated, multiple phase AC. This voltage varies as a function of the speed and load. The output is connected to a solid state power conditioning system. Typically, the solid state power conditioning system uses buck/boost techniques and regulates the entire power output.

Induction

The technology of an induction generator is based on the relatively mature electric motor technology. Induction motors are the most common types of electric motors used throughout the industry. Early developments in induction generators were made using fixed capacitors for excitation, since suitable active power switching devices were not available. Use on fixed capacitors caused the power output to be unstable, since the excitation could not be adjusted as the load or speed deviated from the nominal values. The induction generator approach became possible only where a large power system with infinite bus was available, such as in a utility power system. In that situation the excitation was provided from the infinite bus as demanded by the load and speed conditions. With the availability of high power switching devices, induction generator can be provided with adjustable excitation and operate in isolation in a stable manner with appropriate controls.

Induction generators also have two electromagnetic components: the rotating magnetic field constructed using high conductivity, high strength bars located in a slotted iron core to form a squirrel cage; and the stationary armature similar to the one described earlier for the permanent magnet technology. Figure 3 shows the construction of a typical induction generator in a cross sectional view.

Voltage output from the generator is regulated, multiple phase AC. The control of the voltage is accomplished in a closed loop operation where the excitation current is adjusted to generate constant output voltage regardless of the variations of speed

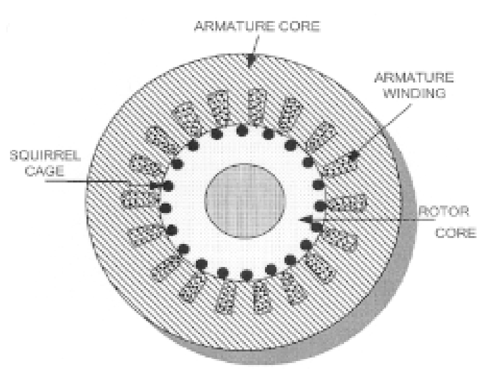


Figure 3. Induction Generator Cross-sectional view

and load current. The excitation current is supplied to the stationary armature winding from which it is induced into the short circuited squirrel cage representing the secondary winding in the rotor.

Switched Reluctance (SR)

The technology of the switched reluctance generator is based on the concepts that magnetically charged opposite poles attracts. Typically, there are an unequal number of salient poles on the stator and the rotor. Both stator and rotor are constructed using laminated electrical grade steel. Figure 4 shows a cross sectional view of the construction of the switched reluctance generator. The number of poles shown on the stator is 6. The number of poles shown the rotor is 4. Other pole combinations such as 8/6 or 10/8 are possible. There is no electrical winding on the rotor. Armature coils located on stator poles are concentric and are isolated from one another. When the coils on opposite poles such as 1 and 1 shown in Figure 4 are excited, the corresponding stator poles are magnetized. The rotor poles A-A are closest to the stator poles 1 and 1. These are magnetized to opposite polarity by induction and are attracted to the stator poles. If the prime mover drives the rotor in the opposite direction, voltage is generated in the stator coil to produce power.

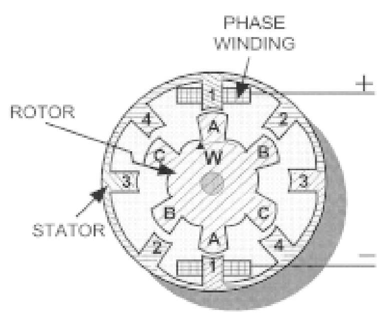


Figure 4. Switched Reluctance Generator Cross-sectional view

Voltage output from the switched reluctance generator is DC. It has high ripple content. The voltage output can be filtered, and is regulated by adjusting the duration of the excitation current. Commutation of the current through the stator coil is accomplished by the controller.

WHY INDUCTION GENERATOR

Induction generator has several benefits to offer for the micro and mini turbine based power systems under consideration. These benefits are:

i) Cost of Materials: Use of electromagnets rather than permanent magnets means lower cost of materials for the induction generator. Rare earth permanent magnets used in the permanent magnet generators are substantially more expensive than the electrical steel used in electromagnets. They also must be contained using additional supporting rings.

ii) Cost of Labor: Permanent magnets require special machining operations and must be retained on the rotor structure by installation of the containment structure. Handling of permanent magnets that are pre-charged is generally difficult in production shops. These requirements increase the cost of labor for the permanent magnet generator.

iii) Generator Power Quality: The permanent magnet generator produces raw ac power with unregulated voltage. Depending upon the changes in load and speed, the voltage variation can be wide. This is all the more true for generators exceeding about 75 kW power rating.

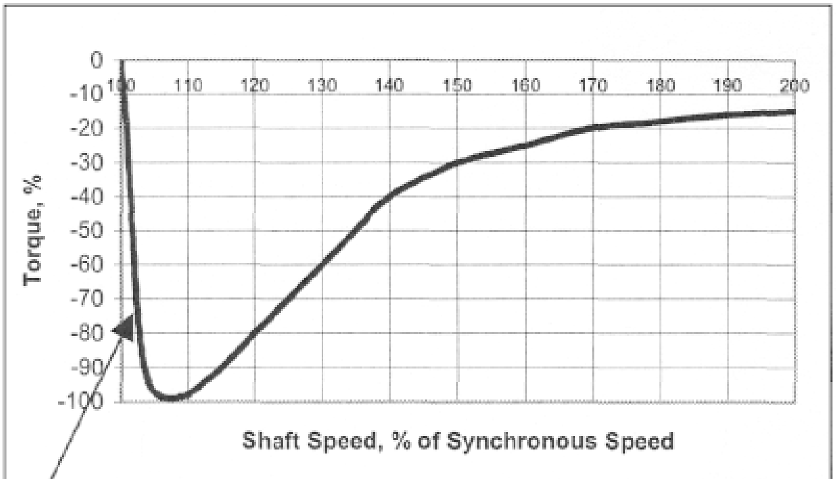
The induction generator produces ac voltage that is reasonably sinusoidal. This voltage can be rectified easily to produce a constant dc voltage. Additionally, the ac voltage can be stepped up or down using a transformer to provide levels of voltages if required.

iv) Fault Conditions: When an internal failure occurs in a permanent magnet generator, the failed winding will continue to draw energy until the generator is stopped. For high-speed generators, this may mean a long enough duration during which further damage to electrical and mechanical components would occur. It could also mean a safety hazard for the surrounding area. The induction generator on the other hand is safely shut down by de-excitation within a few milliseconds, preventing the hazardous situations.

INDUCTION GENERATOR OPERATION

If an induction motor is driven to a speed higher than the synchronous speed, the shaft torque is negative, implying the generate mode. This is shown in Figure 5. In the stable region of this curve, electric power is generated utilizing the mechanical input power from the prime mover. The generated power is a function of the slip, which is defined as the speed in excess of the synchronous speed.

In the generator mode, if the slip is controlled in accordance with



Stable Region

Figure 5. Induction Generator Torque vs. Speed

the load requirements, the induction generator will deliver the necessary power. It must be remembered that the synchronous speed is a function of the electrical frequency applied to the generator terminals. On the other hand, the operating shaft speed is determined by the prime mover. Therefore to generate power, the electrical frequency must be adjusted as the changes in the load and the prime mover speed occur.

In addition to the requirement stated above, the excitation current must be provided to the generator stator windings for induction into the rotor. The magnitude of the excitation current will determine the voltage at the bus. Thus the excitation current must be regulated at specific levels to obtain a constant bus voltage. The controller for the induction generator has the dual function as follows:

i) Adjust the electrical frequency to produce the slip corresponding to the load requirement.

ii) Adjust the magnitude of the excitation current to provide the desirable bus voltage.

Figure 6 depicts the region of generator mode operation for a typical induction generator. A number of torque speed characteristic curves in the stable region of operation are shown to explain the operation. As an example, consider the situation when the prime mover is at the nomi-

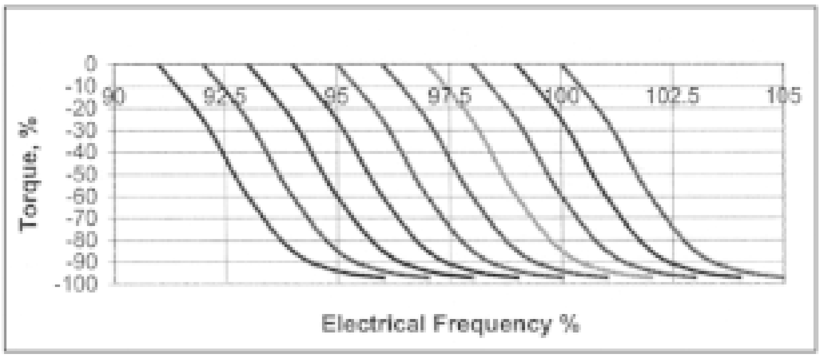


Figure 6. Induction Generator Torque vs. Speed in Operating Range

nal or 100% speed. The electrical frequency must be adjusted for load changes from 0 to 100% of the load. If a vertical line is drawn along the speed of 100%, it can be observed that the electrical frequency must be changed from 100% at no load to about 95% at full load if the prime mover speed is held at 100%.

OPERATION OF THE CONTROLLER FOR INDUCTION GENERATOR

The controller has three sections, the power section, the sensing circuits, and the control section. Power transistors using IGBTs or MOSFETs are used in the power section of the generator controller in a conventional multiphase configuration, the number of phases being the same as the number of phases in the generator winding. Anti-parallel diodes are connected across each of the transistors. The DC rail is connected to a power capacitor. An additional power inverter is used when an AC output at a constant frequency such as 60 or 50 Hz is required. Sensing of currents and voltages is provided at the load as well as in the power section of the controller. In addition, the speed of the shaft is measured. All the parameters sensed by the sensing circuits are conditioned by filtering and digitizing as required. The control section receives the information provided by the sensors. The parametric model of the generator is incorporated in the control section. In conjunction with a PID (proportional/integral/derivative) control algorithm, appropriate switching commands for the power transistors are generated in the control section.

This creates the necessary frequency and amplitude of the excitation currents that flow in the induction generator windings and are induced into the squirrel cage rotor. The control section also includes protective functions such as over-current, over-voltage, and over-temperature protection circuitry. Figure 7 shows the controller in a block diagram.

INDUCTION GENERATOR CONTROLLER FEATURES

When compared to permanent magnet and switched reluctance generator controllers, induction generator controllers offer the following benefits:

i) The control of induction generator slip required precise measurement of speed. On the other hand, the control of the switched reluctance generator requires precise measurement of the rotor position. This is a much more difficult task to accomplish than the measurement of speed.

ii) Switching and control speed: For the switched reluctance generator, the operating frequency is extremely high, in the range of 6 kHz at 60,000 rpm. This requires high speed switching of power transistors. The switching commands also must be provided at a high rate. For the induction genera-

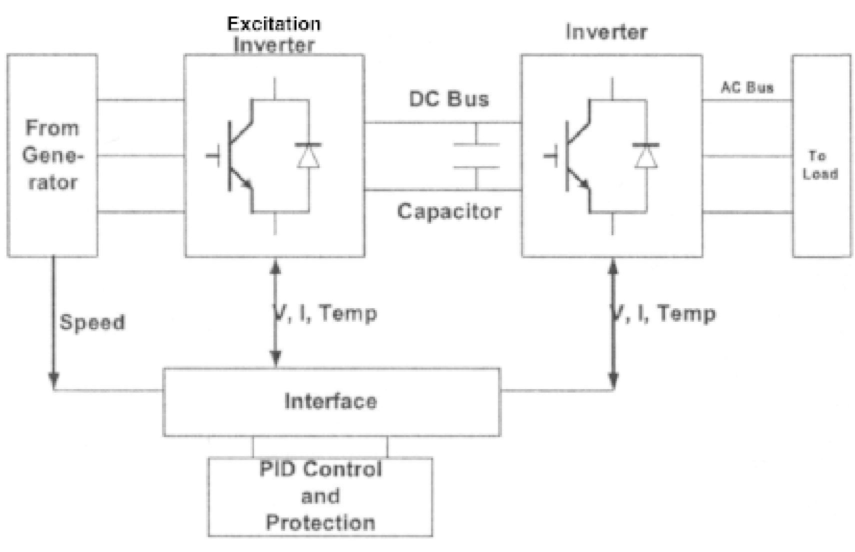


Figure 7. Controller Block Diagram

tor, the operating frequency is in the range of 1 kHz to 2 kHz at 60,000 rpm depending upon whether 2-pole or 4-pole generator design is selected.

iii) Power Section Sizing: In the case of the permanent magnet generators, due to the wide variation in the voltage output, complexities are introduced in the controller requiring voltage boost mechanisms. The power electronic components must function at high stress levels. In the switched reluctance generator controller, high rates of change of currents and voltages result in high stress levels for the power electronic devices. The induction generator has a well-regulated sinusoidal output that can be conditioned without using highly stressed electronic components. Overall it is believed that the controller for the induction generator is more robust, smaller in size, and costs less than the controller costs for permanent magnet or switched reluctance generators in the power range under consideration.

STATUS OF CURRENT TECHNOLOGY

Electrodynamics Associates, Inc. is currently developing a 125-200 kW induction generator to operate at 62,000 rpm on an SBIR contract from the Air Force Research Laboratory, Wright Patterson Air Force Base, Dayton, OH. The generator is air-cooled. Two identical machines are built to operate as a motor generator set. The generator and the motor are mounted on a base plate and coupled together. An optical speed counter is attached at one shaft extension. Figure 8 shows the photograph of this assembly.

Figure 8. Motor Generator Set Under Test

Controllers for both the generator and the motor have been developed for the test purposes. While the current design of the controller is PC based, next generation of the controller uses fast operating DSP. Figure 9 shows photographically the controller with the DSP module.

The generator and controller development program are scheduled for completion later in 2004. Development of the 200 kW generator and the controller is funded by Air Force Research Laboratory, Propulsion Division, at Wright Patterson Air Force Base in Ohio.

Figure 9. 200 kW Induction Generator Controller