Electric Generators for Direct Coupled High Speed Turbo Generators in Distributed Power Systems

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ABSTRACT

This article addresses various technical challenges in developing high speed, lightweight electric generators for applications in direct coupled high speed generators for distributed power systems. These challenges involve the technologies of electromagnetics, thermodynamics, rotor dynamics, and engineering assembly practices. How those challenges are being addressed and the results of activities to date relating to generators from several hundred kilowatts to a few megawatts will be discussed. Current status and the test data relating to these generators will be presented.

While the requirements of power and voltage levels as well as the duty cycle vary, the applicable generator technology is mainly impacted by the power level. The electric generator is typically driven by a high speed turbine. The operating speeds of the turbine and the mechanical and thermal interfaces with the generator have a substantial impact on the design details of the generator.

The best approach in interfacing the high speed turbine to the generator is to directly couple the two by means of a mechanical coupling and exclude the need for gear, belt or other mechanical transmission systems. The high speed turbine operates most efficiently at their rated speed, which varies with rated power output. Thus while a typical 200 kW turbine may operate at 60000 rpm, a MW class turbine may operate in the range of 15000 rpm to 30000 rpm. It is often details such as the coupling and mounting arrangement and the suitability of coolants and lubricants that affect the generator design and impact the weight and size of the final product. Selection of the appropriate generator technology is highly dependent on the operating speed requirements. Examples of specific power and speed ratings as well as suitability of generator technologies such as permanent magnet (PM), wound rotor synchronous, switched reluctance (SR) and induction will be discussed. Current development programs for 30 kW to 2.5 MW power generators will be presented.

HIGH SPEED GENERATOR SETS

Most commercial generator sets operate at speeds to 3,600 rpm and produce 60 Hz voltage output. Generators directly coupled to diesel engines are heavy and require large space and structures for installation. Especially for portable installations, and for installations in urban areas, smaller lightweight generator sets with generators coupled to high speed turbines are very attractive. Multi-fuel turbines are available for high speed operation for the power range from several kilowatts to multiple megawatts. When directly coupled to generators designed for high speed operation, a compact generator set with substantially reduced weight and size results. To provide commercial frequency of 60 Hz, an additional power electronic converter is needed. These are usually small and compact static units as well.

Power and Speed Range

In the 30 kW to 60 kW range of power, typical turbine speeds are in the range of 60,000 rpm to 120,000 rpm. In the 60 kW to 500 kW range, the turbine speeds are in the range of 30,000 to 60,000 rpm. In the 1 MW to 5 MW power range, the typical speeds are from 15,000 to 30,000 rpm. When selecting the generator speed, it is important to consider the speed capability of the available turbine for the given application.

Direct Coupling

The generator must be mounted to axially align the shaft center line with the corresponding center line of the turbine shaft. This allows the use of a flexible coupling or a quill shaft to drive the generator. The result is a compact generator set with no need for a gear-box, which tends to adversely affect reliability as well as cost.

FACTORS AFFECTING SELECTION OF GENERATOR TECHNOLOGIES

Several types of generator configurations are in use for generators. Judicious selection of the most suitable technology for a given application ensures that the end product is cost effective, efficient, and reliable. These generator technologies are: brushless synchronous with wound rotor, permanent magnet, induction, switched reluctance, and homopolar. There are sub-classes of these configurations that will not be considered at this time. Specific issues that affect the selection of the generator configuration relate mainly to the interfaces with the turbine as well as certain other specific needs for a given installation. These issues are discussed in the following paragraphs.

Operating Speed

Operating speed affects the structural design of the generator rotating components and is the foremost consideration for selection of the generator configuration. In configurations with rotating components such as electrical windings, connections, insulation, and/or semiconductors, high speed operation beyond certain limits may not be feasible.

Power Rating

This goes hand in hand with operating speed. Electrical machines are "torque generators" and therefore, the size of the rotor and the stator is a function of the ratio of power to speed. Thus, the rotor diameter would typically increase as a function of this ratio. The larger the diameter, the more difficult it is for the rotating electrical components to sustain the centrifugal loads at high speed.

Heat Removal

Depending on the generator configuration and design, heat is produced in the stationary and rotating components. This heat must be removed by a cooling system using air, fuel, lubricant oil, water, or other coolant. Out of these coolants, air is the least effective in removing heat. In case of the high speed generators, the total mass of the generator is small by design. Thus, the cooling system has to be efficient and effective in removing the heat. Liquid cooling is a better option, and the selection of the coolant will have an impact on the generator configuration design.

Performance

Basic performance requirements include steady state voltage regulation, and efficiency. Transient operation with loads such as motor starting, which require power surges of short duration, and unbalanced loads are other types of requirements that are also important.

Electric Start

Certain applications, especially in the lower power range will require an electric start function to be incorporated in the generator itself. This helps reduce the overall size and cost of the generator system. Requirement of electric start will affect the selection of the generator configuration.

Protective Functions

Typical protective functions for electric power systems are over-voltage, under-voltage, short circuit or over current. In addition to protecting the external circuit with the use of protective devices, the generator configuration itself must be protected and should not cause hazards. This issue is discussed in later paragraphs.

Isolated Operation or Connected to Grid

While operation in isolation is feasible in all the configurations listed, operation in electric grid may impose additional constraints that may have to be carefully analyzed. For isolated operation, the self starting function may impose additional design requirements.

Operating Environment

This includes operating ambient temperatures, and other atmospheric conditions such as altitude, humidity and others. Whether the application is for airborne, marine or land based system will have additional impact on selection of the generator configuration.

GENERATOR TECHNOLOGIES

Before discussing the applicability of various generator technologies for specific applications, a brief review of these technologies is appropriate.

Brushless Synchronous with Wound Rotor

These are two stage machines where each of the two machines operates as a wound field synchronous generator. The first stage is the exciter stage, with a stationary field and rotating armature. The second stage is the main or output stage with a rotating field and stationary armature. The power produced by the exciter armature is rectified and supplied to the rotating main field. The power output is received at the stationary main armature, thus making it a brushless machine. Figure 1 illustrates the generator schematically. Note that the rotating components are shown in dark grey, and the stationary components are shown in light grey.

It may be observed that the wound field generator has two rotating windings, one set of rotating rectifiers, and several rotating connections. The output voltage is easily controlled by adjusting the dc current input to the exciter field winding. Because of the two stage operation, the excitation power is a small fraction of the output power. The output voltage for a high speed generator is well regulated sine wave of high frequency in three phase format for easy step up transformation and/or rectification. The voltage regulator size is small.

Permanent Magnet (PM)

Permanent magnets provide excitation power for this type of synchronous machine. Permanent magnets are located in the rotor, and the armature is stationary. The power is produced in one stage. Figure 2 illustrates the PM generator schematically.

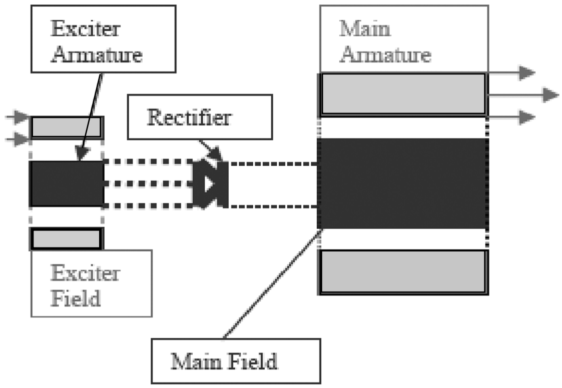

Figure 1. Brushless Synchronous Generator

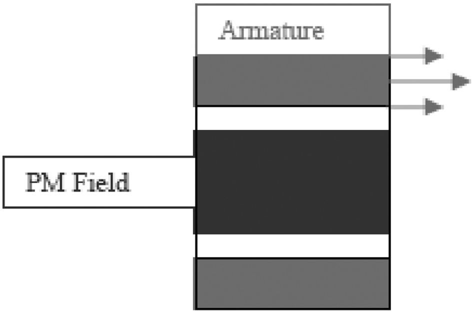

Figure 2. PM Generator Schematic

The PM generator is not complex in structure. However, the voltage generated is unregulated and the external controller must process the total power and provide regulated voltage output at the desired level. This implies a large and expensive controller. The generator can not be de-excited in case of internal fault and must be brought to low speed quickly in case of internal failure to prevent hazardous operation.

Induction

The induction generator relies on asynchronous operation of the generator, where the stationary armature currents are switched at an electrical frequency that produces a rotating magnetic field, which rotates at a speed somewhat lower than the rotational speed of the rotating field. This allows the field winding to extract the required excitation power from the stationary armature by magnetic induction. The rotating field winding is a short-circuited set of conductive bars that are not insulated and are solidly located in the rotor. This is often referred to as "squirrel cage" winding. Figure 3 illustrates the induction generator schematically.

The induction generator produces well regulated sine wave voltage. However, the regulation is accomplished by processing the power through a controller, and the controller is relatively large. The rotor construction is solid, and there are no rotating components that are particularly affected by high speed operation. The output voltage at high frequency can be easily stepped up if required.

Switched Reluctance (SR)

There is only one winding located in the stator for this type of

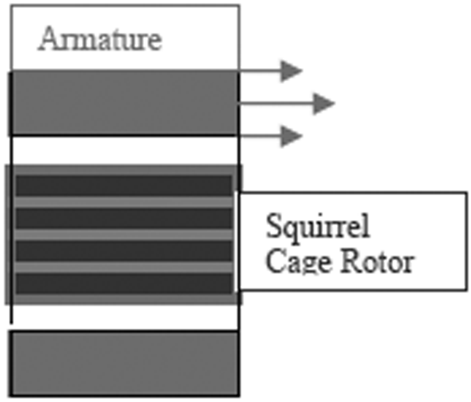

Figure 3. Induction Generator

generator. The rotor is built of magnetic iron only and is robust. Excitation is developed through creation of a varying magnetic field using variable air gap geometry. Thus, the stator and rotor have an unequal number of salient poles that produce the variations in the magnetic field observed by the armature winding. These variations in the magnetic field are not sinusoidal, nor bi-directional. The resulting voltage is non-sinusoidal and requires filtering to produce dc voltage output. Figure 4 illustrates the SR generator cross-section showing the saliency of the magnetic field.

The armature windings of the SR generator armature are concentrically located on the stator poles and are isolated from one another. This allows physical and magnetic separation of windings, which is often used effectively to provide redundancy. The controller must precisely switch the armature coils depending on the relative position of the rotor. A typical SR

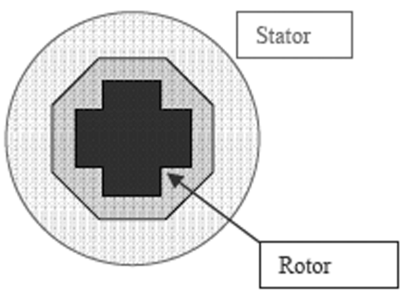

Figure 4. SR Generator

generator operates at high frequency magnetic fields causing large power losses in the magnetic cores when operated at high speeds.

Homopolar Family

Homopolar family of generator configurations allows the field windings to be made stationary with respect to the rotating magnetic field created by specific rotor construction. This allows the rotor to be constructed without windings, while the field winding excitation can be adjusted so that a well regulated three phase sinusoidal voltage is generated in the stationary armature. High speed of operation is feasible. Thus, the out power of high frequency can be easily stepped up to higher levels. The magnetic geometry has to provide complex flux paths resulting in large size. This is particularly true as the power rating is increased, and becomes impractical for large power applications. Figure 5 illustrates one type of machine named "Rice," after the inventor. Magnetic structure to support the flux path is shown as the outer light gray areas.

TECHNOLOGY COMPARISON

Various technologies are compared for operation under various criteria described earlier. It is clear from the discussion that the brushless generator with wound rotor is generally the prime choice as long as certain conditions and constraints are satisfied. This is true because it provides well regulated sine wave voltage and requires a relatively simple

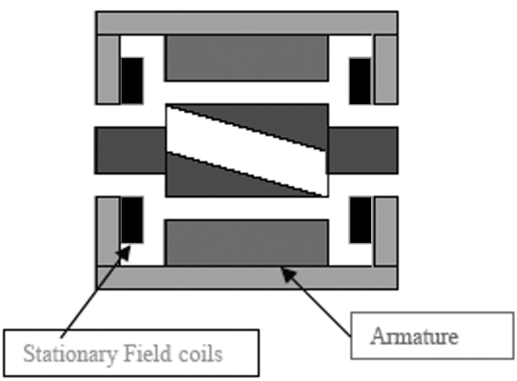

Figure 5. Rice Generator Schematic

and small controller. However, the constraints in high speed generator systems may very well require that other configurations serve better.

High Speed Operation

Brushless generators with wound rotors have proved their capabilities to operate to speeds up to 30,000 rpm with excellent reliability. Beyond this speed, or especially beyond 40,000 rpm, other options must be considered. PM generators require containment of the permanent magnets, which have negligible structural strength. The size of containment ring in the radial direction requires further increases in the size of the permanent magnet itself, thus making it difficult to design the rotor structures for high speed operation. Other generator configurations are well suited for the high speed operation.

Power Rating Constraints

For power ratings over 80 kW or so, the homopolar configuration becomes difficult to implement especially at high speeds. On the other hand, for ratings below 80 kW, and at high speeds, PM generators may be a good choice because of their simplicity of construction, and because their available voltage regulation may be acceptable.

Heat Removal from Rotor

In the brushless generators with wound rotors, the heat generated in the rotating windings and rectifiers must be efficiently removed. Typically this is accomplished by use of coolant oil flowing at a high rate of flow. In ratings beyond a few hundred kW, air cooling of the rotor for such machines becomes impractical. In induction generator rotors, some heat is generated in the rotor cage. It is relatively easier to remove this heat from un-insulated conductors. In SR generators, substantial heat is generated especially at high operating speeds and this can be a problem. On the other hand, the PM generator has very little heat produced in the rotor because of the secondary heat sources. Here the heat can be removed easily by air flow. Also the homopolar machine has very little heat generated in the rotating components.

Performance Parameters

It is often thought that the PM generator is most efficient because no excitation power is needed. This may not be true in most cases, where the power required from the generator varies from the peak or the optimum rated power. Brushless generators with wound rotors or the homopolar generators are perhaps the best choices for high operating efficiency, low EMI and filtering issues, and good voltage regulation under steady state and transient load conditions.

Electric Start Function

Certain applications require that the generator provide the starting torque for the prime mover that is rated for much greater capacity than the generator itself. This is true in the case of vehicles that use the propulsion engine to drive the generator as well. In this case, if the starting current requirement is near the rating of the generator output, then the solid state controller must be rated at the full power level. The same controller then can be used during the generate mode to process the power output. In this case, the choice is thrown wide open, and all the generator configurations must be considered. In fact, the brushless generator with wound rotor is not capable of providing large torque because of the limited rating of the exciter.

Equipment Protection

The PM generator can not be turned off. This causes hazardous situations if the generator system is located near working areas. Even otherwise, the hazard from the generator can affect the associated components including the prime mover and the controller.

Isolated Operation

All generator configurations except the PM generator need an excitation source to get started. This can be provided by a small battery or by a small PM generator located in line with the other generator.

Extreme Operating Environment

PM generators are susceptible to high temperatures. Although permanent magnets operating at 350 degree Celsius are available, there is a substantial deterioration in their performance at high temperatures. The SR generator is perhaps the most robust because its rotor contains no current carrying circuits.

APPLICATIONS

The following generator products developed by Electrodynamics illustrate how the principles described above are implemented for specific applications.

2.5 MW 15,000 RPM GENERATOR

A number of multi-fuel turbines are available as prime movers for this rating. The generator configuration is a brushless synchronous machine with wound rotor. Figure 6 shows the generator dimensions. The weight of the generator is set at 360 lb. An additional cooling system weighs about 70 lb. Excitation power is 6 kW, which is relatively small. Hybrid bearings are lubricated with the same oil as the coolant itself. The generator design is scalable from 1 MW to 5 MW using mostly identical or similar components.

It is anticipated that the complete generator set with the prime mover, cooling system and the controller to provide 3-phase, 60-Hz power will weigh less than 2000 lb. This generator can ideally provide electric power for 2,000 homes and can be used in co-generation, for distributed power systems, or in situations where power is needed for immediate use with little or no infrastructure, and in case of natural or other disasters.

200 kW 60,000 RPM GENERATOR

For the application of 150 kW to 300 kW with a turbine speed range of 40,000 rpm to 70,000 rpm, an induction generator configura-

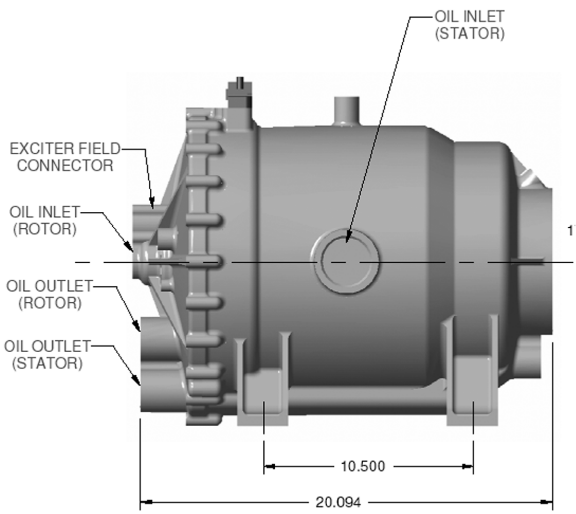

Figure 6. 2.5 MW Generator Dimensions

tion is selected. Figure 7 shows the generator picture. The weight of the generator is 55 lb. It is about 7.5 inch in diameter and 10 inch long. The stator is cooled with water or oil, whereas the rotor may be cooled with air or fluid. Hybrid bearings are damped with squeezed film. The generator can provide starting torque. The generator design is scalable from 100 kW to 300 kW using identical or similar components.

30 KW AND 5 KW 60000 RPM GENERATORS

These generators are designed to start large propulsion engines and to operate under a high temperature environment of 400 degree F inside the prime mover cavity so that they can be integrated closely with the prime mover.

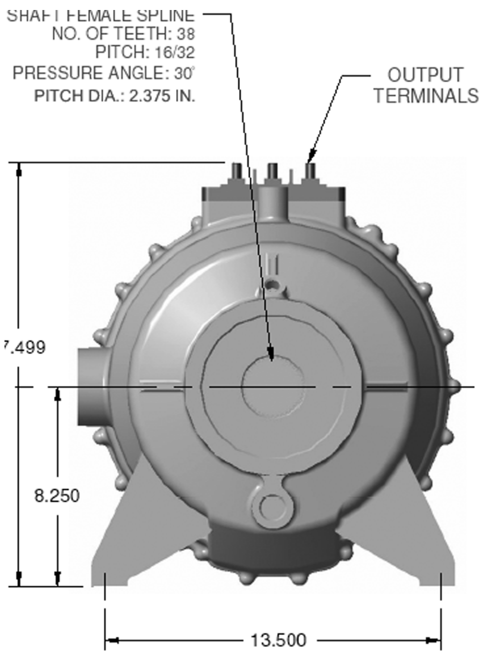

Figure 7. 200 kW Generator

SUMMARY AND CONCLUSIONS

In this article, generator technologies for high speed generators in distributed power systems, for co-generation, and for emergency power applications are discussed. A comparison is made to provide relative merits of available generator configurations. Finally examples of generators from 5 kW to 5 MW ratings are described. Following conclusions are made:

1. A number of generator configurations are available for high speed direct coupled generator sets.

2. A careful selection of generator configuration must be made depending on the application characteristics such as operating speed, performance requirements, cooling system availability, and environment.

3. High speed direct coupled generator sets are light in weight and are most suited for applications in distributed power systems, for co-generation, and for emergency power requirements.

ABOUT THE AUTHOR

Jay Vaidya is the founder, president and the principal engineer of Electrodynamics Associates, Inc. In addition, Jay was named Entrepreneur of the Year by the Orlando section of IEEE. Jay holds BSEE, DIISc, and MSEE degrees with specialization in Electric Machinery and Controls. He has designed several generators and motors for automotive, aerospace and industrial applications as a consultant to various companies. Jay Vaidya has over 45 years of experience in development of electric machines and controllers for commercial, aerospace, and military applications. He holds 8 patents and has published 15 technical papers. Jay may be reached by e-mail at jayvaidya@ieee.org.