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Electrical Power Generator Design: A Review

Awarun OA[1] and Aziaka DS[1,2*]

[1]*Department of Power and Propulsion, Cranfield University, Cranfield Bedfordshire MK43 0AL, UK*

[2]*Center for Multidisciplinary Research and Innovation, Africa*

[*]Corresponding author
Aziaka DS, Department of Power and Propulsion, Cranfield University, Cranfield Bedfordshire MK43 0AL, UK and Center for Multidisciplinary Research and Innovation, Africa.

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ABSTRACT
Generators are the heart of electric power production. A well-designed generator ensures contin-uous, stable, and reliable power output, including reliability of power utilization. This paper pro-vides an over view of the design and selection techniques of an electrical power generator pow-ered by a heavy industrial gas turbine engine. Extensive analysis is emphasized with a view on the general design theories in existence and also the types of generators that have been used in past years. Synchronization of the electrical generator with the prime mover are of different kinds depending on the power requirement and purpose, this is a major design focus and is duly ana-lyzed in this paper. This design specifically provides for a power plant that has a synchronized 100MW gas turbine engine and a 100MW generator that would be running on base load hence the requirement of the generator to match the power delivered by the prime mover as well as the necessary parts and systems that must be in place for the proper operation are provided. This pa-per provides design techniques used with the gas turbine background

Keywords: Gas turbine; Synchronize; Electrical Generator

Abbreviations

AC	:	Alternating Current
DC	:	Direct Current
RPM	:	Revolutions Per Minute
IGT	:	Industrial Gas Turbine
CACA	:	Closed Air Circuit Air-Cooled
CACW	:	Closed Air Circuit Water Cooled
OAC	:	Open Air Cooled
VRS	:	Voltage Regulator System
MW	:	Mega Watts
NEMA	:	National Electrical Manufacturers

Introduction

Electricity unlike other sources of energy is a secondary source of energy this means there must be a primary source of energy such as fossil fuels and also machines that converts this chemical energy found in these fuels to mechanical energy which is then converted to electrical energy by another device called a generator. The electrical generator is a machine, which converts mechani-cal power into electrical or power. Energy conversion is based on the principal of the production of dynamically induced electromagnetic force in the force field making the conductor and the magnetic field the most important parts in topic. The heavy-duty electrical power generators are powered by different heavy-duty machines called prime movers, and one of such prime movers is the industrial gas turbine engine which works on the principle of converting chemical energy found in these fuels into mechanical shaft power in this case, a 100MW gas turbine is designed and would in turn power a 100MW generator [1].

The torque produced drives the generator which converts the mechanical energy to electrical en-ergy. Electrical generators can be classified on bases of load delivery. The electrical generator in view delivers base load.

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Principles of Electrical Generation

Electromagnetic Induction

In 1831, Michael faraday discovered that if a conductor is moved across a magnetic field an electrical voltage is induced on the conductor. An alternating current (AC) takes advantage of this principle [2]. The magnitude of this generated voltage is directly proportional to the rate at which the conductor crosses the magnetic field; this is known as the magnetic flux density as well as the length of the Conductor [1].

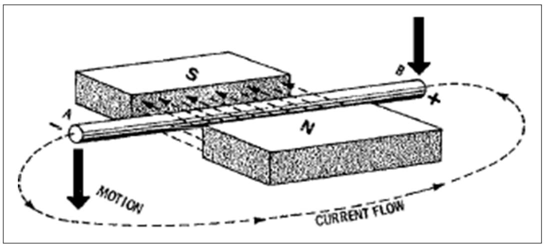

Figure 1: Induction of voltage in a conductor

Therefore, the three elements necessary to voltage production includes;

- Magnetic field
- A conductor
- Relative motion between the field and conductor Mathematically,

Induced voltage = Velocity x flux density x length

Alternating Current

The above equation shows that the magnitude of this voltage depends on the strength of the magnetic field created and the velocity at which the conductor crosses through the path of the magnetic field, more so, in a case of a shaft/rotor driven by a gas turbine which rotates about its central axis, one side of the loop will pass through the magnetic field in opposite direction to the other side of the loop as seen in A in Figure 2, this is seen as both sides of the loop moving in parallel to the field hence a zero voltage is produced since it cuts no line of force.

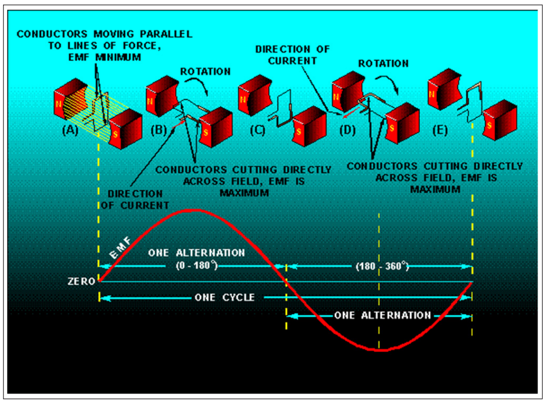

Figure 2: Alternating-current generator

Further rotation of the shaft at B means the conductor cuts through more lines of force per sec-ond therefore it brings about the passage of the loop further through the magnetic field till it gets to a right-angle interception (900 quarter of a revolution) which is enough to induce voltage as it cuts directly across the field. The first half revolution brings about positive voltage and the other half built towards the negative direction, hence it is said to be alternated [2].

Alternating action of a 100MW Generator

The voltage polarity (positive and negative) alternates when current is passed across the loops as the field is seen to exert torque on these loops which tends to rotate a shaft at a certain torque and speed. This must be matched with the gas turbine generator which acts as a prime mover to the Electrical Generator.

Voltage at load = Velocity (RPM of shaft of gas turbine) x Magnetic flux density x Length of conductor.

From the alternating current description above, the length of conductor which is twice the length of one side of the rotor multiplied by number of turns. The RPM which is fixed at 3000 leaves the excitation voltage as the only variable.

Electrical Energy Generation

Electrical energy generation involves the conversion of other kinds of energy into Electrical en-ergy. It can be said to be a secondary source of energy. Electrical generation in the context of this paper is primarily generated from chemical energy converted to mechanical energy in a 100MW gas turbine engine. This can be described simply as a Thermal Power plant comprising the gas turbine engine and the synchronized Electrical power Generator. Other means of electrical gen-eration are described below [1].

Hydro Power plant

This converts mechanical from water into electrical energy using the gravitational force of falling water. It is one of the cheapest ways to produce electricity.

Fuel Cell

Converts the chemical energy found in oxygen generation-controlled reaction directly into elec-tricity.

Nuclear Power Plant

Converts nuclear energy released by nuclear fuel into electrical energy with a reactor furnace us-ing uranium as fuel.

Fossil-fuel Power Plant

This involves the chemical conversion of chemical energy found in fossil fuels into electrical en-ergy, fuels such as oil and natural gas is used to drive a gas turbine. They are referred to as Ther-mal Power plants.

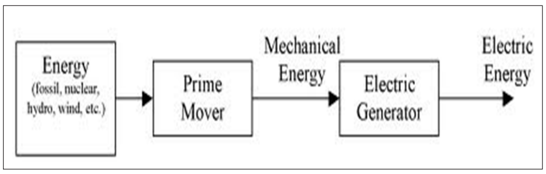

Figure 3: Energy conversions in a thermal plant

The process of electricity production involves several stages and energy conversions; in this in-stance a fossil fuel is burned in a gas turbine generator which is the primary source of energy and a prime mover of the Electrical power generator. Chemical energy is converted to mechanical en-ergy which powers the generator.

Gas Turbine Generator

The gas turbine of today is popular source of providing prime movers for the power generation, oil and gases, and other similar industries. As years past, the advantages of the gas turbine, in terms of capacity, flexibility of operation can be said to have outweighed its disadvantages of high component costs and maintenance cost. The electrical power generator is dependent on the size and overall characteristics of the prime mover (Gas turbine) and its associated accessories. These gas turbines vary in sizes ranging from 10MW to as high as 300MW used for electrical Power Generation. Depending on the capacity, these gas turbines will range from high speed to low speeds as low as 3000RPM or geared high speed turbine to reduce the speed to that com-pactable with the electrical generator.

Direct Drive vs. Mechanical Drive

The direct drive consideration involves the gas turbine generator turning the turbine shaft at the electrical generators design speed. This is usually used for base load conditions.

In events where large pumps, air compressors and other variable speed loads are driven by gas turbines, different power variations occur at quick intervals therefore resulting in variable speeds. This requires special governing equipment's to give best balance between the turbines which is the driver and the driven machine which is the generator.

Turbine Generator Features and Accessories

Gas turbine generator when supplied by the manufacturer comes with some basic accessories based on its intended purpose. Some of these accessories are important in order to be synchro-nized properly to the generator. This includes;

- Generator with cooling system, excitation and voltage regulator, couplings and speed reduc-tion gear where necessary
- Turbine and Generator gear lubrication system including tanks, pumps and piping
- Load and speed governors
- Rigid base plates, jacketing, insulation and mountings.

Gas Turbine Arrangement

The turbine generator in view here consists of a horizontal shaft with horizontally split casing. The turbine rotor shaft is supported with a sleeve type and self-aligning bearing. The outpour shaft consists of a mechanical safety coupling device which is coupled to the shaft of the gener-ator in cases of reversal current or torque differentials. The shaft is a cold end mount having a direct drive with the generator. A recuperator is also connected for power augmentation.

Balance

The turbine, couplings and generators rotating parts integration and balance design is very im-portant as it brings about freedom from torsion and lateral vibrations as well as expansion dam-age during operation.

Foundation

Pedestals for the turbine and electrical generator must be carefully designed to accommodate, insulate and protect the machines. Also, the vibration characteristics of both machines cannot be overemphasized.

Governing and Controls

Turbine Generator Speed/Load Control

The electrical generator and its driving gas turbine are synchronized hence the electrical genera-tors output can be said to be in form of a synchronized AC electrical power which causes both machines to rotate at similar speeds or frequency. The speed and frequency of the generator and turbine is 3000RPM and 50 Hz respectively.

The speed/load governing equipment is designed to give allowance for each individual unit to hold its individual load steady and at constant frequency or to accept its share of variations of load in this instances variation in frequency. Heavy units such as the 100mw generators will use either the mechanical systems or electro-hydraulic system.

Over Speed Governors

This is referred to as an emergency governor which prevents over speeding of the shaft/rotor. This safety governing system is specially designed with a mechanism which signals various safety de-vices if the shaft speed exceeds the safe speed for the generator. This can be done either by sig-naling a reduction in fuel flow or use of bleeds.

Turning Gear

Heavy duty turbine generators consist of a motor and various timing gears which is mounted at the exhaust end of the turbines with its controls for slow starting and deceleration at sufficient low speeds which provides uniform and steady cooling.

Lubrication System

The turbine generator and the driven electrical generator requires adequate lubricating, these in-clude; pressurization, filtration, oil cooling and a backup lubrication.

Instrument and Special Controls

The gas turbine generator is equipped with appropriate instrumentation and signals to monitor the operating conditions of the synchronized parts including speeds, vibration, rotor expansions as well as the hydraulic system.

Electrical Generator

Evolution of Design Technology

The commercial birth of synchronous generators also known as alternators can be dated as far back as 1891, during which the pioneering demonstration and transmission of AC power was performed. This was done within Germany. This development triggered the inception of the Ni-agara Falls power plant in Newyork by 1895. It can be noted that amongst the various develop-ment and technology in power generation over this 100 years period the basic constituents of the machine have remained unchanged [2].

Working Theory

Referring to Faradays law, a conductor cutting across the magnetic field lines induces a voltage, the closing of this circuit brings about the flow of electric current but the induced current also produces a force acting on the conductor, Lenz's law states that 'Electromagnetic induced cur-rents and forces will try to cancel the originating cause'' in other words, it would reduce the magnetic field strength and act opposite the conductor in its original direction. This can be seen to manifest in the case of a loaded generator [2]. It would be noticed that more current would flow in its windings as it cuts through the magnetic field and more force is required from the driving turbine generator to counteract the induced larger forces by simply supplying larger loads, therefore there is an increase in current supply of a motor as its load increases [2].

The electrical power generator is therefore an electromagnetic device that converts mechanical energy which is supplied in a gas turbine in form of rotational speed and torque in to electrical energy (voltage and current).

Types of Generators

Generators can generally be grouped under the type of current it delivers such as Direct and in-direct currents. They are also grouped based on the matching of the prime mover and the electri-cal power generator such as the asynchronous generator and synchronous generator.

Asynchronous Generators

These are also called induction generators, they run either as a motor below the synchronous speed of the motor or above the speed of the electrical generator. This type of generators must be connected to the grid through an expensive capacitor excitation system; they also suffer from lack of precise controls due to different speeds. It is mainly used in wind mills and small hydro power generators.

AC Synchronous Generator

When an alternating current generator operates at a speed exactly proportional to the frequency of the output voltage it is said to be a synchronous generator

$$\text{Speed of Generator (rpm)} = \frac{F \times 120}{N\,(Number\ of\ Poles)}$$

A speed reduction gear is required if the generator speed required is below 3000rpm offered by the gas turbine. A major advantage is the ability to run alone and its widely used for gas turbine generators.

Components of Electrical Generator

The electrical power generator consists of various systems and parts which are linked and helps in its.

- Operation Stator: This is the stationary part of the generator which contains a winding called the amarteur winding
- Rotor: This is the rotational part of the generator which drives its speed and torque from the shaft of the gas turbine
- Excitation System: This consist of an exciter. In order for the rotating magnetic field to be created, a direct current voltage is applied to the rotor.
- Jackling system: This consists of a lift pump which is used on the rotor shaft before start up or shut down to provide even cooling of the shaft as this prevents the sagging and bowing of the shaft due to thermal stress
- Support System: These systems perform system functions such as regulating the voltage of the produced electrical energy to matching values which matches the system in which it is being utilized with. They also control relative sharing of loads when the generator is connected to the utility grids and also in the synchronization of the generator with other power sources

Generator Construction

Rotor

The rotating part of the magnetic field located on the shaft. It is usually manufactured from forged steel and supported at each end by sleeve bearings which are lubricated by the lubrication system. The oil film helps give it a safe life design as the shafts easily rotates over an oil film eliminating friction. The exciter, diode assembly are also mounted on the shaft.

Rotor windings

The Exciter which is located on the shaft along with the diode's rectifier generates the required fields. The rotor fields is given low power in form of D.C from the exciter as the field is located on a rotating member relative to the stator.

Stator

The field where the electricity is generated are embedded around the generator casing which has an advantage of easy connection to external loads. The casing is known as the stator. The stator core is made from insulated steel laminates and coated with heat resistant vanishes, where the thickness and material is chosen to minimize electrical losses and provide insulation and vibration thereby increasing efficiency.

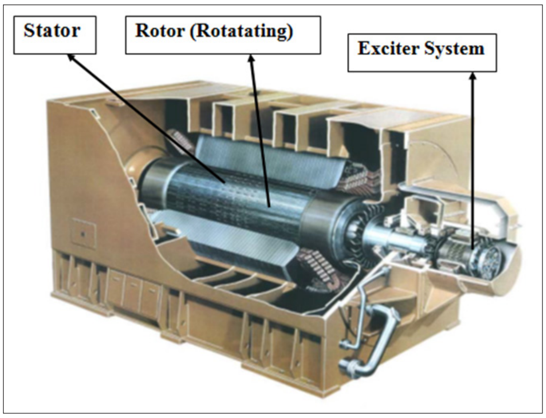

Figure 4: Major Components of a generator

Stator windings

The magnitude of the induced voltage in the stator winding is proportional to the magnetic flux density, the number of turns in the stator windings and the speed of the rotor. The goal is to achieve three balanced and sinusoidal voltages discussed below.

Bearings

Due to the size and duty requirements, anti-friction and sleeve bearings are usually used on ro-tating machinery of this sort. They are either lubricated by oil lubrication or force fed due to the high temperatures. A fail-safe design consisting of a lead-based Babbitt material is used just in case of a bearing failure, the surface fails before the delicate shaft. Insulation of some bearings is done to reduce pitting and deterioration of oil due to presence of electric current flow across the bearings.

Cooling

The high operating temperatures is very limiting on the performance of a generator of this capac-ity as the insulating and materials would fail if their operational temperatures are exceeded [1].

Closed Air Circuit Air-Cooled

This consists of dual cooling circuits. the internal air cooling as one circuit which is circulated through the windings and then passed through a heat exchanger which is cooled by the second circuit of external air forced though the electric motor driven fan, these are used mostly in marine applications.

Closed Air Circuit Water Cooled

Similar to the CACA except that the external cooling is done by water instead of air. This is suitable for installation where a chilled supply of demonized water is available for cooling. This method of cooling is more efficient but gives a bulky system [1].

Open Air Cooled

The filter ventilated inlet with open outlet type ventilation system is widely used. Fans on the ends of the rotor pull in air through a vent which passes over the winding and exits through the vent located at the top. this is mostly used for indoor installations [3].

Voltage Regulator System

This system maintains the generator output voltage against the rated voltage. The automatic voltage regulator is part of the control system which provides sensors from a transformer and the excitation supply fed from the generator to the primary magnet generator. With the excitation current being the main concern, the voltage regulator must know the value of the generators out-put voltage, this is then matched with a reference datum voltage, if it signals the voltage as low, the voltage regulator in turn increase the excitation current until it matches the reference voltage and vice versa [4].

Synchronization

Tesla's induction motor replaced the synchronous motor as the choice of most motor applications although synchronous generators have remained the universal choice for power generation [2].

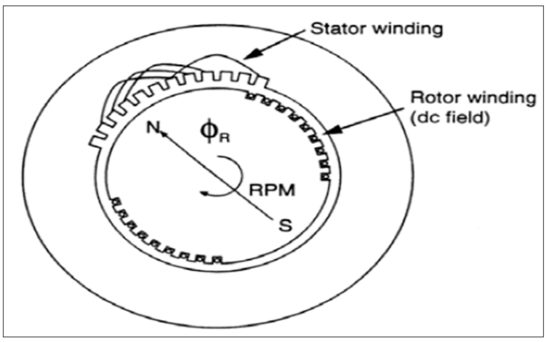

Figure 5: Stator and rotor windings are installed in slots [2]

This paper focuses on large turbine-driven generators of about 100mw and the typical arrange-ment used is the rotating magnetic field. The revolving-field also known as the rotating magnetic field synchronous machine has the field-winding wound on the surface of the rotor, however it has an amateur which is wound around the stator. A direct current which creates the magnetic flux and at synchronous speeds energizes the rotating field windings [2]. The stator made of steel laminations is mounted directly through spring bars into the frame, the core have slots created in them where the windings are placed. The rotor field in this case is of a non-salent construction also known as the cylindrical rotor usually utilized in large two poles machines. They are made by forging of steel [2]. The windings however are placed in slots and maintained against the signifi-cantly large forces (centrifugal) by metallic wedges usually made of steel.

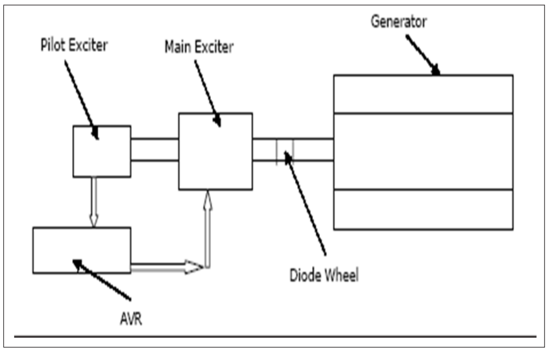

Figure 6: Exciter and Voltage regulator arrangement

Generation Efficiency

The efficiency η gen of the electromechanical conversion in the generator is given by

$$\eta\ gen = \frac{Power\,output\,at\,ter\min als}{Power\,input\,to\,shaft\,at\,coupling}$$

Design Methodology [5]

The usual design trend described here is the steps required to obtain the requirement parameters used in d construction and design of the various generator parts.

Equivalent Torque obtained based on the speed and power out of the Gas turbine

$$Teq = \frac{P}{2\pi\left(\frac{N}{60}\right)}$$

Where P = 100mw, N= Speed =3000RPM, therefore Teq = 265KN

Outer diameter of stator (Do)

Do=(Fs-3)- 2

Where Fs = frame size which is selected from the NE-MA standards

Frequency and pole number

$$RPM = \frac{F \times 120}{N}$$

where F is the frequency of the generator = 50HZ and N =2

Determination of the stator pole area 'As', the angle of stator and rotor angles are used. L is the estimated stack size of the generator, Bs is the flux density se-lected from the breath – height curve of the used mate-rial. [8]

$$As = \frac{D0}{2} \times L \times BS$$

Estimated stator pole flux (QS) given by

Qs=Bs x As

Stator pole height (hs) can also be estimated and given by

$$hs = \frac{Do}{2} - C - \frac{Do}{2}$$

Where C is the back iron thickness which is given by

$$C = \frac{As}{L}$$

Rotor Pole area (Ar)

$$Ar = \left(\frac{D}{2} - g\right) L \times Br$$

Where Br is the rotor pole arc angle selected from standards, g is the air gap length [9]

Area of rotor core (Arc) is given by

$$Arc = L \times \left[\frac{D}{2} - g - hr - \frac{Dsh}{2}\right]$$

where Dsh is the shaft diameter and hr the height of rotor pole

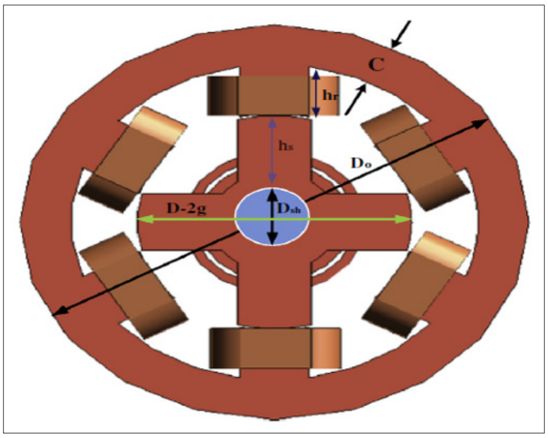

Figure 6: Calculated rotor and stator parameters [4]

General Turbine Generator Specification

The combination of the power generator and 100MW gas turbine generator that would drive the power generator (prime mover) is the thermal power plant and the final specification given below [8,9].

Gas Turbine

Industrial single shaft cold end drive, Supper cycle with recuperator efficiency: 40.4%

- **16 stage Axial Compressors**

Pressure ratio: 12:1, Inlet mass flow: 310kg/s horizontally split casing

- **Combustor**

10 can-annular combustors, Dry low Nox reverse flow combustion system, Dual fuel injection system

- **Fuel system**

Natural gas, diesel

- **Turbine**

3000RPM, Frequency 50 Hz

- **Bearings**

Journal bearing thrust bearing

Generator

- 2-pole, non-salent type, synchronous with permanent magnet rotor exciter, 50Hz, 3000rpm rotor speed
- Base load, constant speed delivery
- Open air cooled, closed air circuit air-cooled system construction
- Sleeve bearings, vibration monitoring synchronized system [10,11].

Conclusion

A complete design analysis required by an electrical power generator that would be attached to a heavy industrial gas turbine engine has been carried out. The different types of techniques and systems used by other existing generators are described and the most suitable design with refer-ence to the prime mover analyzed and shown.

With the ever-increasing demand for energy to meet every growing world population and the need for reliability and availability favors the heavy-duty gas generator designs and construction.

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