

# Generator & Exciter Basics

## Whitby Hydro Energy Services Corporation: Engineering & Construction Services

The relationship between magnetism and electrical current was discovered and documented by Oersted in 1819. He found that if an electric current was caused to flow through a conductor that a magnetic field was produced around that conductor.

In 1831, Michael Faraday discovered that if a conductor is moved through a magnetic field, an electrical voltage is induced in the conductor.

The magnitude of this generated voltage is directly proportional to the strength of the magnetic field and

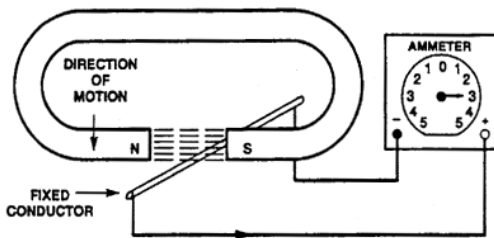
the rate at which the conductor crosses the magnetic field. The induced voltage has a polarity that will oppose the change causing the induction – Lenz’s law.

This natural phenomenon is known as Generator Action and is described today by Faraday’s Law of Electro Magnetic Induction:  $(V_{ind} = \Delta\Phi/\Delta t)$ , where  $V_{ind}$  = induced voltage,  $\Delta\Phi$  = change in flux density,  $\Delta t$  = change in time

All rotary generators built today use the basic principles of Generator Action.

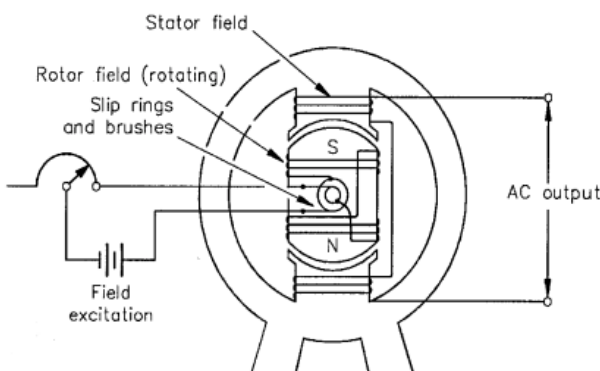
## GENERATOR ACTIONS

### THE PHYSICS OF GENERATOR ACTION



A VOLTAGE IS INDUCED IN THE STATIONARY CONDUCTOR WHEN THE MAGNETIC FIELD MOVES ACROSS IT. REVERSING THE DIRECTION OF MOVEMENT OF THE MAGNETIC FIELD WILL CAUSE THE DIRECTION OF THE INDUCED VOLTAGE AND RESULTING CURRENT FLOW TO REVERSE.

### THE BASIC GENERATOR



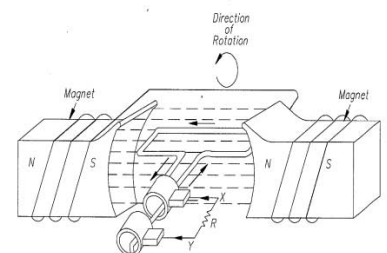
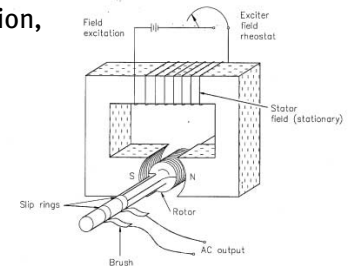
### THE ELEMENTARY AC GENERATOR

The elementary ac generator consists of a conductor (or loop of wire) in a magnetic field (usually produced by an electromagnet). The two ends of the loop are connected to slip rings and they are in contact with two brushes.

When the loop rotates it cuts magnetic lines of force, first in one direction and then the other.

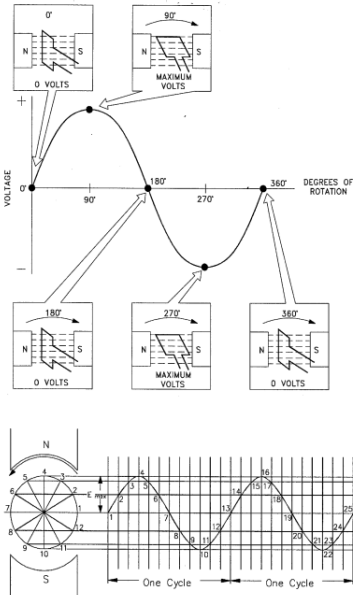
In the first half turn of rotation, a positive current is produced and in the second half of rotation produces a negative current.

This completes one cycle of ac generation.



## DEVELOPMENT OF THE SINE WAVE

At the instant the loop is in the vertical position, the loop sides are moving parallel to the field and do not cut magnetic lines of force.



In this instant, there is no voltage induced in the loop. As the loop rotates, sides will cut the magnetic lines of force inducing voltage in the loop.

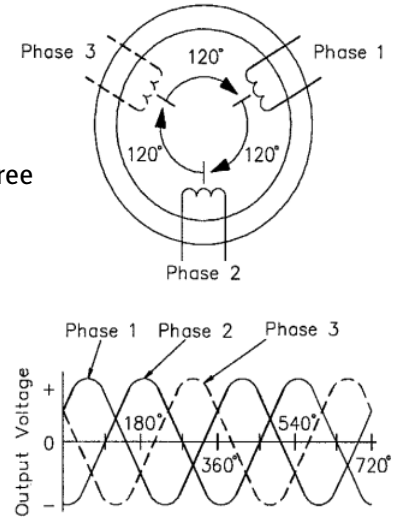
When the loop is in the horizontal position, maximum voltage is induced. The rotation of the coil through 360 degrees results in an ac sine wave output

## THREE PHASE VOLTAGE

Three phase voltage is developed using the same principles as the development of single phase voltage.

Three (3) coils are required positioned 120 electrical degrees apart.

A rotating magnetic field induces voltage in the coils which when aggregated produce the familiar three phase voltage pattern.



## TYPES OF GENERATORS

Essentially, there are two basic types of generators:

- DC generators
- AC generators
  - Asynchronous (Induction) generators
  - Synchronous generators

### INDUCTION GENERATORS

The induction generator is nothing more than an induction motor driven above its synchronous speed by an amount not exceeding the full load slip the unit would have as a motor.

Assuming a full load slip of 3%, a motor with a synchronous speed of 1200 rpm would have a full load speed of 1164 rpm. This unit could also be driven by an external prime mover at 1236 rpm for use as an induction generator.

The induction generator requires one additional item before it can produce power – it requires a source of leading VAR's for excitation. The VAR's may be supplied by capacitors (this requires complex control) or from the utility grid.

Induction generators are inexpensive and simple machines, however, they offer little control over their output. The induction generator requires no separate DC excitation, regulator controls, frequency control or governor.

## SYNCHRONOUS GENERATORS

Synchronous generators are used because they offer precise control of voltage, frequency, VARs and WATTS. This control is achieved through the use of voltage regulators and governors.

A synchronous machine consists of a stationary armature winding (stator) with many wires connected in series or parallel to obtain the desired terminal voltage. The armature winding is placed into a slotted laminated steel core. A synchronous machine also consists of a revolving DC field - the rotor.

A mutual flux developed across the air gap between the rotor and stator causes the interaction necessary to produce an EMF. As the magnetic flux developed by the DC field poles crosses the air gap of the stator windings, a sinusoidal voltage is developed at the generator output terminals. This process is called electromagnetic induction.

The magnitude of the AC voltage generated is controlled by the amount of DC exciting current supplied to the field.

If "FIXED" excitation were applied, the voltage magnitude would be controlled by the speed of the rotor ( $E=4.44fnBA$ ), however, this would necessitate a changing frequency!

Since the frequency component of the power system is to be held constant, solid state voltage regulators or static exciters are commonly used to control the field current and thereby accurately control generator terminal voltage.

The frequency of the voltage developed by the generator depends on the speed of the rotor and the number of field poles. For a 60 Hz system,  $\text{Frequency} = \frac{\text{speed(rpm)} \times \text{pole pairs}}{60}$ .

## GENERATOR PARTS & FUNCTION

**Generator Frame:** Provides the structural strength and rigidity for the generator and serves as a housing to guide cooling air flow

**Inner End Shield:** Is a baffle used to form a path for cooled air

**Generator Fan:** Provides continuous circulation of cooling air

**Rotating Field:** A magnetic field which induces AC voltage in the stator windings

**Collector Rings:** Provide a connection and path for DC power into the rotating field windings

**Main Coupling:** Is the connection to the drive shaft

**Generator Coolers:** Remove heat from the generator cooling air

**Stator Core:** Houses the stationary windings and forms a magnetic path necessary for induced voltages

**Air Gap:** Is the radial clearance between the rotating field and the stator core

**Stator Coil End Turns:** Formed when coils leave one slot in a stator core and are returned to a different slot

**Terminal Leads:** Serve to conduct the three phase voltage and current flow from the generator stator to the external system

## STATOR DESIGN

The stator frame is fabricated from mild steel plate, forming a rigid structure. The core is built up from segmental laminations of grain oriented silicon steel for low loss and high permeability. Radial ventilating ducts are formed at intervals along the core by steel spacers. The core is hydraulically pressed during the assembly operation to ensure uniform compaction. When finished, it is clamped between heavy steel end plates. The stator winding is usually a two layer conventional lap-wound design. The insulation is class F (155C)

## SALIENT VS CYLINDRICAL ROTOR

There are two (2) basic rotor structures used, depending on speed.

For low speed machines, such as hydraulic turbines, a relatively large number of poles are required to produce rated frequency, hence a rotor with salient poles is well suited to this application. Such rotors often have damper windings (amortisseurs) in the form of copper or brass rods embedded in the pole face, they are intended to dampen out speed oscillations.

For high speed machines, such as steam and gas turbines, a relatively small number of poles ( 2 to 4 ) are required to produce rated frequency, hence a cylindrical rotor is well suited to this application.

Salient pole rotors are too weak mechanically and develop too much wind resistance and noise to be used in large, high speed machines.

Cylindrical rotor machines have a relatively uniform air gap, therefore, it can be assumed that a cylindrical rotor field will produce a uniform air-gap flux regardless of angular direction.

This cannot be said of a salient -pole machine as the air-gap is much larger between the poles (i.e. along the quadrature axis) than it is at the centres of the poles (i.e. on the direct axis).

## GENERATOR COOLING

Depending upon rating and design, the generator stator core and windings may be cooled by air, oil, hydrogen or water. For direct cooled generators, the coolant is in direct contact with the heat producing members such as the stator winding. For indirect cooled generators, the coolant cools the generator by relying on heat transfer through the insulation.

For any generator, a failure of the cooling system can result in rapid deterioration of the stator core lamination insulation and/or stator winding conductors and insulation.

### AIR COOLED GENERATORS

Air cooled generators are produced in two (2) basic configurations: open ventilated (OV) & totally enclosed water -to-air-cooled (TEWAC)

In the OV design, air is drawn from outside the unit through filters, passes through the generator and is discharged outside the generator.

In the TEWAC design, air is circulated within the generator passing through frame mounted air-to-water heat exchangers.

## REASONS WHY GENERATORS FAIL

### FOREIGN OBJECT DAMAGE

**Problem:** Objects can come from external sources or failure of internal components, they can pick up energy from the spinning rotor and do extensive damage

**Prevention:** Inspect on a regular basis all internal parts that are prone to failure or can be dislodged. Inspection tests can be a combination of visual inspection along with ultrasonic or magnetic particle tests on rotating components

### STATOR WINDING VIBRATION

**Problem:** Primarily a design related problem that affects large (>300Mw) generators which have insufficient end winding bracing to limit the movement of end turns.

**Prevention:** Proper bracing of the end winding is required to limit motion caused by steady state and transient electromagnetic forces.

## ROTOR WINDING DISTORTION

**Problem:** Rotor winding distortion caused by poor end turn blocking support design or by foreshortening of the rotor coils. Foreshortening is caused by thermal forces which compress rotor coils.

**Prevention:** Proper design of rotor coils and bracing to support the coils under axial load is essential. Rotors should be tested for turn to turn shorts at operating speed.

## STATOR WINDING VIBRATION

**Problem:** Primarily a design related problem that affects large (>300Mw) generators which have insufficient end winding bracing to limit the movement of end turns.

**Prevention:** Proper bracing of the end winding is required to limit motion caused by steady state and transient electromagnetic forces.

## OVERHEATING

**Problem:** Overheating of the rotor or stator can lead to insulation failure, shorting of turns and ground faults. Overheating can result from blocked ventilation passages caused by shifting insulation components or slot wedges.

**Prevention:** Inspect on a regular basis to ensure all rotor wedges are "locked" in place preventing migration and thus blocking of cooling passages.

## CONTAMINATION

**Problem:** For air cooled machines, dirt and dust cause tracking which can lead to electrical ground faults.

**Prevention:** Inspect air filters on a regular basis, the filters must be checked and cleaned regularly. Polarization index (PI) tests give a good indication of overall cleanliness of the rotor winding.

## ROTOR VIBRATION

**Problem:** There are many causes, turn-to-turn shorts, rotor coil foreshortening, electrical grounds, mechanical imbalances, overheating, etc.

**Prevention:** Comprehensive vibration measuring is effective combined with a regular maintenance program.

## STATOR WEDGE LOOSENESS

**Problem:** When stator wedges become loose, coils can vibrate causing insulation wear leading to ground faults or turn-to-turn shorts.

**Prevention:** Inspect on a regular basis tightness of wedge blocks.

## STATOR CORE DAMAGE

**Problem:** Stator core looseness can occur over time as pre-tensioned through bolts relax. A loose core results in insulation wear to coils and laminations resulting in hot spots and core-to-coil failures.

**Prevention:** Inspect bolt tightness on a regular basis.

# GENERATOR MAINTENANCE

The following tests which should be carried out annually in addition to vendor recommended maintenance.

## A) INITIAL GENERATOR TEST

- "Megger" rotor winding
- "Megger" exciter armature winding
- "Megger" exciter field winding
- Complete polarization index (pi) on main stator
- Check bearing insulation

## B) INSPECTION ON STATIC EXCITER

- Remove exciter end cover
- Examine condition of diode carrier
- Examine exciter armature/stator for contamination
- Examine exciter armature/stator for winding wear
- Check pmg magnets for contamination

### C) ELECTRICAL CONTROL/PROTECTION PANEL

- Visually inspect external surfaces of panel
- Complete insulation resistance checks of panel wiring
- Check function of all relays
- Check all fuses
- Check all lamps
- Check operation of all switches
- Check operation of panel heaters
- Run generator; recalibrate avr
- Secondary inject all protective relays

### D) LINESIDE CUBICLE/NEUTRAL CUBICLE

- Check condition of main generator terminal bushings
- Check all busbar/cable connections
- Check ct/vt connections
- Check condition of neutral earthing transformer
- Check condition of neutral earthing resistor
- Check operation of cubicle heaters
- Clean all post insulators and examine for damage
- Carry out insulation check

### E) ROTOR EARTH FAULT PROTECTOR

- Carry out static checks to confirm operation of detector
- Carry out functional check to confirm operation of detector

### F) SLIP-RINGS AND BRUSH-GEAR (IF FITTED)

- Check all brushes for grade and length
- Check condition of brush holders/mountings
- Check that spring tensions are correct
- Check conditions of slip-rings
- Check mechanical run-out of slip-rings
- Check cooler and leakage alarms

## EXCITOR BASICS

The exciter is the "backbone" of the generator control system. It is the power source that supplies the dc magnetizing current to the field windings of a synchronous generator thereby ultimately inducing ac voltage and current in the generator armature

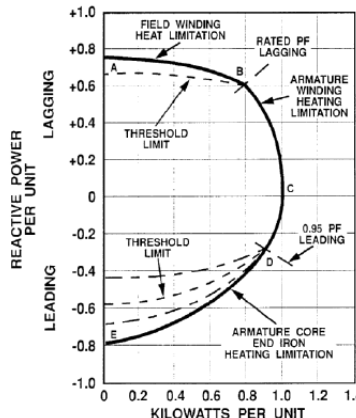
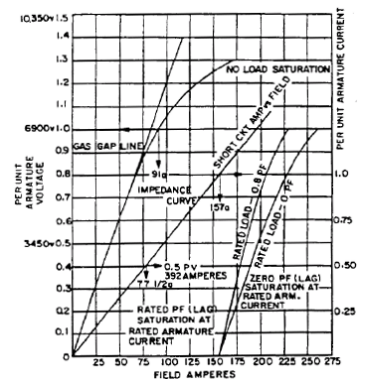
Two basic kinds of excitors

- Rotating (Brush and brushless)
- Static exciters (Shunt and series)

The amount of excitation required to maintain the output voltage constant is a function of the generator load. As the generator load increases, the amount of excitation increases.

- Reactive lagging pf loads require more excitation than unity pf loads
- Leading pf loads require less excitation than unity pf loads

The amount of excitation required by a generator for a particular load is defined by the "generator saturation curve".



The amount of power that a generator can deliver is defined by the "generator capability curve".



## ROTATING EXCITERS

**Brushless:** do not require slip-rings, commutators, brushes and are practically maintenance free.

**Brush Type:** require slip-rings, commutators and brushes and require periodic maintenance

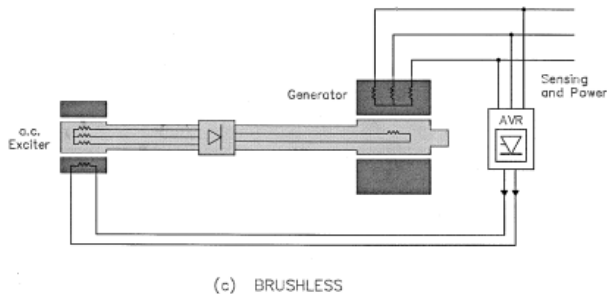
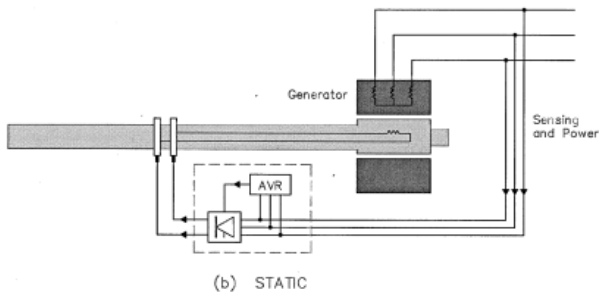
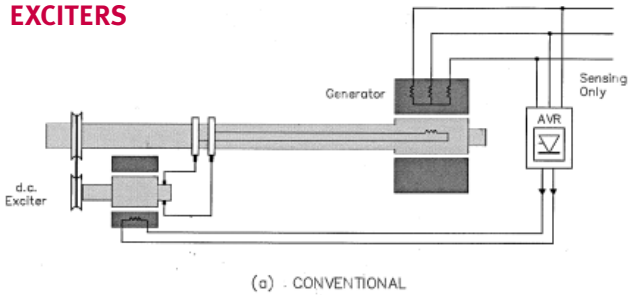
## STATIC EXCITERS

Static excitation means no moving parts. It provides faster transient response than rotary exciters

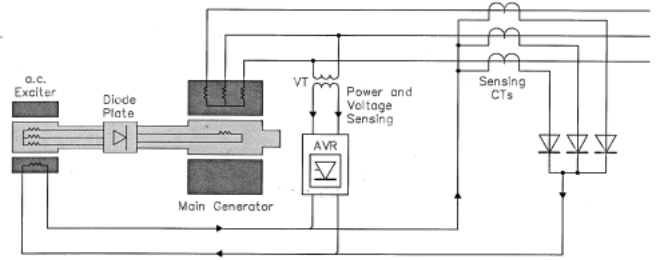
**Shunt Type:** operating field power from generator output voltage

**Series Type:** operating field power from generator output voltage & current

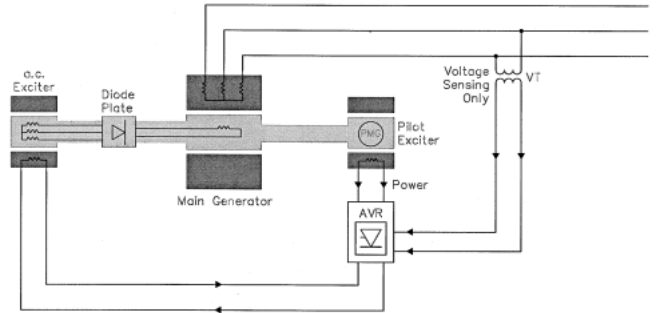
## EXCITERS



## BRUSHLESS EXCITERS



(a) BRUSHLESS WITHOUT PILOT EXCITER



(b) BRUSHLESS WITH PILOT EXCITER

## PRINCIPALS OF AUTOMATIC VOLTAGE CONTROL

Voltage transformers provide signals proportional to line voltage to the avr where it is compared to a stable reference voltage. The difference (error) signal is used to control the output of the exciter field.

For example, if load on the generator increases, the reduction in output voltage produces an error signal which increases the exciter field current resulting in a corresponding increase in rotor current and thus generator output voltage.

Due to the high inductance of the generator field windings, it is difficult to make rapid changes in field current.

This introduces a considerable "lag" in the control system which makes it necessary to include a stabilizing control to prevent instability and optimize the generator voltage response to load changes.

Without stabilizing control, the regulator would keep increasing and reducing excitation and the line voltage would continually fluctuate above and below the required value.

Modern voltage regulators are designed to maintain the generator line voltage within better than +/- 1% of nominal for wide variations of machine load.

## GENERATOR OPERATION

When a generator is used to supply power, it can be operated in the following modes:

- isolated (sometimes referred to as island) mode or
- parallel with a system or other machines.

In both cases, the power (WATTS) supplied at the generator terminals is a function of the fuel supplied to the prime mover, which is controlled by the governor.

## ISLAND OPERATION

The machine speed is determined by the load and fuel supply.

The generator voltage is determined by the excitation.

For example, an increase in load will have two effects:

- Speed will initially fall because the energy being supplied by the fuel is less than that required by the load. The speed reduction is detected by the governor which opens the fuel valve by the required amount to maintain the required speed.
- Voltage will initially fall, the reduction is detected by the AVR which increases the excitation by the amount required to maintain output voltage.

## PARALLEL GENERATORS (INFINITE BUS)

When a machine operates in parallel with a power system, the voltage and frequency will be fixed by the system.

The voltage regulator no longer controls the generator output voltage.

The fuel supply to the prime mover which is controlled by the governor determines the power which is supplied by the generator .

The generator excitation determines the internal emf of the machine and therefore affects the power factor.

When excitation is increased above the level to achieve nominal no load voltage, rather than the voltage increasing, the reactive current (vars) flowing from the generator to the load increases resulting in a lagging pf condition on the generator.

When the excitation is reduced below the level to achieve nominal no load voltage, rather than the voltage decreasing, the reactive current (vars) flowing to the generator from the load increases resulting in a leading pf condition on the generator.



**For more information contact:**

Kevin Whitehead, Director -  
Engineering & Construction Services