# Electrical Equipment - Course 230.2

## AC GENERATORS: PART 9

## OPERATING LIMITATIONS

## 1. OBJECTIVES

The student must be able to:

(1) Explain how a generator output is limited by:

a) Rotor heating
b) Stator winding heating
c) Stability
d) Core end heating
e) Stator core heating

(2) Explain the precautions that must be taken to ensure the limitations listed above are not exceeded and the consequences of exceeding each of these limitations.

## 2. INTRODUCTION

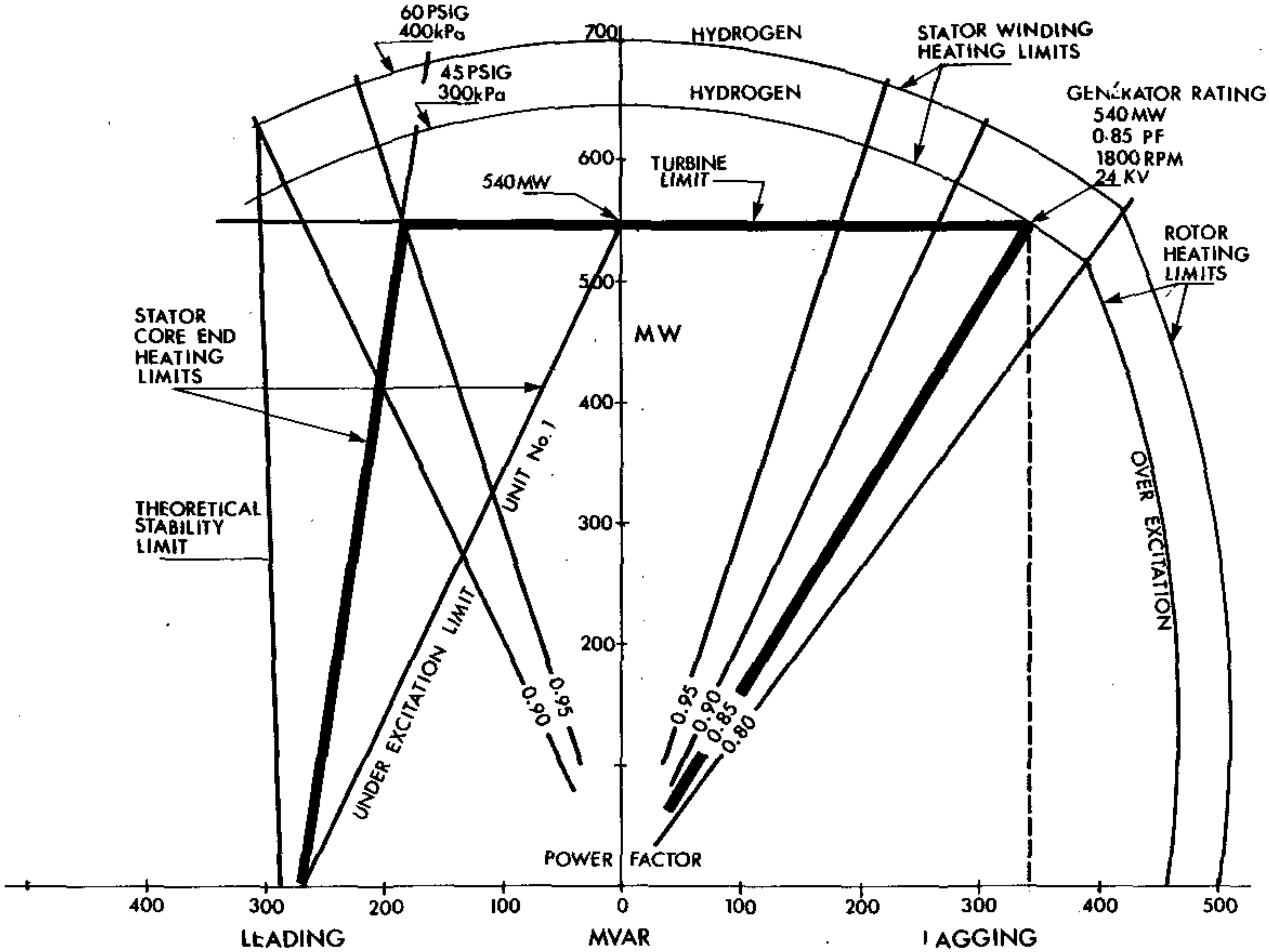
This lesson explains the generator thermal or heating limitations and relates these limitations to the generator capability curves. The lesson also explains the precautions that must be taken to ensure the limits are not exceeded and the consequences of exceeding the limits.

## 3. GENERATOR LIMITATIONS

Figure 1 shows the operating limitations, usually referred to as the "capability curves" for the Pickering generators. These capability curves are shown by the heavy black lines. Full rated output of 540 MW, 24 kV at 0.85 pf (lag) is achieved without exceeding any of the generators limitations.

Examination of these curves will show that they define four of the five limitations stated in the objectives, ie,

(a) Rotor heating
(b) Stator winding heating
(c) Stability
(d) Core end heating




PICKERING GENERATORS CAPABILITY CURVES

Figure 1

The gas pressure is usually maintained at 300 kPa, (45 psig). The pressure can be increased to 400 kPa (60 psig) to improve cooling and increase output. Any increase in pressure above 400 kPa gives little improvement in cooling and gives excessive hydrogen leakage rates and increased windage losses.

## 3.1 Rotor Heating Limitation

The rotors of large generators (typically above 60 MW) are hydrogen cooled. For reliable operation, it is essential that at all times, the temperature of the rotor conductors and insulation is not exceeded. An indication of the rotor temperature can be obtained from the temperature of the hydrogen cooling gas as it returns to the coolers. An accurate method rotor conductor temperature measurement is obtained from the rotor temperature indicator. This indicator computes the temperature from the change in resistance of the rotor winding.

Exceeding the rotor temperature will shorten the life of the insulation. Differential expansion, due to excessive temperature differences between the rotor copper and rotor iron components, may cause cracking of the rotor copper or insulation.

Parsons have specified that the maximum value for the field current for the Pickering generators is 3750A. This limitation is imposed by rotor conductor $I^2R$ heating and by the sliprings and brushes, which are unable to carry larger currents to the rotor.

## 3.2 Stator Winding Heating Limits

Figure 1 shows that when the generator is producing 540 MW at 0.85 pf lag with 300 kPa (45 psig) hydrogen pressure, the generator stator conductors are operating at their thermal limit. This limit is due to the $I^2R$ heating in the stator conductors. If the generator power factor is altered to a value nearer 1.0, then due to the lower stator current, the generator stator conductors would be operating well within their thermal limit. Provided the turbine could produce the necessary power, the generator could produce about 630 MW at 1.0 pf with 300 kPa hydrogen pressure, before the stator conductor thermal limit is reached.

The temperature of the rotor stator conductors is monitored by measuring the temperature of coolant leaving the conductors. Exceeding the rated temperature will shorten insulation life. Excessive differential expansion between the copper conductors can cause cracking of the copper conductors and/or insulation.

## 3.3 Stability Limit

When a generator is operating at a leading power factor, the excitation and hence the flux produced by the rotor is weak. Consequently the magnetic coupling between rotor and stator rotating magnetic fields is also weak. If the generator is loaded under this condition, a large load angle (rotor angle) is produced. When this load angle reaches 90°, the generator is producing the maximum amount of power for the excitation being used and is said to be operating at its steady state stability limit. Any further increase in load will cause the magnetic fluxes to stretch further and the load angle to increase further. A point is reached when the rotor is at the 180° position, see Figure 3, where there is no magnetic coupling between the rotor and stator. When this occurs, the rotor will speed up and the generator, instead of giving a steady output, will only give surges of power as the rotor N pole passes the stator S pole. This effect is known as "pole slipping" and the generator is now unstable.

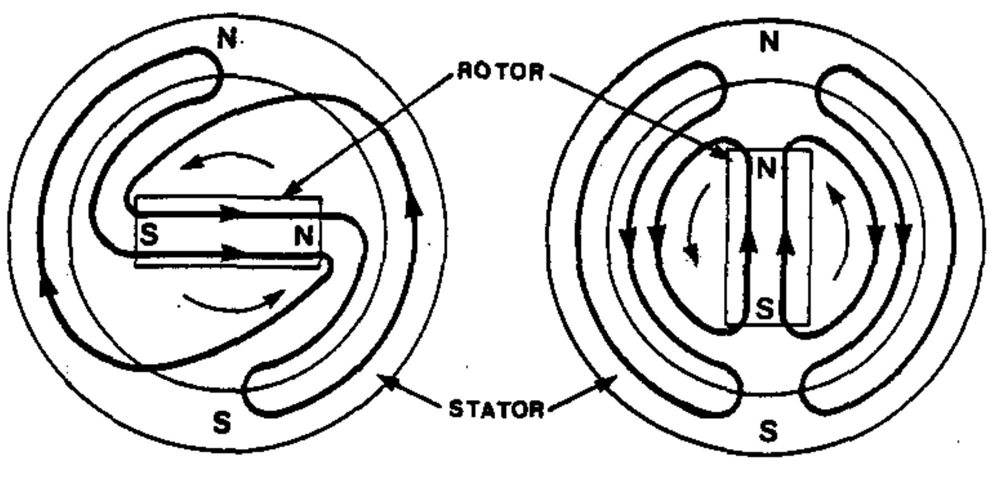



Figure 2: Generator rotor at limit of stability. 90° rotor angle.

Figure 3: Generator unstable. Rotor at 180°.

It is very bad operating practice to allow a generator to pole slip. The large surges of power, from a mechanical point of view, puts great strain on the generator to turbine coupling, the bearings and foundations. From an electrical point of view the surges of power will cause current surges and hence magnetic stresses to all load carrying components. These surges of power will also cause the voltages to fluctuate rapidly and cause lights to flash.

Should instability occur, automatic protection trips the generator. This protection operates when the generators' power factor becomes excessively leading.

To make sure that the generator will remain stable, it must not be operated with more **leading** vars than is shown by the **stability limit** line.

## 3.4 Stator Core End Heating Limits

When a generator is operating at unity or lagging power factor, a strong flux is produced by the rotor. Under this condition, little flux is able to leak out from the ends of the stator core and there is no excessive heating at the core ends.

When the generator is operating at a leading power factor, the flux produced by the rotor is weaker and more flux is able to leak out from the ends of the stator core. When this flux leaks out from the ends of the stator core, it passes through the face of each lamination and causes large eddy currents to flow in these laminations. These eddy currents can cause excessive heating. See Technical Paper TP-9 for a detailed explanation of this effect. (1)

To minimize heating at the ends of the core, two techniques are employed. They are:

(a) Extra cooling ducts are provided at the ends of the core. These ducts allow the hydrogen to remove the additional heat produced in the iron.

(b) Copper screens are employed. These screens, which are water cooled in Parsons generators, have currents induced in them by the fluxes passing out from the end of the core. The currents in the copper screen produce fluxes which due to Lenz's law, **oppose** the fluxes coming out of the end of the core. To a great extent, the fluxes leaking from the ends of the core are *forced* to take a path which gives a better flux pattern through the iron at the end of the core. Less core end heating results. Figure 4 shows typical curves of relative heating of stator core ends versus power factor for a generator operating at 100% full load MVA and 80% full load MVA.

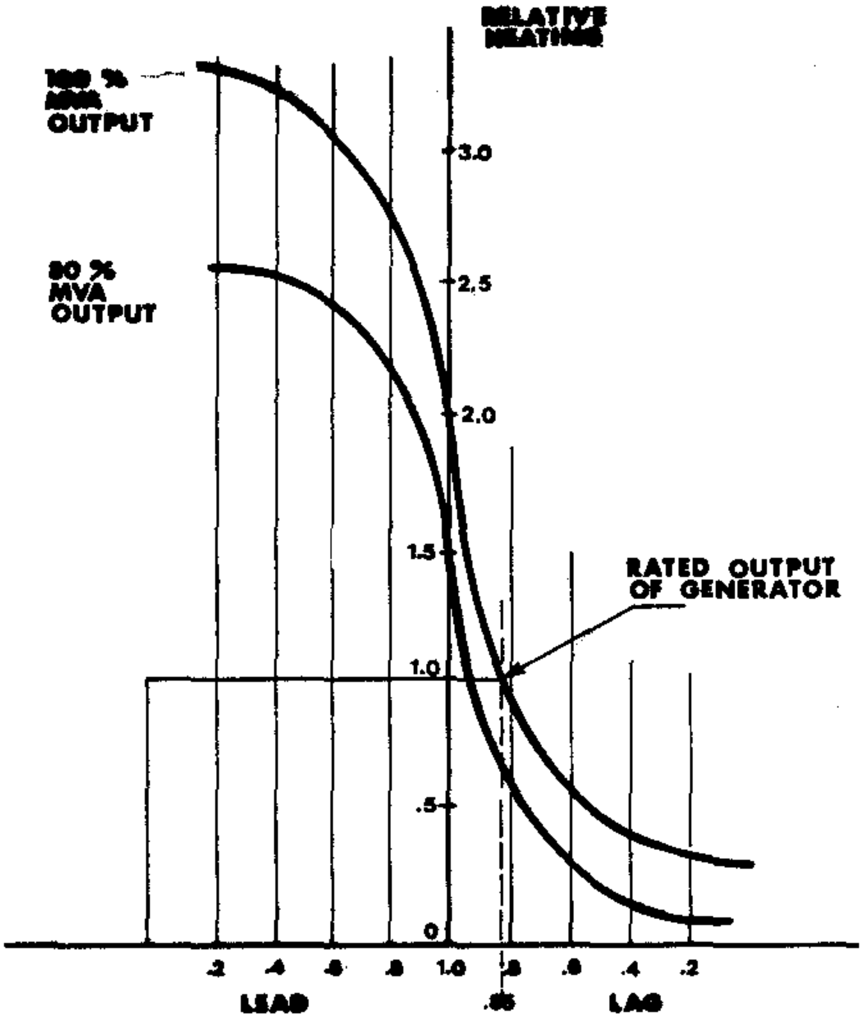



Figure 4: Curves of relative heating of stator core ends versus power factor

## 3.5 Stator Core Heating

The stator core heating limitation is not shown on Figure 1. It should be remembered that the voltage output $V_T$ for a generator is governed by the relationship:

$V_T \;\alpha\; N\Phi_m f$ where N is the number of turns,

$\Phi_m$ is the maximum value of flux

f is the frequency

As the frequency and number of turns are fixed, then the voltage output is proportional to the flux, ie,

$$V_T \propto {}_m$$

Lesson 230.25-7 stated that the flux in a generator must not be kept at a value greater than 10% above normal for more than a few minutes. It follows then that the terminal voltage of a generator should not be kept appreciably above its rated value for any significant length of time. This will prevent excess heating due to eddy currents and hysterisis in the stator iron.

It should not be forgotten that, if the flux and hence the voltage in the generator is higher than normal, the flux in the transformers connected to the generators will also be higher than normal. The cores of these transformers can easily be damaged due to overfluxing, see lesson 230.25-7. Excessive voltages produced by the generator will also stress the insulation of all electrical components in the generator and components connected to the generator. This stressing of the insulation is usually a minor problem compared with the magnetic stressing and heating of the iron.

## 4. SUMMARY

From an operational viewpoint, a generator is normally operated within its operational area shown by the heavy lines on Figure 1. With full power output at 0.85 pf lag, the generator is operating at the thermal limits quoted by the manufacturer. These thermal limits assume that the cooling water is at the maximum temperature (40°C) that can be expected in service. If any of the thermal limits are exceeded, the life of some components, in particular the insulation, will be reduced. As a rough estimate, the life of insulation is halved for each 9°C rise in temperature above the design figure.

Increasing gas pressure will increase the generators thermal capabilities. It will not increase the generators stability capabilities.

Therefore, for a generator operating at its rated speed (frequency) the:

(a) MW output is limited by turbine output and stator conductor heating

(b) Mvar output (lag) is limited by the rotor heating

(c) Mvar output (lead) is limited by stator core end heating and also by stability considerations

(d) Terminal voltage output is limited by the heating of the stator iron core, as distinct from the core end heating

(e) The maximum permissible continuous field current specified by the manufacturer.

5. REFERENCES

(1) RNTC Technical Paper, TP-9 "Stator core end heating".

(2) For further reading, reference may be made to "Modern Power Station Practice", Volume 7, Chapter 2.

## ASSIGNMENT

1. Given the capability curves for a generator (see Figure 1), *explain how the following four limitations limit the* output (MW and Mvar) of a generator.

   (a) rotor heating
   (b) stator conductor heating
   (c) stability
   (d) core end heating

2. Explain how core heating will limit the output voltage of an ac generator.

3. If each of the following alarms were received, explain the action(s) that you would take to prevent damage to a generator.

   (a) rotor temperature
   (b) stator conductor temperature
   (c) core temperature
   (d) core end temperature

4. Explain how you would prevent a loaded generator from "pole slipping".

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