Uprating Considerations in Turbogenerator with Indirectly Hydrogen-Cooled Stator Winding

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WHY UPRATE? WHY NOT?

Uprating of existing plant equipment has been of significant interest in today's power industry to:

- Achieve higher over-all plant efficiency
- Extend life of plant
- Increase revenue/profit!

In doing so, there are always some trade-off such as:

- Reduction in reliability
- Advanced aging of other components in the system

Cost-benefit study may sometimes conclude that replacement is better option than uprating!

DRIVERS FOR UPRATING TURBOGENERATOR

I. Improvement on the generator components

- Limited to upgrading individual components

Ex. Insulation improvement, winding improvement

II. Improvement on mechanical components

- Commonly the main driver for an uprate
- Generator capacity will be the limiting factor

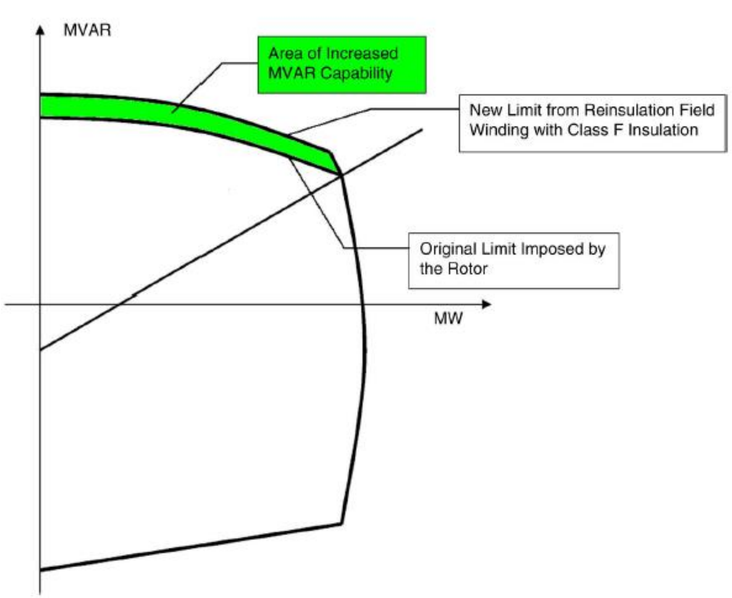
Ex. Design improvements on turbine, boiler, etc.

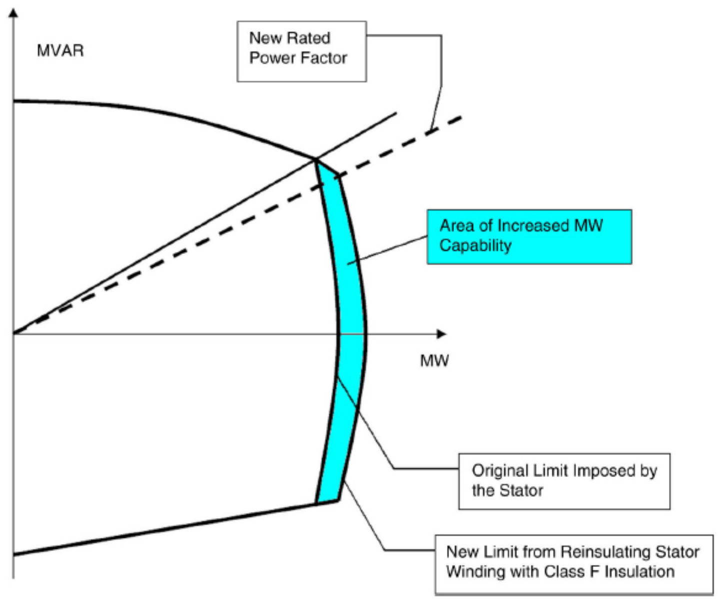
Uprating requires design work to determine issues that pose limitations on the extent of power increase

INSULATION IMPROVEMENT

Class B to Class F insulation (Stator and Field)

- Can the generator step-up transformer accommodate additional MVA output?
- New turbogenerators are already using Class F and H insulation!





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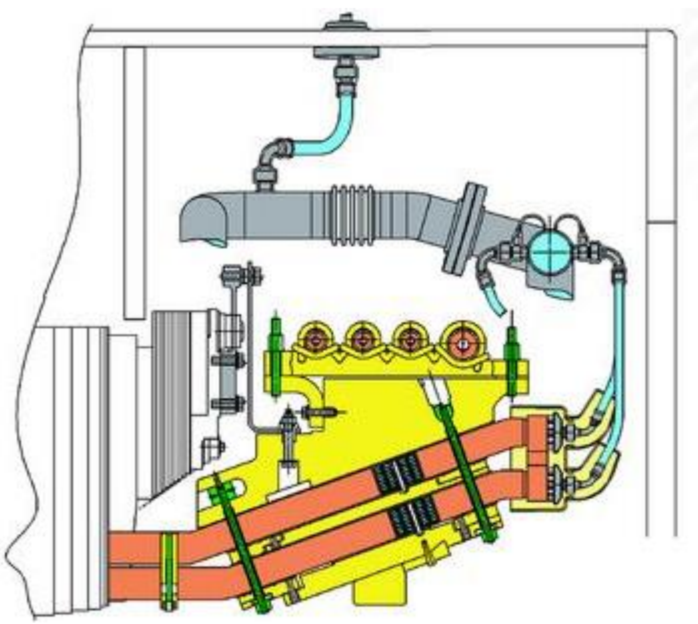
WINDING IMPROVEMENT

Direct gas-cooled stator winding to direct water-cooled stator winding

- Can existing generator foundation carry the additional weight?
- Is the new design fit to existing stator casing and geometry?



Big Brown and Monticello coal-fired power plant in Texas, USA were upgraded from 645 MVA to 700 MVA by undertaking a rewind based upon a conversion from direct gas cooling of old stator winding to direct demineralized water cooling for the new stator winding (October 2000)

Source: https://www.modernpowersystems.com

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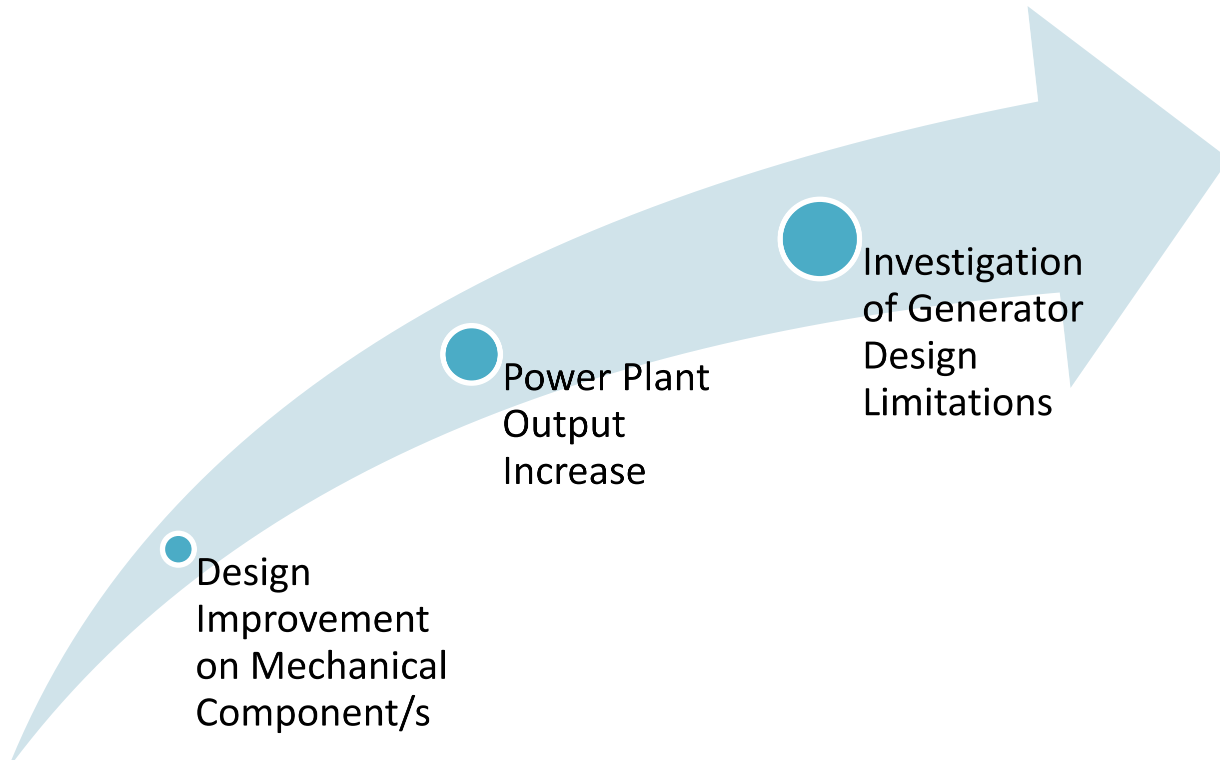
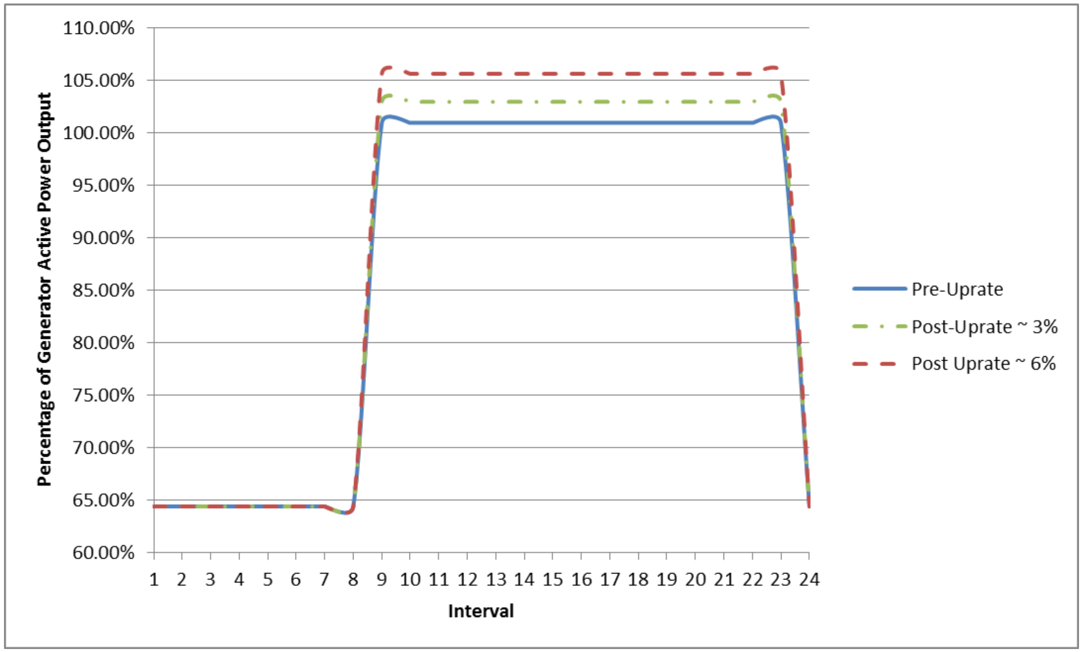
MECHANICAL COMPONENT IMPROVEMENT

Generally, the key drivers for increasing the power plant output are the improvements on existing mechanical components. If achieving higher output from these components is viable, then the existing electrical components such as generator should be subsequently analyzed.



UPRATING OF TURBOGENERATOR

Case Study: After the implementation of design improvement on gas turbine, a combined cycle gas turbine power station was able to achieve a power increase of 3%. Further design improvement on the boiler resulted to an additional power output of 3%.



Interval	Pre-Uprate	Post-Uprate ~ 3%	Post Uprate ~ 6%
1	64.40%	64.40%	64.40%
2	64.40%	64.40%	64.40%
3	64.40%	64.40%	64.40%
4	64.40%	64.40%	64.40%
5	64.40%	64.40%	64.40%
6	64.40%	64.40%	64.40%
7	64.40%	64.40%	64.40%
8	64.40%	64.40%	64.40%
9	100.92%	102.92%	105.60%
10	100.92%	102.92%	105.60%
11	100.92%	102.92%	105.60%
12	100.92%	102.92%	105.60%
13	100.92%	102.92%	105.60%
14	100.92%	102.92%	105.60%
15	100.92%	102.92%	105.60%
16	100.92%	102.92%	105.60%
17	100.92%	102.92%	105.60%
18	100.92%	102.92%	105.60%
19	100.92%	102.92%	105.60%
20	100.92%	102.92%	105.60%
21	100.92%	102.92%	105.60%
22	100.92%	102.92%	105.60%
23	100.92%	102.92%	105.60%
24	64.40%	64.40%	64.40%

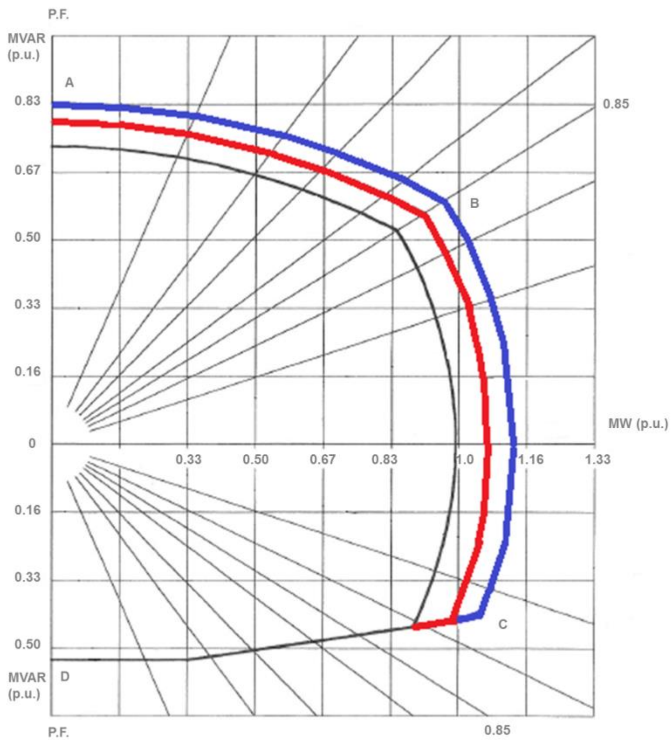
UPRATING OF TURBOGENERATOR

The following parameters of the power station's turbogenerator with indirectly hydrogen-cooled stator winding were analyzed to safely accommodate the power increase due to the design improvement on mechanical components (i.e. gas turbine, boiler):

- Generator capability curve
- Temperature rise of stator winding
- Temperature rise of rotor winding
- Seal oil system
- Protection limits

GENERATOR CAPABILITY CURVE

Upon checking and consulting with OEM, the generator can accommodate the power increase based on its capability curve:



Legend:

- Original Capability Curve
- Capability Curve @ 3% uprate
- Capability Curve @ 6% uprate

Note:

Curve AB limited by Field Heating

Curve BC limited by Armature Heating

Curve CD limited by Armature Core End Heating

(IEEE Std C50.13-2014)

Turbogenerator has now larger capability for delivering both active and lagging reactive power

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TEMPERATURE RISE OF STATOR WINDING

Considering the power output increase, temperature rise in the stator winding was anticipated. To check if the existing hydrogen coolers can still sufficiently cool the hotter hydrogen used to indirectly cool the stator windings, the following calculation would provide estimation on this:

$$H_2\ cooler\ water\ Tout_{new} = \left[\left(H_2\ cooler\ water\ Tout_{old} - H_2\ cooler\ water\ Tin_{old)}\right) x \left(\frac{Ia_{new}}{Ia_{old}}\right)^2 x \left(\frac{Heat\ dissipating\ capacity_{old}}{Heat\ dissipating\ capacity_{new}}\right)^{0.5}\right] + H_2\ cooler\ water\ Tin_{old}$$

$$Stator\ current, Ia = \frac{MVA\ rating}{\sqrt{3}\ x\ Vt}\ , A$$

where:
MVA = rated apparent power
Ia = stator current
Vt = terminal voltage

Existing hydrogen cooler's heat dissipating capacity needs to be checked if still sufficient for cooling

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TEMPERATURE RISE OF STATOR WINDING

To check if the existing hydrogen cooler's heat dissipating capacity is still sufficient for cooling considering the **3%** power increase:

$$H_2\ cooler\ water\ Tout_{new} = \left[(42.5\ °\mathrm{C} - 35.0\ °\mathrm{C})\ x\ \left(\frac{1.03\ p.u.}{1.0\ p.u.}\right)^2 x \left(\frac{2700\ kW}{2700\ kW}\right)^{0.5}\right] + 35.0\ °\mathrm{C}$$

$$H_2\ cooler\ water\ Tout_{new} = \mathbf{42.96°C}$$

$$Max.\ allowable\ H_2\ cooler\ water\ Tout_{old} = 43.0°\mathrm{C}$$

No need to replace existing hydrogen coolers since new outfall temperature of cooling water is still within limit

TEMPERATURE RISE OF STATOR WINDING

To check if the existing hydrogen cooler's heat dissipating capacity is still sufficient for cooling considering the **6%** power increase:

$$H_2\ cooler\ water\ Tout_{new} = \left[(42.5\ °\text{C} - 35.0\ °\text{C})\ x\ \left(\frac{1.06\ p.u.}{1.0\ p.u.}\right)^2 x\ \left(\frac{2700\ kW}{2700\ kW}\right)^{0.5}\right] + 35.0\ °\text{C}$$

$$H_2\ cooler\ water\ Tout_{new} = \mathbf{43.43°C}$$

$$Max.allowable\ H_2\ cooler\ water\ Tout_{old} = 43.0°\text{C}$$

Need to replace existing hydrogen coolers since new outfall temperature of cooling water is beyond acceptable limit!

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TEMPERATURE RISE OF STATOR WINDING

To compute for the minimum required cooling capacity of new hydrogen coolers considering the **6%** power increase:

$$42.5\ °C = \left[(42.5\ °C - 35.0\ °C)\ x\ \left(\frac{1.06\ p.u.}{1.0\ p.u.}\right)^2 x \left(\frac{2700\ kW}{Heat\ dissipating\ capacity_{new}}\right)^{0.5}\right] + 35.0\ °C$$

$$Heat\ dissipating\ capacity_{new} \sim \mathbf{3410\ kW}$$

New hydrogen coolers are still of the same dimension as the existing but with higher heat dissipating capacity

TEMPERATURE RISE OF ROTOR WINDING

Considering the power output increase, temperature rise in the rotor winding was anticipated. To check if the new temperature of rotor winding is still within the allowable limits based on the rotor insulation class, the following calculation would provide estimation on this:

$$Rotor\ winding\ temperature_{new} = \left[(Rated\ rotor\ temperature\ rise)\ x\ \left(\frac{If_{new}}{If_{old}}\right)^2\right] + cold\ H_2\ gas\ temperature_{rated}$$

<u>where:</u>

Rated rotor temperature rise = 75 °C *(Class F insulation, directly H_2 cooled rotor winding, IEEE C50.13-2014)*

Rated cold H_2 gas temperature = 40 °C

Need to evaluate new temperature since insulation deterioration increases at higher temperature

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TEMPERATURE RISE OF ROTOR WINDING

To check if the new rotor winding temperature is still within allowable limits considering:

3% <u>power increase</u>

$$Rotor\ winding\ temperature_{new} = \left[(75.0\ °\text{C})\ x\ \left(\frac{1.03\ p.u.}{1.0\ p.u.}\right)^2\right] + 40.0\ °\text{C}$$

$$Rotor\ winding\ temperature_{new} = \mathbf{119.57°C}$$

6% <u>power increase</u>

$$Rotor\ winding\ temperature_{new} = \left[(75.0\ °\text{C})\ x\ \left(\frac{1.06\ p.u.}{1.0\ p.u.}\right)^2\right] + 40.0\ °\text{C}$$

$$Rotor\ winding\ temperature_{new} = \mathbf{124.27°C}$$

$$Allowable\ rotor\ winding\ temperature = 115°\text{C}$$

Need to maintain allowable temperature to avoid shortening of rotor winding remaining life!

TEMPERATURE RISE OF ROTOR WINDING

To maintain the allowable rotor winding temperature, hydrogen gas pressure needs to be increased. To compute for the minimum required hydrogen gas pressure, the following calculation would provide estimation on this:

$$Rotor\ winding\ temp_{new} = \left[(Rated\ rotor\ temperature\ rise)\ x \left(\frac{If_{new}}{If_{old}} \right)^2 x \left(\frac{H_2\ pressure_{old}}{H_2\ pressure_{new}} \right)^{0.5} \right] + cold\ H_2\ gas\ temperature_{rated}$$

<u>where:</u>

Rated rotor temperature rise = 75 °C *(Class F insulation, directly H_2 cooled rotor winding, IEEE C50.13-2014)*

Rated cold $\mathrm{H_2}$ gas temperature = 40 °C

Rated $\mathrm{H_2}$ pressure = 4.0 bar

Increasing the gas pressure results to improvement of hydrogen cooling effectiveness

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TEMPERATURE RISE OF ROTOR WINDING

To compute for the minimum required hydrogen gas pressure considering:

3% power increase

$$115\ °C = \left[(75.0\ °C)\ x \left(\frac{1.03\ p.u.}{1.0\ p.u.}\right)^2 x \left(\frac{4.0\ bar}{H_2\ pressure_{new}}\right)^{0.5}\right] +40.0\ °C$$

$$H_2\ pressure_{new} = \mathbf{4.5\ bar}$$

6% power increase

$$115\ °C = \left[(75.0\ °C)\ x \left(\frac{1.06\ p.u.}{1.0\ p.u.}\right)^2 x \left(\frac{4.0\ bar}{H_2\ pressure_{new}}\right)^{0.5}\right] +40.0\ °C$$

$$H_2\ pressure_{new} = \mathbf{5.0\ bar}$$

$$Rated\ H_2\ pressure = 4.0\ \mathrm{bar}$$

Need to check if casing, end doors and hydrogen seals can withstand the increase in hydrogen pressure

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SEAL OIL SYSTEM

Considering the required increase in hydrogen gas pressure to accommodate the power increase, seal oil pressure of the seal ring was also adjusted:

3% power increase

$$Seal\ oil\ pressure_{old}\ (before\ shaft\ seal)\ = 5.2\ \text{bar}$$

$$Seal\ oil\ pressure_{new} = \mathbf{5.7\ bar}$$

$$H_2\ pressure_{new} = 4.5\ \text{bar}$$

6% power increase

$$Seal\ oil\ pressure_{old}\ (before\ shaft\ seal)\ = 5.2\ \text{bar}$$

$$Seal\ oil\ pressure_{new} = \mathbf{6.2\ bar}$$

$$H_2\ pressure_{new} = 5.0\ \text{bar}$$

Seal oil pressure needs to be maintained above H_2 pressure to stop gas from leaking past the seals

PROTECTION LIMITS

Considering the power increase due to the design improvement on mechanical components (i.e. gas turbine, boiler), protection limits on the following parameters were reviewed and adjusted:

- H_2 casing pressure alarm
- Cold gas temperature protection setting of stator winding
- Cold gas temperature protection setting of rotor winding

Short-circuit ratio and other generator constants will change due to uprating hence system stability must be re-evaluated

PROTECTION LIMITS

The following adjustment were done on the H_2 casing pressure alarm:

3% power increase

$$H_2\ casing\ pressure\ alarm_{old} = 3.8\ \mathrm{bar}$$

$$H_2\ pressure_{old} = 4.0\ \mathrm{bar}$$

$$H_2\ casing\ pressure\ alarm_{new} = \mathbf{4.3\ bar}$$

$$H_2\ pressure_{new} = 4.5\ \mathrm{bar}$$

6% power increase

$$H_2\ casing\ pressure\ alarm_{old} = 3.8\ \mathrm{bar}$$

$$H_2\ pressure_{old} = 4.0\ \mathrm{bar}$$

$$H_2\ casing\ pressure\ alarm_{new} = \mathbf{4.8\ bar}$$

$$H_2\ pressure_{new} = 5.0\ \mathrm{bar}$$

PROTECTION LIMITS

The following adjustment were done on the cold H_2 gas temperature protection setting of stator winding for the **3% power output increase**:

Cold H_2 gas temperature	Old Alarm Setting (A)	New Alarm Setting (A)	Old Trip Setting (A)	New Trip Setting (A)
5 – 10°C	1.46 p.u.	**1.46 p.u.**	1.50 p.u.	**1.50 p.u.**
40°C	1.24 p.u.	**1.26 p.u.**	1.29 p.u.	**1.31 p.u.**
50°C	1.09 p.u.	**1.10 p.u.**	1.16 p.u.	**1.17 p.u.**

PROTECTION LIMITS

The following adjustment were done on the cold H_2 gas temperature protection setting of stator winding for the **6% power output increase**:

Cold H_2 gas temperature	Old Alarm Setting (A)	New Alarm Setting (A)	Old Trip Setting (A)	New Trip Setting (A)
5 – 10°C	1.46 p.u.	**1.46 p.u.**	1.50 p.u.	**1.50 p.u.**
40°C	1.24 p.u.	**1.28 p.u.**	1.29 p.u.	**1.33 p.u.**
50°C	1.09 p.u.	**1.11 p.u.**	1.16 p.u.	**1.18 p.u.**

PROTECTION LIMITS

The following adjustment were done on the cold H_2 gas temperature protection setting of rotor winding for the **3% power output increase**:

Cold H_2 gas temperature	Old Alarm Setting (A)	New Alarm Setting (A)	Old Trip Setting (A)	New Trip Setting (A)
5 – 10°C	1.31 p.u.	**1.31 p.u.**	1.35 p.u.	**1.35 p.u.**
40°C	1.13 p.u.	**1.16 p.u.**	1.16 p.u.	**1.19 p.u.**
50°C	1.01 p.u.	**1.02 p.u.**	1.07 p.u.	**1.08 p.u.**

PROTECTION LIMITS

The following adjustment were done on the cold H_2 gas temperature protection setting of rotor winding for the **6% power output increase**:

Cold H_2 gas temperature	Old Alarm Setting (A)	New Alarm Setting (A)	Old Trip Setting (A)	New Trip Setting (A)
5 – 10°C	1.31 p.u.	**1.31 p.u.**	1.35 p.u.	**1.35 p.u.**
40°C	1.13 p.u.	**1.20 p.u.**	1.16 p.u.	**1.23 p.u.**
50°C	1.01 p.u.	**1.03 p.u.**	1.07 p.u.	**1.09 p.u.**

UPRATING CONSIDERATIONS

The table summarizes the considerations taken in uprating the turbogenerator with indirectly hydrogen-cooled stator winding:

Generator Component	3% Uprate	6% Uprate
H_2 casing pressure	Increase H_2 pressure	
H_2 coolers	Existing equipment	Replace with higher heat dissipating capacity
Seal oil pressure	Increase seal oil pressure	
Protection and alarm limits	Adjustment of settings required	
System stability	Re-evaluation needed	

Thank you!

Questions?

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