EFFECT OF GRID DISTURBANCE ON PLANT DYNAMICS OF A NUCLEAR POWER PLANT

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Abstract- Power generation in a nuclear plant is dependent on the Nuclear steam supply system (thermal energy source), the turbine generator (energy conversion), the circulating water system (heat rejection) and condensate/feed water system (regenerative heat and recycle of working fluid) and the plant electric system supporting these. These power generation processes must be operated so as to maintain energy and mass balance under changing conditions of load and environment. Grid electrical disturbances cause significant deviations in grid supply voltage and frequency. The abnormal conditions that accompany the imposition of grid electrical disturbances on a nuclear plant can disrupt the dynamic state of process systems equilibrium. The impact of grid electrical disturbances are in two different ways viz. (i) process degradation and (ii) impact on electrical components. Analysis of both these aspects are required to be carried out to design efficient reactor system high plant availability.

In this project, effect of change in grid frequency and supply voltage on performance of motors and generator of a nuclear power plant has been analysed. The study is performed basically based on steady state conservative equations. Transient effects are not considered. It has been found that the impact on the performance of motors and generators are benign. An investigation on the process dynamics shows that due to provision of variable frequency drive systems for the important motors and other control measures, there is negligible impact on the heat transfer process. There is need for more detailed studies to be performed on the turbine control system, variable frequency drives and transient response for complete understanding and improvement.

Keywords—

I. INTRODUCTION

The performance of a Nuclear Power Plant (NPP) performance will be affected by the characteristics of the grid in which it is connected. Grid electrical disturbances such as faults, loss of generation in the grid can have significant impact on the performance of an NPP. Study of the response of major power plant equipments to grid electrical disturbance is essential to improve the safety and operating performance of nuclear power plants. Among various systems in a nuclear power plant the worst affected components are the turbine generating system and motors which are used for driving various process pumps in the plant. In this project influence of grid electrical disturbance on the operation of motors and generator of 500 MWe Prototype Fast Breeder Reactor (PFBR) currently under construction in India has been studied. In the first set of calculation supply frequency was kept constant and voltage was varied for the PFBR generator and motor. In the next set of calculation the supply voltage was kept constant and frequency was varied for the PFBR motor and generator. In both the cases the variation of electrical parameters like slip, torque, stator current, stator copper loss, rotor copper loss, rotational loss were calculated and studied. Based on these results the safety operating limit of motor and generator were calculated for a grid electrical disturbance. Process implications of grid electrical disturbance on the plant have also been subjected to a brief review.

II. DISTURBANCE TYPE AND HARACTERISTICS

A. LOAD DISTURBANCES :

1) Small random fluctuations superimposed on slowly varying loads.

B. EVENT DISTURBANCES:

1) Faults on a transmission lines due to equipment malfunctions or natural phenomena such as lightning strikes.
2) Cascading events due to protective relay action following severe overloads or violation of operating limits.
3) In a real power system, voltage and the severity and the duration of the event disturbance will also be largely influenced by the power system's inertial energy, spinning reserve, inertia capability and natural load damping. Excursions ranging beyond the limits of these load, frequency and voltage control mechanisms have the potential for causing plant trips, load loss and system separation.

III. DISTURBANCE CAUSE AND EFFECT MATRIX

Magnitude	Type			
	Load disturbance		Event disturbance	
	Cause	Effect	Cause	Effect
Small	• Daily load cycle • Small overload • Random load • Fluctuations	• Frequency error • Voltage deviation • Spontaneous oscillations	• Load trips equipment • Large voltage variations	• Frequency excursion • Load shedding • Sustained oscillations
Large	• Generation overload • Winter freezeup • Inadequate reserve • Circuit overloads	• Frequency drop • Time errors • Low voltage • Loss of plant auxillaries • Plant trips • Line trips	• Faults • Plant outages • Line outages • Destructive natural phenomena	• Frequency excursion • Load shedding • Turbine trips • Islanding instability

DEPICTION OF NUCLEAR POWER PLANT RESPONSE DURING GRID ELECTRICAL DISTURBANCE

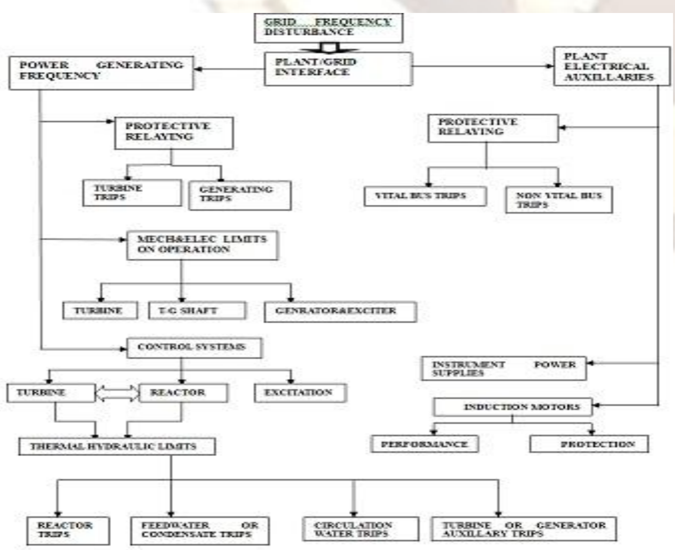


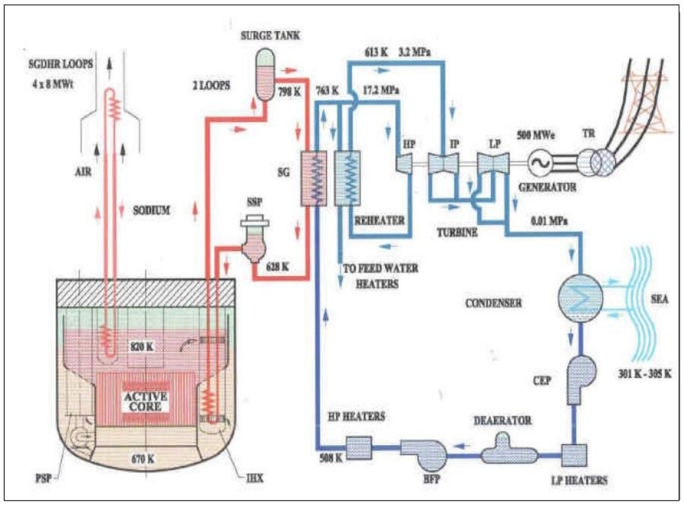
Fig-1

PFBR

PFBR is a 500 MWe, sodium cooled, pool type, mixed oxide (MOX) fuelled reactor with two secondary loops . The reactor is located at Kalpakkam, close the 2 x 220 MWe PHWR units of Madras Atomic Power Station (MAPS).. The primary objective of PFBR is to demonstrate techno-economic viability of fast breeder reactors on an industrial scale. The main characteristics are given in Table. The reactor power is chosen to enable adoption of a standard turbine used in fossil power stations, to have a standardized design with further reduction of capital cost , construction time in future and compatibility with regional grids . Mixed carbide fuel of PuC-UC is used in FBTR due to nonavailability of enriched uranium for MOX fuel option. PFBR being a commercial demonstration plant, a proven fuel cycle is essential. MOX fuel is selected on account of its proven capability of safe operation to high burnup, ease of fabrication and proven reprocessing. Pool type concept is adopted due to its inherently high thermal inertia of the large mass of sodium in the pool which eases the removal of decay heat, use of a simple vessel with no penetrations leading to high structural integrity of the vessel and no radiation damage.

Table-2

PFBR PLANT DESIGN SPECIFICATIONS	
Reactor coolant	Sodium
Thermal power	1,253 MW
Electrical power(gross)	500 MW
Fuel	PuO2-UO2
Core height	1m
Fuel pin dia	6.6 mm
Peak fuel burnup	100 GWD/t
Maximum linear pin power	45 Kw/m
Sodium tempurature at reactor inlet	670 K
Steam condition at TSV	763 K at 16.7 MPa
Reactor shut down systems	2
Decay heat removal system	2
Containment building	RCC/ rectangular
Reactor life	40 years



HEAT TRANSPORT FLOW SHEET OF PFBR
Figure-2

As seen in fig- (A) the heat transport system consists of primary sodium circuit, secondary sodium circuit and steam water system. Primary heat transport from the core is facilitated by two pumps, which drive sodium from the cold pool through the core. The hot sodium flows through the intermediate heat exchanger (IHX), transfers its heat to the secondary sodium and finally returns to the cold pool at the bottom, completing the flow circuit. Use of an intermediate secondary sodium circuit to transfer heat to the steam water circuit prevents the possibility of steam/water leak into the primary system, in the event of a leak in the steam generator tube. This also minimizes the radiation level in the Steam Generator Building, providing better access for maintenance.

IV. ELECTRICAL AND MECHANICAL LIMITATIONS

In this section, the electrical and mechanical limitations of power plant equipment are examined. Particular attention is paid to the main turbine-generator set, which due to the function it provides, represents an obvious potential limitation to plant response capability and which due to its cost and complexity, may represent an absolute limitation as well**.**
Electrical and mechanical limitations on the turbine-generator that may limit nuclear plant response capability occur in the following areas :

C. *TURBINE BLADE RESONANCE*

D. *TURBINE-GENERATOR SHAFT RESONANCE*

E. *GENERATOR TORQUE LIMITS*

F. *GENERATOR EXCITATION*

C.TURBINE BLADE RESONANCE :

Off –speed operation of a turbine of a turbine-generator (T-G) is limited by existence of turbine blade resonant frequencies. A turbine is designed so that at normal operating speed ,it is between blade resonant frequencies. As a result, any departure from the normal speed represents an approach to blade resonant frequency. As a resonant frequency is approached, the affected rows or rows of turbine experience increasing cyclic stress due to increasing amplitude of vibration. The peak magnitude of this vibration rapidly leads to fatigue failure in the affected blade rows. The blade excitation provided by the high steam flows associated with power operation accounts for seemingly allowable frequency bandwidth that does not exist when the machine is unloaded and being either started up or shut down.

D. TURBINE-GENERATOR SHAFT RESONANCE:

Breaker operation associated with synchronizing line switching, fault clearing, and reclosing, as well as faults in the high voltage station bus and transmission lines can cause damage to generator’s air gap flux, and torque transients. In reclosing operations, a serious problem arises as a result of improper timing from the reclosure. The magnitude of the T-G torque transient resulting from the enclosure is actually greater than the initial fault-induced transient. Poor timing may even increase the amplitude of the shaft stress beyond that of the shaft’s torsional yield stress.

Torsional stress cycling induced by generator torque transients of lesser magnitudes are also problematic as stress cycling can significantly contribute to T-G shaft fatigue failure. So we have to monitor the total number of torsional stress cycles as well as the magnitude of stress transients. In monitoring for shaft fatigue failure, not only is the initial transient of concern but subsequent oscillatory peaks are of concern as well, since these subsequent peaks may also be of a significant magnitude. This is true when the natural resonant frequency of the T-G shaft is at natural frequency of the power system.

E. GENERATOR TORQUE LIMITS :

A GED resulting in the imposition of a severe generator overload, particularly in a machine which is underexcited, may cause generator electromechanical torque limits to be exceeded. The ensuing phenomenon of “slipping poles” imposes destructive mechanical stress on generator winding and the T-G shaft. Slipping poles represents a loss synchronism with grid.

F. *GENERATOR EXCITATION*

The performance of generator excitation systems has an important effect on nuclear plant response to grid electrical disturbances. The generator excitation system supplies direct current to the generator field windings. Generator field current controls generator voltage and reactive power output.Field current in turn is controlled by either a DC (field) voltage regulator(form of a manual control) or an AC(generator output) voltage regulator(form of automatic control).

The following are the various operating conditions and the response characteristics which were observed :

1) UNDERFREQUENCY :

Maintaining generator output voltage during underfrequency condition will result in high field and stator currents and high internal temperatures. The high temperature condition will be aggravated by the fact that the flow of hydrogen and stator cooling will be decreased from normal as a result of underfrequency condition. If field voltage is reduced to control the temperature rise, the risk of losing synchronism with the system is increased unless turbine output is decreased.

2) **UNDERVOLTAGE**

Maintaining rated generator voltage during conditions of severe system undervoltage results in both high field and stator currents and high internal temperatures. As in the case of underfrequency, the reduction of field voltage to control the temperature rise must be accompanied by a reduction in turbine output in order to avoid increasing the risk of a loss of synchronism.

3) **OVERFREQUENCY :**

An overfrequency condition has effects on the exciter and generator that are roughly opposite to those described for underfrequency conditions, the maximum attainable generator output voltage increases and if the AC voltage regulator is not in service,the generator output will increase.

Overfrequency also imposes limits on the electromechanical exciter –generator circuit ,however the increased forces associated with overfrequency that are experienced by the rotating parts of the exciter and generator may lead to serious damage.

4) **OVERVOLTAGE :**

An overvoltage imposed on a generator will result in decreased field current and increased stator currents. But the maximum voltage to which the generator may be subjected is limited by Overvoltage results in breakdown of insulation. The dynamic performance of a generator excitation system affects the damping of power oscillations that may occur during a severe

V. METHODOLOGY OF ANALYSIS

$$P_{in}= 1.732V_LI_L\cos\varphi$$

P= Power input of motor
V_L= line voltage in Volt
I_L= line current in ampere
$\cos\varphi$= power factor

$$Pout = 1.732*V_aI_a\cos\theta$$

P= Power output of motor in KW
V_a= load voltage in Volts
I_a= load current in ampere
$\cos\theta$= power factor

$$S= \frac{(Ns – N)}{(Ns)}$$

S = Slip
Ns= Synchronous speed in rpm
N = Rated speed in rpm

$$\omega_s= \frac{(2*\Pi*N_s)}{(60)}$$

ω_s=Angular velocity
N_s= Synchronous speed

$$Torque = \frac{(Power\ o/p)}{((1-s)\ \omega s)}$$

S= Slip
ω_s=angular velocity

$$Pg= 3I^2R_f$$

P_g= Power generated in KW
I= Stator current in ampere
R_f= Field resistance in ohm

$$M_{o/p}= (1-s)P_g$$

$M_{o/p}$= Mechanical output
S= slip
P_g= Power generated

$$S_{cu}\ loss= 3*I^2*Z_{in}$$

I= Stator current in ampere
Z_{in}= Input impedance

$$R_{cu}\ loss = s*P_g$$

R_{cu} loss= Rotor copper loss in KW
S = Slip, Pg = Power generated in KW

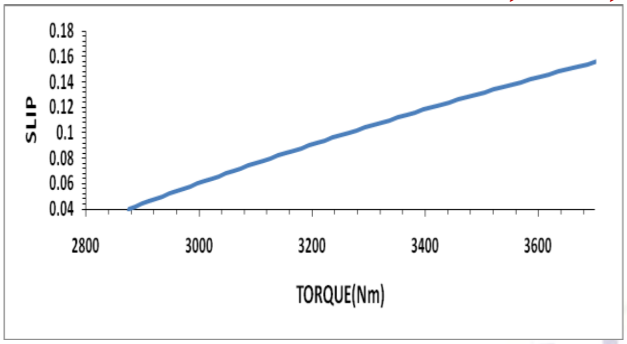
Total loss = Rotational loss+ S_{cu} loss+ R_{cu} loss in KW

$$\dot{\eta} = \frac{(Pout)}{(Pin)}*100$$

$\dot{\eta}$ = Efficiency of motor
P_{out}= Gross output power in KW
P_{in}= Input power in KW

VI. ANALYSIS OF PUMP PERFORMANCE CONSTANT VOLTAGE AND VARIATION OF FREQUENCY FOR PFBR BOILER FEED PUMP

This is an 6600V, 10700KW induction motor. The calculations were done keeping the voltage as constant and frequency was varied from 50Hz to 45 Hz and the dynamic changes that occurred were noted and tabulated.



(Fig- 3 Slip Vs Torque)

As the slip increases from 0.04 to 0.160 the torque increases linearly from 2851 Nm to 3703 Nm. For an increase in slip of 2 % the torque increases by 4 %.

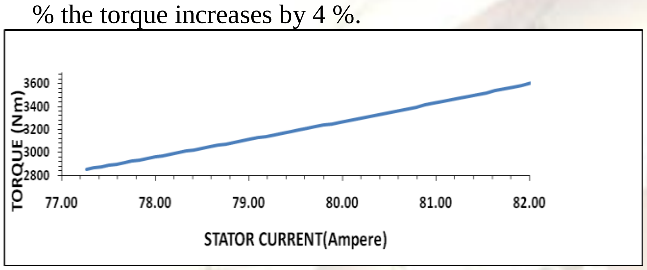
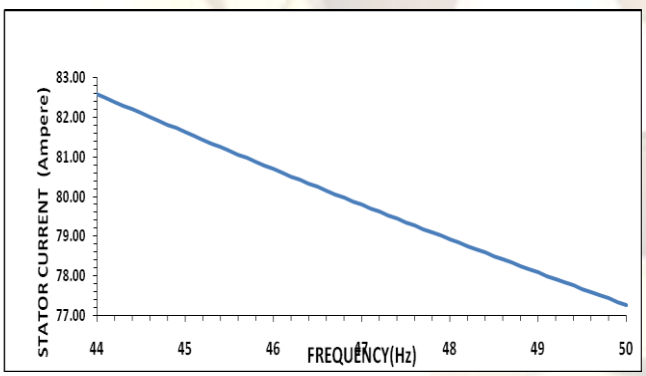


Fig-4 Torque Vs Stator current

Here, as the supply frequency decreases by 10 percent the stator current increases by 6 percent

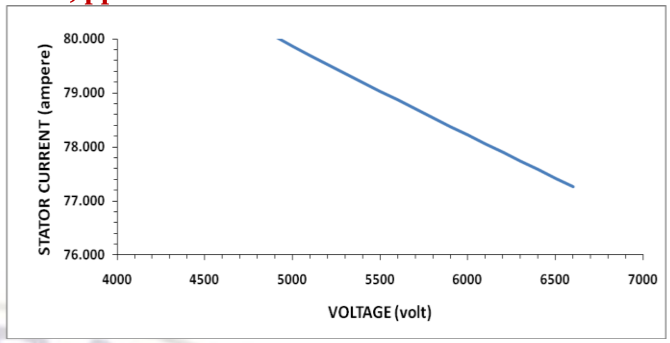


(Fig-5 Frequency Vs Stator current_

As supply frequency decreases by 5 percent the stator current increases by 3 percent.

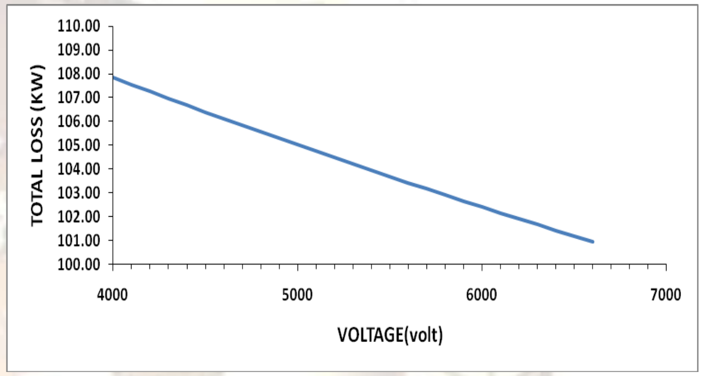
VII. **CONSTANT FREQUENCY AND VARIATION OF VOLTAGE FOR BOILER FEED PUMP**

Supply frequency was kept as constant and supply voltage was varied for the induction motor in steps of 100V. The supply voltage was varied from 6.6kv-4kv.



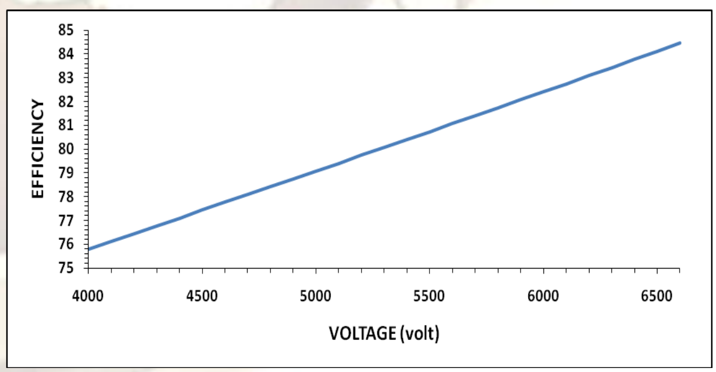
(Fig-6 Stator current Vs Voltage)

As supply voltage decreases from 6.6 kv to 4 kv the stator current increases by 9 percent.



(Fig- 7 Voltage Vs Total loss)

Here, it is observed that as the voltage decreases by 10 percent the total loss (stator copper loss+rotor copper loss+eddy current loss+hysteresis loss) increases by 7 percent.

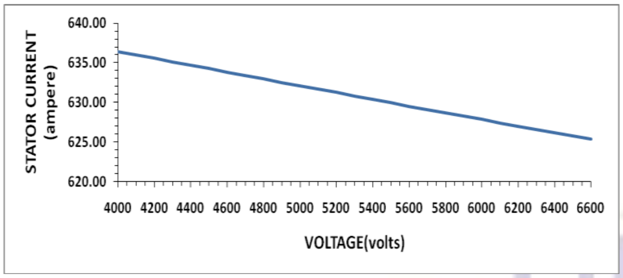


(Fig-8 Voltage Vs Efficiency)

So as the supply voltage is decreased from 6.6 kv to 4 kv the efficiency of the BFP decreases by 7 percent.

VIII. **ANALYSIS OF GENERATOR PERFORMANCE CONSTANT VOLTAGE AND VARIATION OF FREQUENCY**

In the second set of mathematical analysis the supply frequency was kept as constant and supply voltage of generator was varied in steps of 100V. The voltage was varied from 6.6kv-4kv.

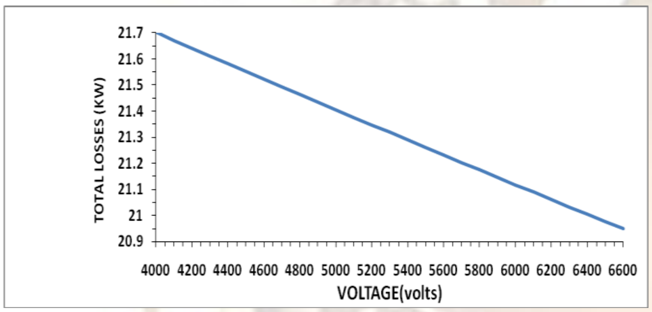


(Fig-9 Stator current Vs Voltage)

Here, when voltage decreases by 10 percent the stator current increases by 4 percent.

(**Fig- 10 Torque Vs Stator current)**

Here as the torque increases by 5 percent, the stator current increases by 7 percent.

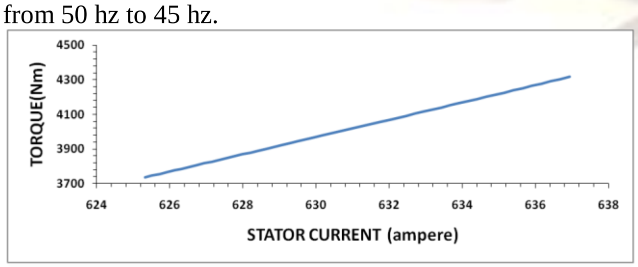


(Fig- 11 Voltage Vs Total loss)

Since the current drawn increases as during the voltage drop to compensate for the increased required torque, the heating effect of increased current on coils and windings also increases. So, total loss that includes the eddy current loss, hysteresis loss also increases with decrease in voltage In the above graph the total loss increases by 9.5 percent when the voltage decreases by 10 percent.

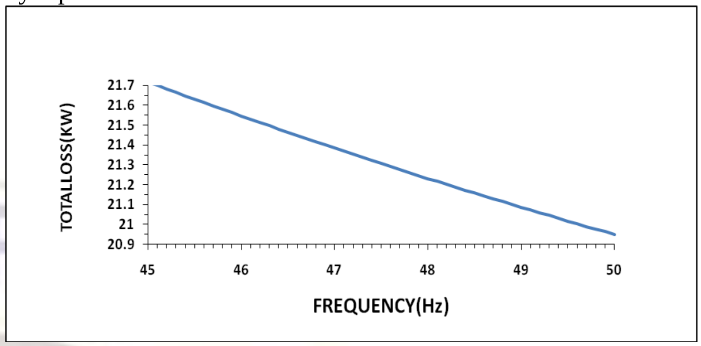
IX. CONSTANT VOLTAGE AND VARIATION OF FREQUENCY

The supply voltage is kept constant and the supply frequency of generator is varied in steps of 0.1hz. The frequency is varied from 50 hz to 45 hz.



(Fig- 12 Torque Vs Stator current)

It is observed that in order to deliver the same power at a reduced grid frequency, torque increases. Thus, to compensate for the increased torque the stator current increases. Here, as the torque increases by 5 percent, the stator current increases by 4 percent.



(Fig- 13 Frequency Vs Total loss)

It was found that during grid frequency decrease the total loss of generator increases ,hence the heating due to these losses increases as the supply frequency decreases by 10 percent the total losses increase by 11 percent .

X. IMPACT OF GRID FREQUENCY VARIATION ON PROCESS DYNAMICS

When the grid frequency reduces, operating speed of all the motors reduces nearly proportional to the frequency variation. According to affinity law, pump supplied flow is proportional to speed of operation of the pump. Thus, frequency variation power supply to motors proportionally affects the flow supplied by pumps. Maximum temperature difference across fuel channels in PFBR is ~ 170 0C. Thus, 3 % variation in flow affects the coolant temperature at the outlet of fuel channels by 5 0C. Alarm will be generated when the coolant temperature increases by this value. In order to overcome this process constraint, primary and secondary sodium pumps are provided with variable frequency drives with a speed controller designed to control the speed within ± 1 rpm. Thus, the there will not be any impact due to supply frequency variation on the primary and secondary heat transport system. Now, coming to the tertiary circuit (i.e. the steam water system), variable frequency drives are not provided for boiler feed pumps, condensate extraction pumps and condensate cooling water pumps. Feed water flow is manipulated by a control valve to control the sodium temperature at the outlet of steam generator. This control action makes the feed water flow in the steam water circuit independent of grid frequency variation. Apart from this, level controller provided for the deaerator manipulates the feed water flow supplied by the condensate extraction pumps to the deaerator. With this control system in place, the flow supplied by condensate cooling pumps also becomes insensitive of grid frequency variation. Turbine is provided with speed as well as pressure control systems. Under a grid frequency variation, the turbine controller will enter into an oscillating mode of operation due to the conflicting requirements of speed and pressure control systems. Thus, it is the turbine performance that generally decides the permissible frequency variation for the plant

XI. CONCLUSION

It was observed that in case of generator, when the when the variation in frequency is from 50-47.5 Hz, torque of the generator increases by 8 %. There is rise in stator current to produce the additional torque required for generator operation. This increase in stator current leads to heating effect in windings of stator and rotor. There is 8 % increase in heat generated which is within the manageable limits.

Similarly, when the supply voltage for reduces from 6.6kV to 6kV, generator draws higher stator current to compensate for the increased torque. It was observed that during the decrease in supply voltage the torque of the generator increases by 9 %. Heat generated in the windings of stator and rotor due to rise in stator current increases by 4.3 % only. Similarly, when the supply voltage for reduces from 6.6kV to 6kV, generator draws higher stator current to compensate for the increased torque. It was observed that during the decrease in supply voltage the torque of the generator increases by 9 %. Heat generated in the windings of stator and rotor due to rise in stator current increases by 4.3 % only. Hence, there is no concern. Impact of grid electrical disturbance on the operation of motors and generators has been found to be benign. Nevertheless, impact on the operation of turbine controller needs to be subjected to a detailed study for arriving at limiting grid electrical disturbances for plant operation, as there is a chance for this controller to enter into an oscillating mode of operation.

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