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Effect of Increased Generation and AVR on the Transient Stability at a Nuclear Power Plant

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Abstract— Automatic Voltage Regulators (AVR) installed on generators play a major role in transient stability analysis. Using DIgSILENT software permits analysis of the behavior of the system under transient condition with and without the AVR. Analysis of the critical clearing time using results from the simulation will give insight into the effect of the AVR on the critical clearing time. This will allow for more defined protection settings to prevent unnecessary trips. In this paper, DIgSILENT is used to determine the critical clearing time at Koeberg nuclear plant taking into account the AVR. Various scenarios such as increase in generation, AVR switched in and out of circuit and three-phase short circuits on the HV busbar were simulated, assessed and analyzed to validate the model and give insight into the critical parameters that can be modified to protect Koeberg generators from pole slipping. The case studies show that the generators will not pole slip with an increase in generation and that the AVR has little to no effect on the critical clearing times when the HV network is subjected to a three-phase fault.

Key Words — AVR, critical clearing time, transient stability, nuclear power plant

I. INTRODUCTION

The South African electricity utility is under immense pressure to ensure continuity of supply. The South African power grid, especially the Western Cape, is susceptible to instability due to the long transmission lines and lack of base load power generation. The nuclear incident at the Fukushima Nuclear Power plant has demonstrated that a more rigorous approach to nuclear power plant operation is required [1]. South Africa's only nuclear power station Koeberg has plans in place to increase its Thermal Power Capability by replacing the steam generators [1]. The replacement will allow an increase in electrical output power from 960MWe to 1100MWe. The increase in electrical power output requires analysis of its protection scheme. This provides us with an opportunity for developing a plant model which could be used for the analysis of plant upgrades as well as fault simulations.

Nuclear power stations rely on internally generated power to supply their safety related equipment. As such, the output of the generator is fed back to the main power supply bus system of the station via a step-down transformer. Serious faults can occur more frequently as plants become older and harsh weather conditions can further compound the ailing health of these plants. It is therefore imperative to perform transient stability analysis for ageing nuclear power stations to ensure minimal disruption to continuity of supply during the said transient conditions.

Transient stability studies are concerned with the ability of the power system to withstand large faults or disturbances. If the system can return to its original operating state or a new state once the disturbance is removed, the system is said to be stable [2]. The types of disturbances range from transmission line loss due to lightning strikes and/or broken conductors, loss of generation, increase in load demand and a decrease in generating capability.

Usually numerous simulations are conducted to verify plant parameters and responses for different scenarios to give insight into the behaviour of the network under different conditions. The simulation results allow system operators to adapt the network to pre-empt failure. Even a well-designed and normally operated system may face the threat of transient instability [2]. Computer based stability analysis is an important component of power systems operations and planning. As a result, it is crucial that the models and parameters of the generators and associated excitation systems are accurately assessed to ensure that results are representative of the real power system. The main objective of this study is to validate the models and parameters of the Koeberg Power Station reticulation network and the effect of the AVR on the critical clearing time of the plant under various conditions. Furthermore, the effect of increasing output power generation on critical clearing times was also investigated [3, 4].

The simulation software package used to validate the results in this paper is DIgSILENT software package [5]. DIgSILENT is a computer-based software package, providing power system modeling, analysis and simulation. This software package is widely used by system operators to validate power system models to quantify risk and uncertainty in simulation models. These model validation studies are considered during planning and design stages of a new power station as well as evaluating changes to an existing system during the operational phase [3, 4].

Load flow studies for the nuclear power station have been completed, but many changes have since been made to the plant which necessitates a re-calculation of these load flow studies to ensure that all plant operating criteria and protection settings are within an acceptable range [6].

Nuclear Power plants are designed and maintained to operate at maximum capacity at all times. Protection systems ensure stability of supply by only isolating the defective component/equipment and ensuring continuity of supply. Although the protection scheme at the nuclear power plant has been in place for quite some years, a verification of the settings needs to be completed from time to time [7, 8].

The settings were based on network and plant parameters and when these parameters change, the protection scheme needs to be adapted accordingly.

II. RESEARCH STATEMENT

The research proposal initially entails performing a short circuit study of the Koeberg Nuclear Power Station. Next, the responses of the AVR during and after grid disturbances are investigated. Then the effects of increased electrical power generation output on the critical clearing times are analyzed. These studies and results can be used for future plant modifications as well as understanding plant behavior during transients. Transient network disturbances are becoming more common on the South African network as it is operating close to maximum capacity with little generation spinning reserve [7, 8].

III. THEORETICAL BACKGROUND

Each generator connected to a power system operates at the same frequency which allows the machines to operate at the same synchronous speed. This network frequency is usually 50 Hz or 60 Hz depending on national standards. In South Africa, the standard is 50 Hz. A delicate balance between supply and demand is maintained by keeping the network frequency stable.

Large fault occurrence and load loss causes unwanted network frequency fluctuations. When large loads are connected to the network and the total load of the network exceeds the generating capacity the network frequency is subsequently reduced.

All power systems are subjected to faults and component failures. Depending on the severity of the fault (disturbance) this could disturb the balance between mechanical power and electrical power. Once this balance is disturbed some generators will increase speed and some will decrease speed. If the generators are unable to maintain their speed due to the disturbance, they will lose synchronism, and will go “out of step” with the rest of the network. The ability of the generators connected to the network to withstand this disturbance and to remain synchronised to the network is known as transient stability [9].

To better explain the transient stability phenomenon a simplified two-machine system as shown in Fig.1. The network consists of a synchronous generator and a synchronous motor which are connected through a series inductive reactance X also shown in Fig.1. The synchronous machines can be independently represented by a constant voltage sources namely E_G and E_M. The machine output terminal voltages are represented by E_{GT} for the generator and E_{MT} for the motor. Each machine has its own internal reactance, namely X_G for the generator and X_M the synchronous motor. The line reactance is X_L. The total reactance which is the sum of all the reactances X_G, X_M and X_L is given by equation 1 [10, 11].

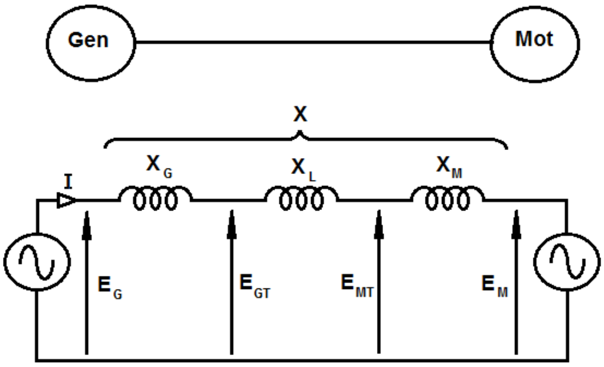

Fig.1.Simplified two-machine power system model [10, 11]

The system can be represented by the following phasor diagram in Fig.2. The angular difference (δ) between the generator voltage and the synchronous motor voltage is determined by the amount of power transferred from the generator to the motor.

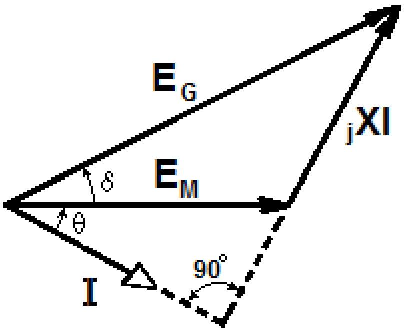

Fig.2.Phasor diagram of the two-machine system [10, 11]

.

$$X = X_G + X_L + X_M \tag{1}$$

The relation between E_G and E_M is given as in equation 2,

$$E_G = E_M + jXI \tag{2}$$

Hence the current I is,

$$I = \frac{E_G - E_M}{jX} \tag{3}$$

The real power output of the generator is given by equation 4,

$$P = \mathrm{Re}\,(\overline{E_G}\, I)$$

$$= \mathrm{Re}\left(\overline{E_G}\,\frac{E_G - E_M}{jX}\right) \tag{4}$$

where Re means "the real part of" and $\overline{E_G}$ means the complex conjugate of E_G
Now let,

$$E_{M=} E_M \angle 0$$

and

$$\overline{E}_{G=} E_G \angle -\delta$$

So,

$$P = R_e\left(E_G \angle\{-\delta\} \frac{E_G \angle\delta - E_M \angle 0}{X \angle 90°}\right)$$

$$= R_e\left(\frac{E^2{}_G}{X} \angle(-90°) - \frac{E_G\, E_M}{X} \angle(-90° - \delta)\right)$$

$$= -\frac{E_G E_M}{X} \cos(-90 - \delta)$$

$$= \frac{E_G E_M}{X} \sin\delta \tag{5}$$

Equation (5) shows that the power P transmitted from the generator to the motor varies with the sine of the displacement angle δ between the two rotors, as plotted in Fig.3.

The curve P versus δ is known as the *power angle curve*.
The maximum power that can be transmitted in the steady state with the given reactance X and the given internal voltages E_G and E_M is,

$$P_{max} = \frac{E_G E_M}{X} \tag{6}$$

This occurs at a displacement angle $\delta = 90°$. The value of maximum power may be increased by increasing the internal voltages or by decreasing the circuit reactance [10, 11].

A. Swing equation

The electromechanical equation describing the relative motion of the rotor load angle (δ) with respect to the stator field as a function of time is known as swing equation [11]. The swing equation in terms of the inertia constant becomes,

$$M \frac{d^2\delta_m}{dt^2} = P_m - P_e \tag{7}$$

M = inertia constant.
P_m = Shaft power input
P_e = Electrical power output
δ_m = mechanical power angle

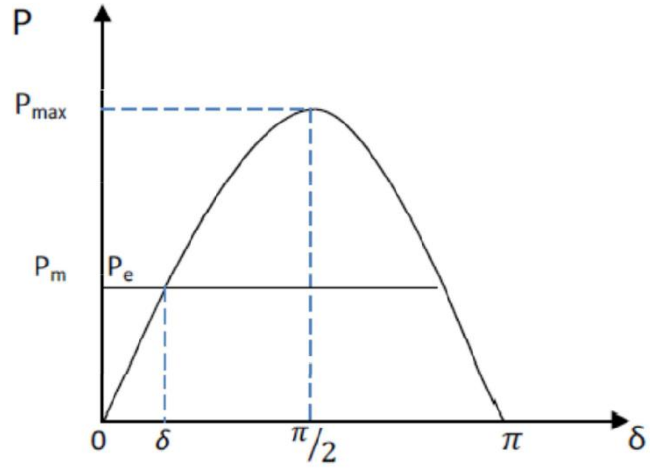

Fig.3.Power angle curve

B. AVR and their effects on transient stability

Automatic Voltage Regulators are commonly used to regulate the terminal voltage of generators. They also aid with reactive power flow.

There are two main types of excitation systems namely:

- Excitation fed through slip rings via brushes (older system)
- Brushless excitation systems

The synchronous generator keeps the terminal voltage magnitude at a pre-set value. A simplified control loop can be seen in Fig.4.

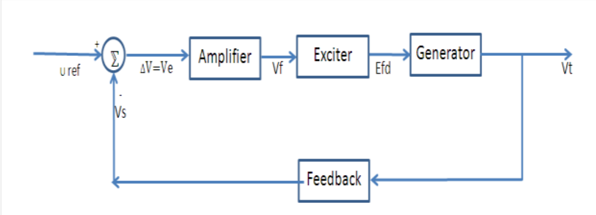

Fig.4.AVR block diagram

If the terminal voltage of the generator in Fig.4 drops the control loop sensors detect a change in voltage compared to the reference voltage and increases the excitation to maintain generator output voltage at a desired value [12].

Exciter models differ depending on the type of design used. Fast acting static exciters respond much faster than rotating exciters. The inertia response time of the rotating equipment severely impacts on the excitation voltage response to large transients when compared to static controlled excitation system which responds almost immediately to maintain output voltage [13].

IV. NETWORK MODEL

The network model used in the paper is based on a simplified model of nuclear power station connected to an infinite bus as shown in Fig.5. The infinite bus (400kV) represents the rest of the reticulation network which is simulated as a grid in-feed with the short circuit parameters of the network at the HV busbar to simulate the entire network. The generator has an output voltage of 24kV which is referred to as the LV busbar in the network.

The internal plant reticulation is modeled up to and including the 6,6kV network with the loads lumped for simplicity. A short circuit analysis was performed on the 6,6kV network to authenticate results and validate the model.

The Nuclear Power Station has a rotating exciter. As a result, the controlled excitation voltage energises the field of the main exciter. The main exciter's output is then rectified via rotating diodes and then routed to the field winding of the synchronous machine. The AVR and exciter model used for the simulation was the IEEE ST5B type AVR and exciter. This model emulates the AVR installed on the plant.

The excitation control system at the Nuclear Power Plant consists of three independent control loops. The normal operating condition of the excitation system consists of two channels (Channel 1 and Channel 2) and is supplied by the shunt connected excitation transformers [14]. Each channel consists of an automatic voltage regulator (AVR) and a field current regulator.

The emergency channel (Channel 3) is fed via a separate excitation transformer. Channel 3 has a dual function. It acts as an emergency channel under operational conditions, i.e., it will take over excitation if neither Channel 1 nor Channel 2 cannot control the required excitation current to the machine. Its second function is exclusively used for testing purposes while it is selected to open loop control [14]. The parameters of the generator are shown in the Appendix 1 and the block diagram of the AVR can be seen in Appendix 2.

V. SIMULATION RESULTS

In this section, results from three case studies are presented to give better insight into the behavior of the system when a three-phase short circuit is applied to a HV busbar close to the generator at a nuclear power station. The analysis of these results will help evaluate vital parameters to ensure correct operation of the nuclear power plant when changes are made.

Case study 1

Investigates the difference between the short circuit levels found on the various 6,6kV switchboards. This is ultimately used to validate the DIgSILENT model with known short circuit results

Case study 2

Studies the effect the AVR has on critical clearing times. A short circuit was placed on the HV busbar and fault clearance times were varied to ascertain the critical clearing times. The reactive power waveforms and the generator rotor angle (with respect to the machine angle) were monitored to confirm stability or the point of instability.

Case study 3

Investigates the effect of increased generation on the critical clearing time. The generator output was increased from 960MW to 1100MW. An iterative approach was used to confirm the critical clearing time. All the auxiliary equipment like the generator and transformer has been upgraded in anticipation of this modification.

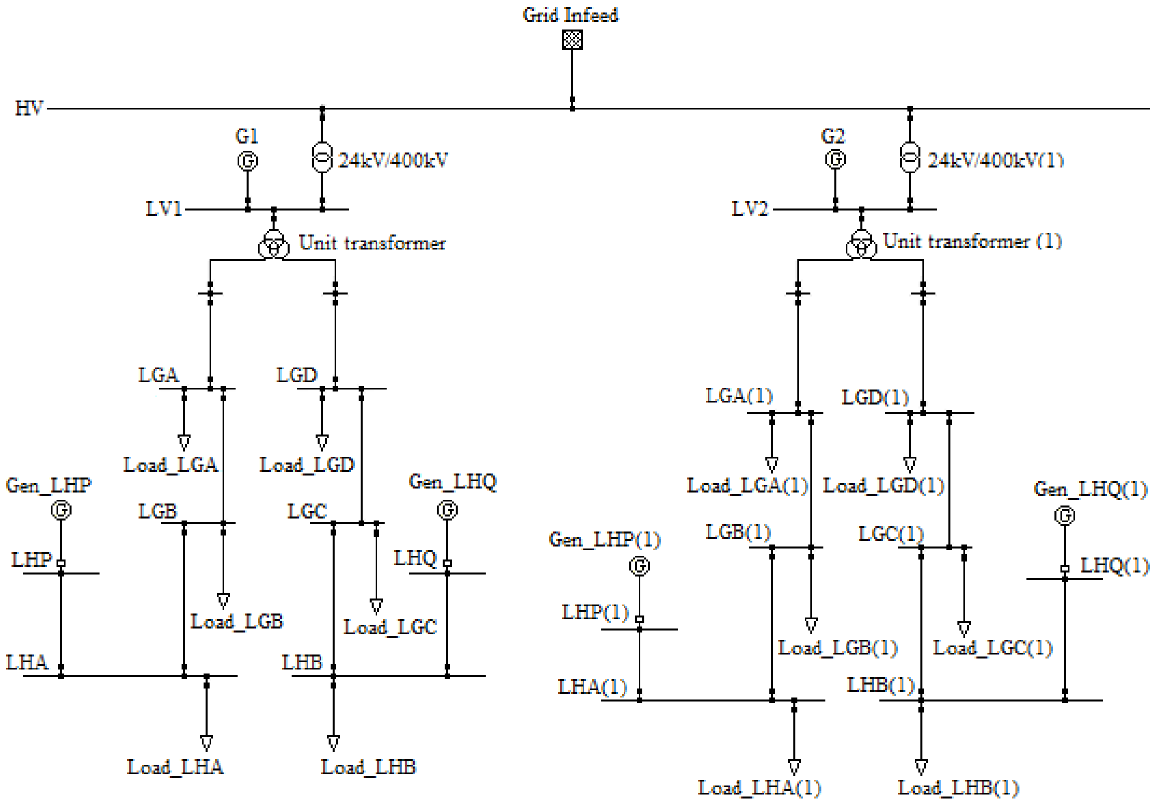

Fig.5.DIgSILENT network model

VI. DISCUSSION OF RESULTS

Case study 1

The short circuit analysis simulated results show good correlation with the plant data. The various 6,6kV switchboard fault data was compared and listed in Table 1.There is an error of between 2-4% which is acceptable for this study.

Table 1 .Short circuit results

Switchboard	DIgSILENT	Plant Data	Error
N/A	kA	kA	%
LGA	27.5	28.09	2.1
LGB	27.03	27.57	1.95
LGC	26.13	27.22	4
LGD	26.36	27.47	4.04
LHA	26.55	27.14	2.17
LHB	25.88	26.80	3.43

Case study 2

The analysis of the simulations confirmed that there is no major difference between the critical clearing times when the AVR (rotary type) was installed and when it was out of service. The critical clearing time with the AVR in service was 0.232s, and without the AVR the clearing time was 0.221s.

There is a difference of 0.011s between AVR in service and AVR out of service. This is mainly due to the slow response of the excitation voltage which took 0.739s to reach maximum excitation voltage. The exciter design is a rotary type which could explain the slow response of the AVR.

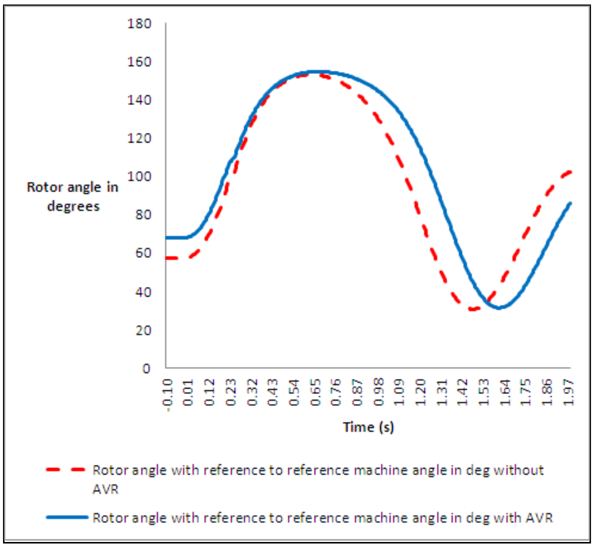

Fig.6. Rotor angle difference between AVR in service and out of service

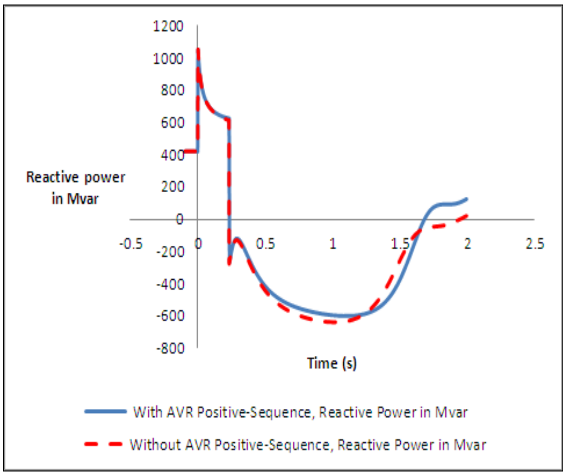

Fig.7.Reactive power difference with AVR compared to no AVR

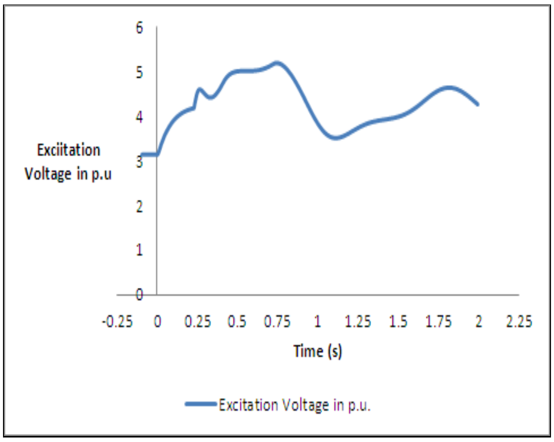

Fig.8.Excitation voltage response

Case Study 3

With the plant planning to increase its generator output from 960MWe to 1100MWe. This case study gives insight into the network configuration when the output power of the generator is increased. The critical clearing time was 0.2322s before the output of the generator was increased. The new critical clearing time is 0.1655s with the generator output increased. This is a difference of 0.066s.Waveforms of the generator speed and rotor angle with respect to machine angle (fault clearing time of 0.166s) can be seen in Fig.9. This fault clearing time puts both generators into a “Pole Slip Condition.” The normal clearing times in the HV transmission plant never exceeds 100ms and thus confirming that no protection setting requires adjustment and new operating parameters can be established [6].

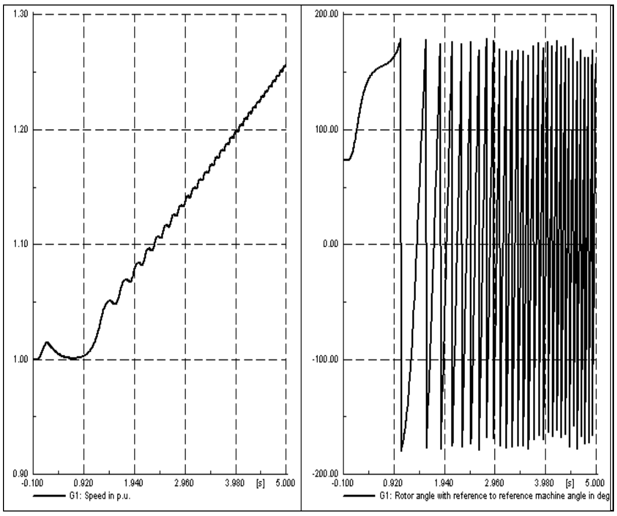

Fig.9.Instability Waveforms at clearing time 0.166s

VII. CONCLUSION

The simulations performed have resulted in a number of insights into the transient stability of the power station.

In the first case study the model validity was proven and gave comparable results compared to existing documentation pertaining to the nuclear plant. The model gives the power station a base platform to perform further studies relating to any electrical modification which could have impact on the short circuit levels and transient stability.

The simulations indicate that the use of a rotary type AVR have no substantial impact on the critical clearing time of the power station.

Case study 3 shows that an increase in generation by 12% reduces the critical clearing time by 28%. The new critical clearing time is very close to the boundaries of the 0.1s maximum operating time of the protection scheme and auxiliaries. Therefore this should be considered in the design of the thermal power upgrade project.

All studies completed give confidence in the system model and the effect different parameters have on the nuclear power station. The study ensured that the integrity of nuclear plant is maintained and that the plant will not trip unnecessary for faults at the HV busbar closest to the power plant. This caters for generator house loading after a transient fault without causing a “Pole Slip” event.

VIII. ACKNOWLEDGMENTS

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Appendix1 Generator Parameters

Generator Parameters	
Manufacturer	ALSTOM
Generator Rating	1072 MVA
Power Factor	0.9
Maximum Continuous Rating	965 MW
Rated Stator Voltage	24 kV
Rated Rotor Voltage	220 V
Rated Frequency	50 Hz
Rated Stator Current	25788 A
Rated Excitation Voltage	443 V @ 5719 A
Ceiling Current	9600 A @ 744 V
Total Mass Inertia Constant	5.93(H –MWs/MVA)

Appendix 2 AVR block diagram