- CHAPTER 7 -

CONCLUSIONS AND RECOMMENDATIONS

"I can do everything through Him who gives me strength"

Philippians 4:13

7.1 INTRODUCTION

The purpose of this study was to develop a pole-slip protection function that can trip a synchronous machine before it falls out of step (or pole-slip) when subjected to a network fault or disturbance. The new pole-slip function will predict whether the generator will become unstable while the fault occurs. The generator will then be tripped before the fault is removed in order to minimize damaging post-fault torque effects. This chapter presents the conclusions and recommendations of the study.

7.2 FINDINGS AND DEDUCTIONS

7.2.1 SYNCHRONOUS MACHINE BEHAVIOUR DURING OUT-OF-STEP OPERATION

The basic theory of synchronous machines was discussed. Machine conventions were reviewed to determine the signs of variables like torque, speed and others to be used in the pole-slip protection function. It was concluded that it is important to include the effect of saliency in the generator model for stability calculations. Equations were derived that can be used to determine the steady-state power angle for a synchronous machine.

A basic approach to excitation systems was also given to understand the transient response of the machine EMF during disturbances. It was found that the transient EMF of a synchronous machine does not vary considerably during a fault of a short duration (up to 300 ms). It was concluded that the pre-fault transient EMF could be used in the pole-slip protection function.

Shaft torque stress during pole-slip scenarios was investigated to determine the mechanical stress effects of pole-slipping on machine shafts. It was concluded that it is not practical to calculate transient shaft torque during the fault due to the complexity of the generator model. It was decided that machine stability will rather be predicted to trip the machine before the fault is cleared to avoid the post-fault shaft stresses.

It was explained in detail why round rotor generators need to be modelled with a transient quadrature axis reactance X_q' and why salient pole generator models do not include X_q'. Due to the presence of X_q' in round rotor generator models, a new reactance was introduced, namely X_{q_avg}. The intent of this new reactance was to use it in the equal area criteria that forms part of the new pole-slip protection function.

Subsynchronous resonance was briefly introduced. Subsynchronous torques on the shaft between the turbine and the generator shaft can be determined by observing the machine active power fluctuations. Subsynchronous resonance can, however, not be determined between the different stages of the prime-mover by observing electrical parameters like the generator active power. It was decided not to include the effects of subsynchronous resonance in the pole-slip function.

7.2.2 IMPEDANCE POLE-SLIP PROTECTION

The method of operation of conventional impedance pole-slip relays was investigated. The algorithm used in the conventional impedance pole-slip relays was derived from first principles to get a proper understanding of the impedance scheme.

An example case study was investigated to determine how a conventional pole-slip relay will perform in certain network switching configurations. It was found that impedance relays can become inaccurate by switching in/out paralleled generators and shunt loads.

The effect that transmission line impedance has on conventional impedance relays and the effect it will have on the new pole-slip protection function were evaluated. Transmission line per-unit impedance data was obtained from transmission line manufacturer's data. This data was processed to obtain a typical per-unit impedance range for transmission lines, which can be used to test the new pole-slip protection function. It was concluded that the effect of the shunt admittance of a transmission line is included in the transfer angle calculation, since the voltage and current measured at the sending end of the transmission line includes the compensation effect of the shunt admittance. No additional shunt admittances are required to be modelled into the pole-slip protection function, and therefore the transmission line shunt admittance parameters are not required to be known for the new pole-slip function.

The shortcomings of impedance relays, such as network switching configurations and operation with shunt loads were investigated. Recommendations on how to incorporate shunt loads in impedance pole-slip relays were also made. It was suggested to measure the active and reactive power of the transmission line feeders, as well as the active and reactive power of the shunt load feeders.

Transmission line feeders were defined as feeders that connect to other power stations via transmission lines. Shunt load feeders were defined as feeders that feed loads like large factories or municipalities and power station internal loads etc. By measuring transmission line feeders, it can be determined which

transmission lines are in operation. The shunt load feeders were treated as loads that will cause the pre-fault transfer angle between the generator EMF and the infinite bus to decrease. This effect was included in the new pole-slip function algorithm.

7.2.3 PROPOSED POLE-SLIP PROTECTION FUNCTION

The new pole-slip protection function was designed and explained in detail. Both the steady-state and transient calculations were discussed. The new pole-slip protection function uses the equal area criteria as a basis to predict stability. The equal area criteria is only useful if the post-fault voltages on the generator and transformer terminals as well as the transient power angles of the generator and transformer is known. Since the post-fault voltages are not known during the fault, these voltage magnitudes have to be predicted while the fault occurs.

The Thévenin theory was used to simplify the network with paralleled generators and shunt loads. Protection relay limitations were kept in mind while designing the pole-slip function. Logics for the ABB REM543 relay as well as PSCAD logics were presented to indicate how the new pole-slip algorithm equations can be implemented in typical protection relay logic format.

The transient state vectors presented in textbooks for synchronous machines are typically only valid for salient pole machines. Round rotor generators have a more complex transient power curve characteristic than salient pole machines because of a transient quadrature axis reactance X_q', which is not present in salient pole machine models. An algebraic expression had to be developed that can describe the post-fault power curve characteristics of round rotor machines, which could be used to determine *Area 2* of the equal area criteria. A new parameter (X_{q_avg}) was introduced, which is the average value of the transient quadrature axis reactance of round rotor generators during the post-fault period. X_{q_avg} had to be predicted for use in the equal area criteria. It was found that the value of X_{q_avg} is not calculated accurately for faults shorter than what is required to put the generator in a *marginally* stable / unstable scenario. Fault durations shorter than the minimum duration that could cause the generator to remain *marginally* stable are of no importance to stability calculations, since the pole-slip function will refrain from tripping for these (short/stable) fault scenarios. The methodology developed of predicting X_{q_avg} proved to be working accurately for all fault scenarios where the generator remained marginally stable and for faults where the generator became unstable.

Correction factors were introduced to compensate for errors where equations were used during Thévenin circuit simplifications that neglect saliency. It was found that the correction factors only needed to be introduced for round-rotor machines and not for salient pole machines. The reasons for this finding were discussed in detail. The correction factors were designed to be “self-tuning” for different pre-fault generator loading conditions.

7.2.4 VALIDATION OF NEW POLE-SLIP PROTECTION FUNCTION

The performance of the new pole-slip function was evaluated by building the new pole-slip algorithm logics in PSCAD. Since it is impractical to do stability tests on a real power system, PSCAD was used to simulate power system pole slip conditions. In parallel to this power system simulation, the new pole-slip protection logics were executed in PSCAD and tested by comparing the results with the PSCAD power system simulation measurements.

Different stages in the new pole-slip algorithm were monitored. Some of the stages include post-fault voltage prediction and transient power angle calculations. The checks confirmed that the algorithm calculated the transient power angles with an error of less than 0.5 degrees. The post-fault voltage magnitudes were also calculated with sufficient accuracy.

The evaluation criteria included tripping before a pole-slip occurs, but to refrain from tripping if stability could be maintained after a fault is cleared. It was found that the new pole-slip function could predict stability within a 10 ms fault duration error margin. This means that the new pole-slip function will predict stability accurately for all fault durations, except for a 10 ms band. In the unlikely scenario that the fault duration lies within this 10 ms band, the pole-slip function will not trip the machine although it will become unstable after the fault. The pole-slip function was designed to be conservative towards not giving spurious trips. For inaccuracies, the new pole-slip function will rather refrain from tripping instead of tripping where stability could be maintained after the fault is cleared.

The ease of setting and commissioning the new pole-slip function was also discussed. It was concluded that the steady-state portion of the new pole-slip function can easily be done with a secondary injection set. When the steady-state power angle and power factor signs are correct for the steady-state conditions, the transient portion of the pole-slip function will also work correctly. If the client insists on testing the transient portion of the pole-slip function, PSCAD simulation data must be used in the form of a *COMTRADE* file to inject currents and voltages with a secondary injection set. It was concluded that the transient portion of the new pole-slip function would require the same skill and effort to test as the conventional impedance pole-slip schemes.

7.2.5 RELAY TESTING WITH A REAL TIME DIGITAL SIMULATOR

An ABB REM543 protection relay was programmed with the new pole-slip protection algorithm. The relay was tested on a RTDS. The steady-state testing and transient testing were performed. Steady-state testing included steady-state power factor and power angle calculations. Transient testing included rotor speed increase during a fault, fault-occurred and fault-clearance detection and the equal area criteria calculations.

The pole-slip algorithm concept was verified to be working correctly, although there were some practical limitations. For example, the voltage frequency could not always be used to determine generator speed during a fault due to voltage distortions when the fault occurs close to the generator terminals. Instead of using the voltage, the inertia of the machine and the active power reduction was used to determine the rotor acceleration during the fault. Some other challenges included a slow reaction time of the active power measurement function block of the relay. Since the active power measurement is a key variable in the equal area criteria, the slow response caused the pole-slip algorithm to be less accurate as was simulated in the PSCAD logics. The PSCAD logics simulated to have a fault duration error margin of less than 10 ms, while an error margin of 10 ms to 30 ms was tested with the protection relay.

The ABB REM543 logics interface is flexible and user friendly, which allow the user to program almost any protection algorithm. However, the slow active power measurement function block makes the ABB REM543 relay not the ideal solution for the pole-slip function. Nevertheless, the powerful ABB REM543 relay logics assisted in proving that the new pole-slip concept can be feasible if the correct relay hardware is used.

7.3 RECOMMENDATIONS

The new pole-slip protection function was thoroughly tested by using PSCAD. Network disturbances were created in PSCAD to check whether the new pole-slip protection algorithm accurately trips a generator before the generator is about to pole-slip. The new pole-slip algorithm was proven to be working accurately in PSCAD.

There have been some difficulties in implementing the new pole-slip algorithm in a protection relay. As discussed earlier, one of the main problems was encountered with the power measurement function block of the protection relay in which the new pole-slip function was programmed. The active power measurement function block of the ABB REM 543 relay did refresh at a high enough frequency for the pole-slip function to be accurate. It was not possible to measure the active power in any other way than to use the slow active power function block in the relay. However, the concept of the new pole-slip protection function could be successfully demonstrated in the ABB REM 543 relay.

Relay hardware that can sample active power measurements every 10 ms is required for optimum performance of the pole-slip function. Furthermore, reliable communication (active and reactive power data etc.) with other relays installed at paralleled generators and transmission line feeders is a requirement, as is done with IEC 61850 protocol relays connected to a hub.

Modern protection relay CPU processing power (equivalent to 486 family of computers or better) is sufficient to execute the new pole-slip algorithm. It is recommended that relay manufacturers investigate the use of this new pole-slip protection function to implement in generator protection relays.

7.4 FIELDS FOR FURTHER STUDY

This study focussed mainly on pole-slip protection for synchronous generators, although the same concept can be applied to synchronous motors as well. It is suggested that detailed simulations be performed in PSCAD to identify the required accuracy to which the upstream network impedance (and paralleled loads) must be modelled to achieve accurate tripping for synchronous motors.

The new pole-slip function is intended for power stations that are not more than 200 km from other power stations in the network, since the series capacitors and associated overvoltage protection that typically form part of longer transmission lines will influence the operation of the pole-slip function. It is suggested that further studies be undertaken to improve the pole-slip function such that it can accurately predict a pole-slip on power stations that are isolated (more than 200 km from the nearest other power station).

It is recommended that the mechanical stress effects on a synchronous machine shaft during pole-slipping should be investigated in more detail. The aim should be to determine when the fatigue life of a generator rotor has been used up, before the shaft fails catastrophically. With the evolution of protection relays and the increasing CPU process power, it could also be feasible to incorporate a detailed mechanical algorithm that could accurately determine the effect of sub-synchronous resonance.

7.5 CONCLUSIONS

Accurate pole-slip protection is very important to protect synchronous generators and personnel. When a generator pole-slips, it is not only damaging the machine, but the extreme mechanical stress on the shaft could cause harm to people as well. This study aimed at developing a new pole-slip protection function that can predict, while a fault occurs, if a generator will lose stability when the fault is cleared. When instability is predicted, the generator will be tripped before the fault is cleared to avoid damaging post-fault torque stress on the rotor.

Although the aim of the study was focussed on pole-slip protection, various *building blocks* had to be developed that contributed to the result of a new pole-slip protection function. It was decided to use the well-known equal area criteria to predict generator stability. The equal area criteria is typically presented in textbooks where saliency is neglected and where only one generator is considered without other

generators operating in parallel. In the textbook environment, the transient power angles and post-fault voltage magnitudes, that are required for stability calculations, are also known.

The *first building block* that was required for the new pole-slip protection function to work in real power system was the inclusion of shunt loads as well as consideration for generators operating in parallel to the generator under consideration. The inclusion of shunt loads and generators in parallel were successfully implemented in the new pole-slip algorithm such that the pre-fault transfer angle was calculated within 0.5 degrees accuracy.

Apart from an effect on the transfer angle, generators in parallel also have an effect on the terminal voltage of the generator under consideration. The terminal voltage of a generator in the post-fault period will greatly influence the stability of a generator after a fault has occurred. The *second building block* that was required for the new pole-slip protection function was the development of an algorithm that can predict the post-fault voltage magnitudes while the fault occurs. This was achieved by using multiple Thévenin circuits to simplify the network (including shunt loads and paralleled generators) into a circuit where the network can be represented by a single Thévenin voltage and impedance. By using this simplified Thévenin network, the terminal voltage of the generator under consideration could be predicted by predicting what the post-fault rotor angle increase of this generator would be. Since the generator speed will increase during a fault, the rotor speed will remain above synchronous speed for some time after the fault is cleared. During the time that the rotor speed is above synchronous speed after the fault is cleared, the rotor angle will still increase, even though the rotor speed will decrease if stability is maintained. With a larger rotor angle (or transfer angle), a larger post-fault generator current will flow, which will result in larger post-fault voltage drops on the generator and step-up transformer terminals.

It was found that, since the Thévenin current calculations did not include the effect of transient saliency, the currents were not calculated accurately in some cases. “Self-tuning” correction factors were incorporated in the new pole-slip algorithm to compensate for these errors (in particular for round rotor machines). The predicted post-fault voltages were used to predict the magnitude of *Area 2* in the equal area criteria. The effect that the rotor angle increase (due to inertia) in the post-fault period has on the post-fault voltages, was successfully implemented in order to predict what the average value of the post-fault terminal voltage magnitudes would be.

The *third building block* to the new pole-slip function was the calculation of the transient power angles of the generator and its step-up transformer while a fault occurs. An iterative algorithm was developed that can calculate the transient power angles with an error of less than 0.5 degrees.

It was realised that the transient power curve of a salient pole generator could be expressed in terms of a constant X_q, whereas the transient power curve of a round rotor generator cannot be expressed algebraically in terms of a constant X_q or X_q', since the quadrature axis reactance of a round rotor machines varies between values as small as X_q' to values greater than X_q. The *fourth building block* to the new pole-slip function was the introduction of a new parameter, X_{q_avg}, which is the average value of the quadrature axis reactance of a round rotor generator in the post-fault stage where the generator will be marginally stable. It was found that the value of X_{q_avg} can be predicted before a fault occurs by considering the pre-fault loading on the generator. The methodology developed of predicting X_{q_avg} proved to be working accurately.

All the *building blocks* were successfully implemented together in achieving the main goal and contribution of the PhD study, namely the new pole-slip protection function. The pole-slip protection function was thoroughly tested with PSCAD with accurate stability calculation results.

This PhD study succeeded in developing a new pole-slip protection function that can predict, while a fault occurs, if a generator will lose stability (and ultimately pole-slip) when the fault is cleared. The algorithm was incorporated in a protection relay and tested on an RTDS, which demonstrated that the pole-slip protection function can be implemented in modern generator protection relays.