- CHAPTER 1 -

INTRODUCTION

> *"Some things have to be believed to be seen."*
> Ralph Hodgson

1.1 INTRODUCTION

Synchronous generators are commonly used in power stations to generate electric power. It is important to protect these assets as efficiently as possible. No commercial relay currently available can accurately predict when a generator is about to experience a damaging pole-slip condition. Existing pole-slip protection relays use the impedance pole-slip protection method to predict a pole-slip. All the relays on the market now will only trip a generator after it has pole-slipped one or more times. It will be shown in section 2.12 that severe mechanical damage could be caused to a machine after only one pole-slip. Figure 1.1 emphasizes the importance of efficient pole-slip protection by illustrating the damage that can happen to a generator without effective pole-slip protection.

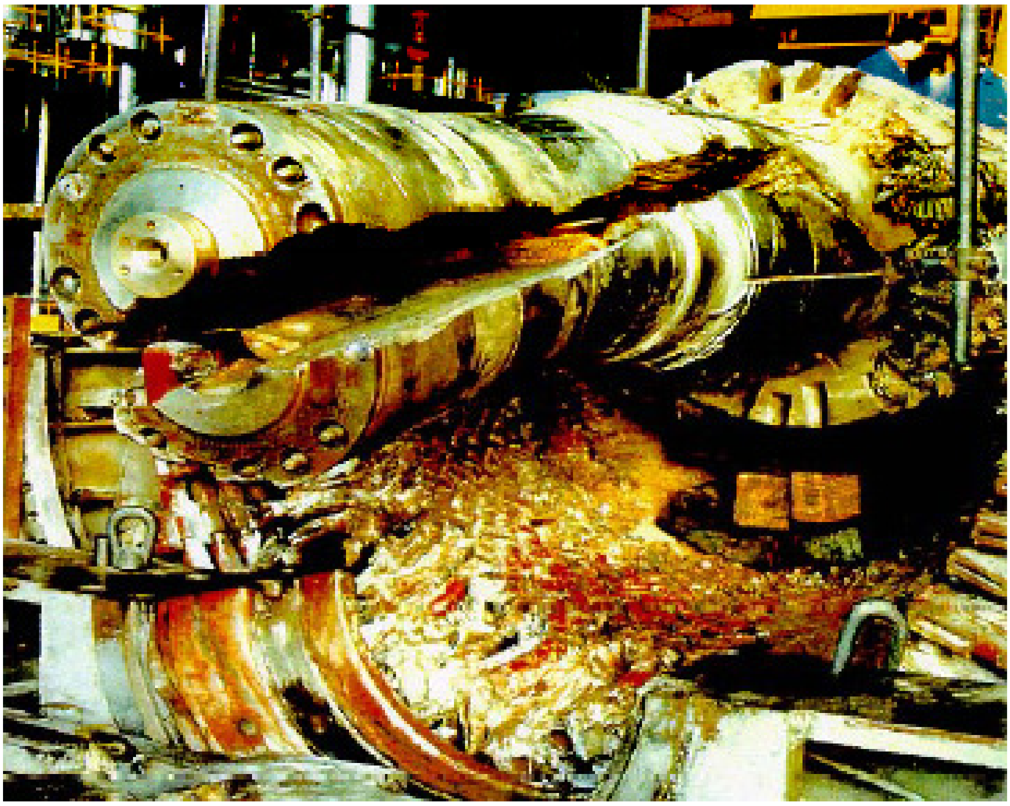

Figure 1.1: Synchronous machine severely damaged due to pole-slipping [1]

1.2 BACKGROUND

1.2.1 POLE-SLIPPING

Synchronous machine pole-slipping occurs when there is insufficient electromagnetic torque to hold the rotor in synchronism with the stator magnetic flux [2]. Pole-slipping typically occurs under severe fault conditions that cause a transient torque on the generator shaft. This transient torque exceeds the ability of the rotor magnetic field to keep the rotor synchronized with the stator-rotating magnetic field. A generator is most susceptible to pole-slipping when it has low field excitation.

At the instant of pole-slipping, the rotor experiences a sudden physical and electrical shift in position relative to the stator field. The field could then recover enough strength to lock the rotor back in synchronism with the stator, or the generator can continue pole-slipping. When this occurs, violent acceleration and deceleration forces associated with pole-slipping cause enormous stress on the generator and prime-mover. These extreme stresses may result in anything from winding movement to shaft fracture or total destruction. A fault causing a pole-slip could thus lead to very dramatic and serious damage resulting in huge economic losses.

A correctly set AVR will prevent operation at or outside the stability limits of a synchronous machine. Faults or incorrectly planned switching operations may exceed the ability of the AVR to respond quickly enough if a machine is already near its stability limit.

When the power system is unstable, one group of generators in close proximity of each other can swing with respect to another group of generators that is far away from the first group. In such conditions, it is desirable to isolate the two groups of generators from each other without losing all the loads connected to these generators. It is not desirable to trip a generator, since it will worsen the network instability. A generator should only be tripped when stability cannot be maintained after the system disturbance [1].

Synchronous *generators* can pole-slip due to faults in the network, power swings and loss-of-excitation. Synchronous *motors* can pole-slip during undervoltage conditions, loss-of-excitation and during sudden mechanical failure.

1.2.2 SHORTCOMINGS OF EXISTING POLE-SLIP PROTECTION SCHEMES

The existing pole-slip protection schemes use an impedance principle of determining when a synchronous machine is pole-slipping. The impedance is calculated by dividing the measured machine terminal voltage by the measured line current. The existing impedance scheme relays cannot determine when a generator will become unstable after a fault, and can therefore not trip a generator before it pole-slips. The existing relays will trip the machine only after the first pole-slip.

1.3 PROBLEM DESCRIPTION

A pole-slip protection function must be developed capable of tripping synchronous machines before a damaging pole-slip is experienced, but must not trip in cases where generator stability could be maintained after the fault is cleared. The equal area criteria can be used to predict generator stability. The voltage magnitudes and power angles required in the equal area criteria cannot always be measured, but must rather be calculated and *predicted*.

The transfer angle between the generator EMF and the network infinite bus must be calculated before the fault occurs for use in the equal area criteria. Shunt loads close to the generator can cause the transfer angle to be calculated inaccurately. A practical method of including shunt loads in the relay algorithm must therefore be developed.

During the fault, the equal area criteria requires the transient power angles of the generator and step-up transformer to predict stability. These transient power angles must therefore also be calculated while the fault occurs.

The voltage magnitudes on the generator and transformer terminals after the fault is cleared will largely influence the stability of the generator. These post-fault voltages are not known while the fault occurs, but the equal area criteria requires these voltage magnitudes to predict stability while the fault occurs. The post-fault voltages on the generator and transformer terminals must therefore be predicted in order to predict generator stability.

It will be shown in chapter 2 that salient pole synchronous machines are modelled with a quadrature axis reactance X_q that is equal to the transient quadrature reactance X_q'. For that reason, X_q (instead of X_q') can be used to determine the salient component of active power during transient conditions for salient pole machines. Round rotor machines have an X_q' that is smaller than X_q. During transient conditions, the quadrature axis reactance of round rotor machines can vary between values as small as X_q' to values larger than X_q, which means X_q cannot be used to determine the salient component of active power during transient conditions on round rotor machines. A method must therefore be developed that can predict what the effective post-fault value of the quadrature axis reactance X_{q_avg} will be for use in the equal area criteria.

The new pole-slip algorithm must be simple enough to be implemented in a protection relay CPU such that the relay can issue a trip within 10 ms after instability of the generator is predicted.

1.4 AIM OF STUDY

The primary aim of the study is to develop a pole-slip protection function based in a standard protection relay (and not to develop a new definition of generator pole-slip). The primary study aim can be subdivided into the following activities:

- To evaluate the existing pole-slip protection schemes commonly used in the industry, highlighting the shortcomings of the existing schemes.
- To evaluate existing synchronous machine modelling practices and to determine in what way the models can be simplified with sufficient accuracy to calculate machine stability during network disturbances in real time.
- To develop a pole-slip protection function (by using PSCAD) that will trip a synchronous machine before it is mechanically damaged due to pole slipping (or to minimize mechanical damage), but which will not trip the machine in cases where stability could be maintained after a fault.
- To demonstrate the implementation of the developed pole-slip protection function in an ABB REM543 multifunctional protection relay.
- To test the ABB REM543 relay on a Real Time Digital Simulator (RTDS) to verify that the pole-slip protection function will protect generators against damaging pole slipping, and to verify that the pole-slip function will not trip the machine when stability could be maintained after a network disturbance.

1.5 OVERVIEW OF THESIS

Chapter 1 contains the introduction and background to the study, the problem description and aim of the study, an overview of the contents of each chapter and the contributions of the study.

Chapter 2 presents the general theory of synchronous machines. Different synchronous machine parameters that are required for the new pole-slip function are investigated. These parameters include the transient EMF and power angle calculations. Synchronous machine excitation systems are also investigated by means of Matlab simulations on a typical excitation system. The mechanical stress on a synchronous machine shaft during pole slipping is also investigated.

Chapter 3 presents the operation of existing pole-slip protection relays, based on the impedance principle. The shortcomings of the impedance pole-slip protection functions are discussed. A method of allowing for shunt loads in impedance relays is introduced, which is used as part of the new pole-slip function.

Chapter 4 describes the development of the new pole-slip protection algorithm that can trip a synchronous machine before it experiences a damaging pole-slip, but without tripping the machine in fault scenarios where stability could be maintained after the fault. The new pole-slip function is designed by using PSCAD. The physical implementation of the new pole-slip protection logics in an ABB REM543 relay is also presented.

Chapter 5 presents case studies to test the different parts of the new pole-slip protection function, like the post-fault voltage prediction and transient power angle calculations. This chapter compares the operation of the conventional- and the new pole-slip protection functions. PSCAD simulations are performed on different generator applications to simulate different pole-slip scenarios.

Chapter 6 presents the testing of an ABB REM543 relay on a Real Time Digital Simulator (RTDS). The testing procedures and results are discussed and evaluated in detail.

Chapter 7 presents the conclusions on how the different parts of the pole-slip protection function was designed and implemented together to develop the new pole-slip protection function. The summary of the results and conclusions made in the preceding chapters are also provided, as well as suggestions for fields of further study.

1.6 CONTRIBUTIONS OF THE STUDY

The new pole-slip protection function will use the equal area criteria as basis of the design. The equal area criteria is a very well known method of predicting stability theoretically, but much more is required to make the equal area criteria work in a real power system. There have been previous attempts by Redfern et al to use the equal area criteria to predict when a generator will become unstable [2],[53],[54]. These equal area calculations were all based on measured quantities after the fault was cleared. It will be shown in section 2.12 of this thesis that damaging torques can occur on the generator while the fault occurs and especially at the instant when the fault is cleared. The method used by Redfern et al waits until the fault is cleared before a decision is made whether the generator must be tripped or not. Another attempt by Wang and Girgis was to monitor the power angle after the fault is cleared in order to predict stability [55]. This method also waits until the fault is cleared before a decision is made to trip the generator.

The proposed pole-slip protection algorithm in this thesis determines whether stability will be lost before the fault is cleared. This will minimise the stress on the generator during the fault, as well as the mechanical stress on the generator rotor the moment the fault is cleared. There are two unknowns that need to be calculated while the fault occurs for the equal area criteria to be useful, namely the transient (during-fault) power angles of the generator and transformer as well as the post-fault terminal voltages.

The main contribution of this thesis is to develop a new pole-slip protection function that can predict, while a fault occurs, if a generator will lose stability when the fault is cleared. This main goal and contribution can only be accomplished with the development of a number of sub-contributions.

The contributions of this PhD study include the following:

- *Contribution 1:* The calculation of the steady-state transfer angle between the generator EMF and the network infinite bus (refer to section 3.6).

  A practical method, which includes the effect of shunt loads and paralleled generators in the transfer angle calculation algorithm, was developed. The identification of a practical "infinite-bus" is discussed and tested for the purposes of the new pole-slip function.

- *Contribution 2:* The calculation of a generator transient power angle during a fault condition (refer to section 4.8.11).

  Predicted post-fault voltage magnitudes are used together with initial estimated generator and transformer power angles in an iterative algorithm to determine what the generator transient power angle will be the moment when the fault is cleared. The effect of generator saliency is included in the transient power angle calculation.

- *Contribution 3:* The prediction of generator and transformer post-fault terminal voltage magnitudes (refer to section 4.8.7).

  The effect of generator rotor inertia on the voltage angle and magnitude, after the fault is cleared, is determined. The post-fault voltage magnitudes on the generator and transformer terminals are predicted by means of multiple Thévenin equivalent circuits.

- *Contribution 4:* The prediction of an effective transient quadrature axis reactance X_{q_avg} for *round-rotor* generators (refer to section 4.7.4).

  The reactance X_q is used in the equal area criteria to include saliency effects in the electrical power calculation. An average value of the effective post-fault quadrature axis reactance (X_{q_avg}) for round rotor machines is developed to be used in the equal area criteria. Salient pole machines only need to be modelled with X_q in transient conditions. The calculation of X_{q_avg} is therefore not applicable to salient pole generators.