

# **Development of a new pole-slip protection function for synchronous machines**

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## DECLARATION

I, Lafras Lamont, (ID No: 7802075055089) hereby declare that all the material incorporated into this PhD dissertation is my own original unaided work, except where specific reference is made by name or in the form of a numbered reference. The work herein has not been submitted to any other university to obtain a degree.

Signed: \_\_\_\_\_  
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## GLOSSARY OF TERMS

### **Automatic Voltage Regulator**

Controls the terminal voltage of a synchronous machine by controlling its excitation current to ensure an optimum power factor and power angle.

### **Electrical centre**

The point in the network where the voltage is zero when the transfer angle is  $180^\circ$  between a generator and the infinite bus.

### **Endurance Limit**

Endurance Limit or Fatigue strength are expressions used to describe the amplitude (or range) of cyclic stress that can be applied to the material without causing fatigue failure.

### **Infinite Bus**

A group of generators close to each other that is considered as one large generator for simplifying simulations. The group of generators is regarded as a voltage source with zero impedance, i.e. an ideal voltage source.

### **Out-of-step**

The occurrence when a synchronous machine loses synchronism with the network although the machine internal power angle can remain stable (less than  $90^\circ$ ).

### **Pole-slip**

The occurrence when a synchronous machine rotor and stator magnetic fields slip with respect to each other. The internal power angle of the machine becomes  $180^\circ$  at the instant of the pole-slip event.

### **Post-fault**

The term “Post-fault” refers to the period directly after a fault on the network is cleared (or the period while the generator is still above synchronous speed) until the generator speed decelerates back to synchronous speed.

### **Power Angle ( $\delta_{gen}$ )**

The angle between a synchronous machine EMF and the terminal voltage.

### **Power Factor Angle ( $\Phi$ )**

The angle between the fundamental frequency voltage and current vectors in a power system.

**Power Swing**

The occurrence when the transfer angle between two parts in a power system oscillates with respect to each other. This typically occurs after a disturbance (like a fault) in the network. Power swings are more common between two parts in a network that are connected via a long transmission line. The network can remain stable after a power swings, or it can become unstable.

**Prime-mover**

The rotating device mechanically coupled to a generator that is supplying mechanical energy to a generator. The mechanical source can be a diesel engine, steam turbine, gas turbine, hydro, etc.

**Real Time Digital Simulator**

A modular, fully digital power system simulator that can be used for performing analytical power system simulations and the testing of protection relays.

**Relay Mimic**

The LCD display on a multifunctional protection relay faceplate.

**Secondary Injection Set**

This equipment is used to test protection relays. Voltages and currents, that represent the secondary side voltages and currents of VTs and CTs respectively, are injected into the relay.

**Subsynchronous resonance**

This is an electric power system condition in which the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system.

**Spurious Trip**

A spurious trip is an unnecessary and unwanted trip that occurred due to mal-operation of the electrical protection system.

**Transfer angle ( $\delta$ )**

It is the angle between the generator EMF and the network infinite bus. This angle should not be confused with the power angle of a synchronous machine.

## LIST OF ABBREVIATIONS

|        |                             |
|--------|-----------------------------|
| A      | ampere                      |
| ac     | alternating current         |
| AVR    | automatic voltage regulator |
| CT     | current transformer         |
| dc     | direct current              |
| d-axis | direct axis                 |
| EMF    | electromotive force         |
| N.m    | Newton meter                |
| PC     | personal computer           |
| pu     | per unit                    |
| RTDS   | real time digital simulator |
| SSR    | subsynchronous resonance    |
| MMF    | magnetomotive force         |
| q-axis | quadrature axis             |
| V      | volts                       |
| VA     | volt-ampere                 |
| VT     | voltage transformer         |
| var    | reactive volt-ampere        |
| W      | watt                        |

## LIST OF SYMBOLS

|                  |                                                           |
|------------------|-----------------------------------------------------------|
| $E_q$            | Steady state EMF                                          |
| $E'_q$           | Transient EMF                                             |
| $E_r$            | resultant air gap voltage                                 |
| $E_{ar}$         | armature reaction voltage induced by the armature current |
| $E_{fd}$         | excitation voltage induced by the field current           |
| $f$              | frequency in Hz                                           |
| $f_n$            | nominal frequency in Hz                                   |
| $I_a$            | line current                                              |
| $I_d$            | d-axis component of the line current $I_a$                |
| $I_q$            | q-axis component of the line current $I_a$                |
| $L_l$            | armature leakage inductance                               |
| $L_{ad}$         | d-axis magnetizing inductance                             |
| $L_{aq}$         | q-axis magnetizing inductance                             |
| $L_{fld}$        | field leakage inductance                                  |
| $L_{1d}$         | d-axis damper winding inductance                          |
| $L_{1q}, L_{2q}$ | q-axis damper windings inductances                        |
| $N$              | number of winding turns                                   |
| $n$              | rated speed (rpm)                                         |
| $P_e$            | electrical active power                                   |
| $P_m$            | mechanical power                                          |
| $p$              | number of synchronous machine pole-pairs                  |
| $R_a$            | armature resistance                                       |
| $S_e$            | endurance limit                                           |
| $S_{ut}$         | ultimate tensile strength                                 |
| $r_{1q}$         | q-axis damper winding resistance                          |
| $T'_d$           | d-axis transient time constant (short circuited)          |
| $T''_d$          | d-axis subtransient time constant (short circuited)       |
| $T'_{do}$        | d-axis transient time constant (open circuit)             |
| $T''_{do}$       | d-axis subtransient time constant (open circuit)          |
| $T_e$            | generator electrical torque                               |

|                 |                                                     |
|-----------------|-----------------------------------------------------|
| $T_m$           | mechanical prime-mover torque                       |
| $T_q'$          | q-axis transient time constant (short circuited)    |
| $T_q''$         | q-axis subtransient time constant (short circuited) |
| $T_{qo}'$       | q-axis transient time constant (open circuit)       |
| $T_{qo}''$      | q-axis subtransient time constant (open circuit)    |
| $V_a$           | terminal line-to-neutral voltage                    |
| $v_q$           | q-axis voltage                                      |
| $v_d$           | d-axis voltage                                      |
| $X_d$           | d-axis unsaturated steady-state reactance           |
| $X_d'$          | d-axis transient reactance                          |
| $X_d''$         | d-axis subtransient reactance                       |
| $X_{ad}$        | direct axis magnetizing reactance                   |
| $X_q$           | q-axis reactance                                    |
| $X_q'$          | q-axis transient reactance                          |
| $X_{aq}$        | q-axis magnetizing reactance                        |
| $X_{fd}$        | field leakage reactance                             |
| $X_{1q}$        | q-axis damper winding reactance                     |
| $X_{tx}$        | transformer reactance                               |
| $\psi_d$        | d-axis flux linkage                                 |
| $\psi_q$        | q-axis flux linkage                                 |
| $\psi_{fd}$     | d-axis field excitation flux linkage                |
| $r_{fd}$        | dc field circuit resistance                         |
| $\Phi$          | Power Factor                                        |
| $\delta$        | Transfer angle                                      |
| $\delta_{gen}$  | Generator power angle                               |
| $\delta_{Tx}$   | Transformer power angle                             |
| $\omega$        | $= 2\pi f$                                          |
| $\omega_{base}$ | rotation speed base                                 |
| $\omega_r$      | rotor rotation speed                                |
| $\alpha$        | acceleration ( $\text{rad.s}^{-2}$ )                |

## ABSTRACT

The rotor shaft of a synchronous machine can experience severe mechanical stress due to torque pulsations during a pole-slip condition. All pole-slip protection relays currently on the market use the impedance pole-slip protection method to detect a pole-slip.

No commercial relay currently available can predict accurately when a generator is about to experience a damaging pole-slip. All the relays will only trip a generator after it has pole-slipped one or more times. Severe mechanical damage could be caused to a machine after only one pole-slip. It is therefore essential to enhance pole-slip protection relays to such an extent that it can trip a generator before it pole slips.

The proposed pole-slip protection function must predict when a generator will become unstable during a network fault. As soon as instability is predicted, the generator must be tripped before the fault is cleared to avoid damaging post-fault torque effects. Conventional impedance pole-slip protection methods are also discussed and the shortcomings of impedance pole-slip protection are investigated.

The new pole-slip protection function was designed by using PSCAD. Detailed PSCAD simulations on different network configurations proved that the new pole-slip protection function will trip a generator before a damaging pole-slip occurs. The new pole-slip protection function was also implemented on an ABB REM543 multifunctional protection relay and tested on a RTDS. The concept of the new pole-slip function was successfully demonstrated on the protection relay.

The operation of conventional impedance scheme relays was compared with the proposed pole-slip function for different fault conditions. Although the new pole-slip protection function is more complex than the existing impedance functions, it was concluded that similar skills are required to test and commission the new protection function. The new pole-slip function outperforms the impedance protection methods, since the new protection function can trip the generator before it pole-slips.

Library Keywords: *synchronous generators; pole-slip protection; out-of-step; power system stability; powerswing; equal area criteria; impedance protection*

## OPSOMMING

Die rotor-as van 'n sinkroonmasjien kan groot meganiese kragte ondergaan as gevolg van pulserende wringkrigte tydens poolglip toestand. Alle poolglip beskermingsrelê's wat tans kommersieel beskikbaar is, maak gebruik van die impedansie-skema om poolglip te bepaal.

Geen poolglip relê wat tans beskikbaar is, kan akkuraat voorspel wanneer 'n generator 'n beskadigende poolglip kan ervaar nie. Met die huidige tegnologie, sal alle relê's slegs die generator klink nadat dit een keer gepoolglip het. Die rotor kan meganiese skade opdoen na slegs een poolglip.

Die voorgestelde poolglip funksie kan voorspel wanneer 'n generator onstabiel sal raak na 'n netwerk fout. Sodra onstabiele voorspel word, sal die generator geklink word voordat die fout verwyder word om sodoende beskadigende "na-fout" wringkrig effekte te vermy. Die beginsel hoe impedansie skema relê's werk word ook bespreek en die tekortkominge van die huidige impedansie relê's word uitgelig.

Die nuwe poolglip funksie is ontwerp deur gebruik te maak van PSCAD. PSCAD simulaties wat gedoen is op verskillende netwerk konfigurasies het bewys dat die nuwe poolglip funksie 'n generator sal klink voordat die poolglip. Die nuwe poolglipfunksie is ge-implementeer in 'n ABB REM543 relê. Die relê met die nuwe funksie is getoets op 'n RTDS. Die konsep van die nuwe poolglip funksie is suksesvol gedemonstreer op die RTDS.

Die werking van konvensionele impedansie relê's is vergelyk met die nuwe poolglip funksie vir verskillende fout toestande. Alhoewel die nuwe pool-gliph funksie meer kompleks is as die bestaande impedansie funksies, kan dit bewys word dat soortgelyke vaardighede benodig word om die nuwe funksie te toets en in bedryf te stel. Die nuwe poolglip funksie presteer beter as impedansie poolglip relê's, aangesien die nuwe beveiligings funksie die generator kan klink voordat dit pool-gliph.

Biblioteek sleutelwoorde: *sinkroon generators; pool-gliph beveiliging; kragstelsel stabiliteit; gelyke area kriteria; impedansie beveiliging*