Pole Slipping Protection: Problems and Solutions

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POLE SLIPPING PROTECTION: PROBLEMS AND SOLUTIONS.

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1. INTRODUCTION.

With the growing number of Dispersed Storage and Generation units (DSG) being installed to operate in parallel with utility distribution systems, synchronous generator instability is increasingly being recognized as an area of concern. Generator instability, pole slipping, can damage the machine and disturb the local power system. Unfortunately, DSG generators generally have high per unit impedances, low inertia and small transient time constants. These together with the long fault clearance times associated with distribution networks all contribute to the increased probability of pole slipping.

Pole slipping of a synchronous generator connected to a supply system is the process by which an imbalance between the mechanical power input to the machine and its electrical power output causes the rotor to accelerate and eventually slip with respect to the power system frequency. This can be caused by short circuit faults, general disturbances on the power system, or problems with the generator's prime mover, its excitation or its control system.

Traditional techniques for detecting pole slipping examine the variations in the apparent impedance of the generator as seen from its terminals. Several schemes are commercially available which are based on distance type relays [1,2,3,4], and use combinations of mho and linear characteristics. Some of these schemes are able to trip before the pole slip occurs, whereas others rely on the pole slip having taken place before they will disconnect the generator from the network.

Unfortunately, the impedance of a generator is not as predicable as would be expected and depends on the type of disturbance. Hence the concept of the sub-transient, transient and dynamic impedance. It is therefore generally recommended [1,4,5] that transient stability studies are performed so that the location of the impedance loci are known and the most appropriate relaying scheme and its settings can be selected. These simulations can be time consuming and expensive, and due to the vagaries of pole slipping do not guarantee reliable tripping or the absence of nuisance tripping.

Pole slipping is a power based phenomena and an alternative approach to detecting pole slipping has been developed which uses the Equal Area diagram as a basis to assess the stability of the machine and determine when it is committed to a pole slip. The settings for this technique rely on data which is generally available from the generator's manufacturer and stability studies are not required. Since this approach [6] is able to recognise the conditions where a pole slip is inevitable, it therefore offers the prospect of tripping before the actual pole slip and hence disconnecting the machine from the system before it can be damaged and before there is a major disturbance to the adjacent power system.

The technique takes advantage of the processing capabilities of modern multi-function microprocessor numeric relaying platforms and has been designed to share sub-functions with other protection functions required for the protection of Dispersed Storage and Generation units.

2. POWER BASED TECHNIQUE FOR DETECTING POLE SLIPPING.

The Equal Area Criterion demonstrates the conditions where synchronism is lost and pole slipping occurs. Figure 1 shows the power/load angle relationship and the rate of change of load angle (slip, s) for a generator losing synchronism with the utility supply to which it is connected following a loss of power transfer capability due to a disturbance on a double circuit line [7]. For this scenario, the generator is connected to a double circuit line and the power system disturbance is caused by switching one of the lines out of service for a short period. Removing the electrical load from the generator, while keeping the mechanical power constant, causes the generator to accelerate and eventually pole slip.

The most severe disturbance for a generator is the close-up three phase fault, for which all of the generator's load is lost and therefore all of the prime mover power is used to accelerate the rotor. For less severe short circuit faults, a greater fault duration is required to cause pole slipping.

The Equal Area Diagram, figure 1, illustrates that for a stable swing, the machine operating point cannot exceed point 5, the critical stability point. This corresponds to the point at which the electrical output of the machine, P, equals the mechanical input from the prime mover, P_m. Instability occurs if the machine moves beyond the critical stability point. This point can be identified in terms of real power as the condition when:-

$$P < P_m$$

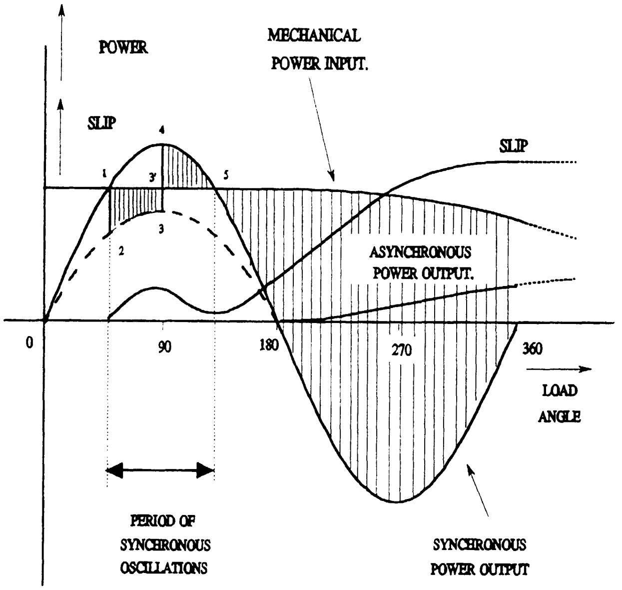


FIGURE 1. EQUAL AREA DIAGRAM FOR GENERATOR LOSS OF SYNCHRONISM.

Since this criterion can also be satisfied for machine operating between points 0 and 1 shown on figure 1, the reactive power measurement is used to differentiate between the two. The steady state reactive power/load angle relationship for a round rotor machine is given by:-

$$Q = \frac{E*V}{X_d}(\cos(\ \delta\ )) - \left(\frac{1}{X_q} + \frac{1}{X_d}\right)\frac{V^2}{2} + \left(\frac{1}{X_q} - \frac{1}{X_d}\right)$$

This shows that for load angles between 90° and 270°, the reactive power will always be less than Q_{trip}. Since point 5 of figure 1 occurs for load angles greater than 90°, then if :-

$$Q < \frac{-V^2}{X_q} \qquad (\ Q = Q_{trip}\ )$$

the machine must be operating at point 5 and not point 1.

The transient reactive power characteristics vary in magnitude from the above steady state values. This does not corrupt the above method since the value of reactive power corresponding to a 90° load angle is identical to the steady state value. The transient reactive power characteristics above and below this load angle are such that in steady state terms, it appears as if the load angle is correspondingly higher or lower.

Finally, it must be ascertained whether or not the load angle is still advancing. To determine this, the rate of change of real power is used. It can be seen from the synchronous power output characteristic of figure 1, that if the load angle is still increasing when point 5 is reached, the machine output power will be decreasing, i.e. the rate of change of real power will be negative.

In practice a margin for error is allowed for in this rate expression $(\Delta P/\Delta t)$, to ensure the algorithm does not mal-operate. A minimum negative value, $(\Delta P/\Delta t)_{min}$ is designated, based on a minimum value of slip and an assumed sinusoidal power/load angle relationship. The conditions which determine that a generator is about to pole slip are therefore :-

$$P < P_t\ , \quad where\ \ P_t \propto P_m$$

$$Q < Q_{trip}$$

$$(\Delta P/\Delta t) < (\Delta P/\Delta t)_{\min}$$

These conditions are used to give the trip criteria for the algorithm. The real power trip level, P_t , is derived from the generator's monitored power output and is proportional to the mechanical power input P_m. This setting is automatically adjusted periodically. The rate of change of power trip setting, $(\Delta P\backslash\Delta t)_{min}$ is also continuously adjusted by the algorithm according to the generator operating point.

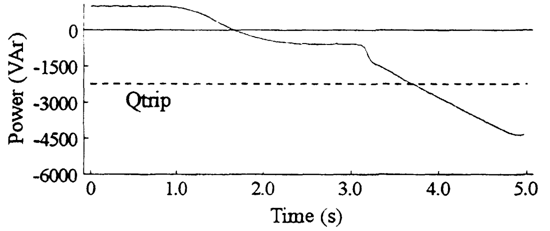
Short circuit faults cause added complications since they cause dramatic changes in the relay measurands. These transitions produce negative values of $(\Delta P/\Delta t)$ which are a potential source of instability to the algorithm. Fortunately, the faults generally introduce sinusoidal terms of twice the power system frequency into the power measurements. Since pole slipping is a relatively slow process in comparison to faults, then an imposed minimum tripping time of one and a half power system cycles will inhibit fault tripping.

3. SIMULATION STUDIES.

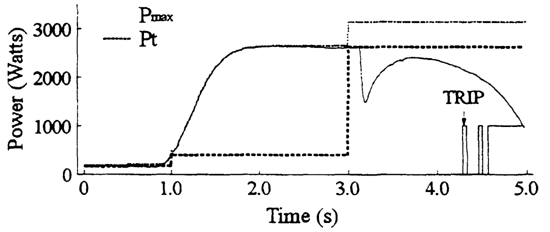
The performance of the pole slipping algorithm was tested using a laboratory dispersed generation model, computer based dynamic simulation and field tests.

The laboratory dispersed generation model used two 5 kVA synchronous generators driven by 8 horse power dc motors. These were connected to a 'local' load and a 200 V, 3 phase laboratory 'Utility' supply. This was useful for testing the algorithm in a real life situation, since harmonics and heavily alternating loads nearby made the supply far from ideal.

a) Generator Reactive Power



b) Generator Real Power



c) Generator Rate of Change of Power

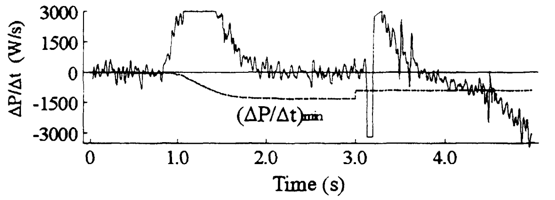


FIGURE 2 - 5 kVA GENERATOR POLE SLIP..

The laboratory model was also used to test the algorithm during power system fault conditions. All of the fault types possible were placed temporarily on the local load busbar by switching in 'fault' resistance.

The computer based dynamic simulation package was used to test the algorithm's performance against power swings and pole slipping. The model used was based on the simple one machine model (588 MVA) connected to an infinite bus model (58.8 GVA). A stable swing was caused by placing a fault on the generator transformer terminals of sufficient duration to cause the generator rotor to swing up to the critical stability point and back down to a stable operating area.

To test the algorithm for detecting a pole slip, the simulated generator was initially set to run at maximum output power. The input power was then reduced to half rating to test the adaptive setting section of the algorithm. A three phase fault of slightly longer duration than the one used to trigger the power swing, was then used to cause a pole slip.

4. SIMULATION TEST RESULTS.

Figure 2 shows the algorithm variations for the laboratory system weak field pole slipping test. Inspection of plots (a) and (b) show that the generator was initially operating overexcited at very low power. At a time of 1s on the record the power input to the generator was increased so that the machine operated at approximately 2.5 kW. Observation of the $(\Delta P/\Delta t)_{min}$ curve in plot (c) shows that because Pt was not updated during this period, the trip setting $(\Delta P/\Delta t)_{min}$ gradually decreased, resulting in a de-sensitising of the algorithm. This is beneficial since the likelihood of a pole slip is higher during adjustment to a higher output level.

At a time of 3s on the record, the adaptive setting part of the algorithm updates the value of Pt to the new operating level. This caused a drop in magnitude of $(\Delta P/\Delta t)_{min}$, but it did not drop back to the initial value, due to Pt being at a higher level. This is the desired effect since at higher input powers, more severe pole slip can occur and more negative values of $(\Delta P/\Delta t)$ are produced.

Shortly after the update, the resistor was connected in parallel with the field, causing the pole slip to occur. Inspection of the reactive power plot shows that this criterion was satisfied at 3.75 s, when the reactive power fell below the trip setting, *Qtrip*, indicating that the load angle had increased to a value above 90°. Inspection of the real power plot shows that after insertion of the parallel resistor, the generator's field was weakened sufficiently so that the generator could not maintain the level of output required, the real power criterion was therefore satisfied on inserting the resistor.

The final criterion (ΔP/Δt) , can be seen to fall below its trip setting $(\Delta P/\Delta t)_{min}$ at a time of 4.3s. This meant that all three criteria were satisfied for the one and a half cycle required and a trip signal was therefore produced. The trip signal can be found on the real power plot, it can be seen that the trip was issued a significant time before the pole slip occurred. The usual point where pole slip is said to have occurred is when the machine goes from generator to motor action, i.e when the power output of the machine goes negative. Unfortunately, in this case the whole pole slip could not be recorded, due to limitations in the data acquisition system.

Figure 3 shows the algorithm's response to a two phase to earth fault. Of all the fault types tested, this and the three phase faults provided the toughest conditions for testing algorithm stability. The reactive power criterion was satisfied for a small period on removal of the fault, at 1.4 s on the record. During this time the real power criterion is satisfied for a very short amount of time, before the real power output of the generator jumps above the trip setting *Pt*. It is this short interval where algorithm mal-operation is most likely. However, inspection of the $(\Delta P/\Delta t)$ plot shows that during this period, the $(\Delta P/\Delta t)$ signal jumps to a negative value off the scale for a very short time, before escalating to a very high positive value for a short time. These oscillations took less than one power system cycle, and so the algorithm was continually restrained.

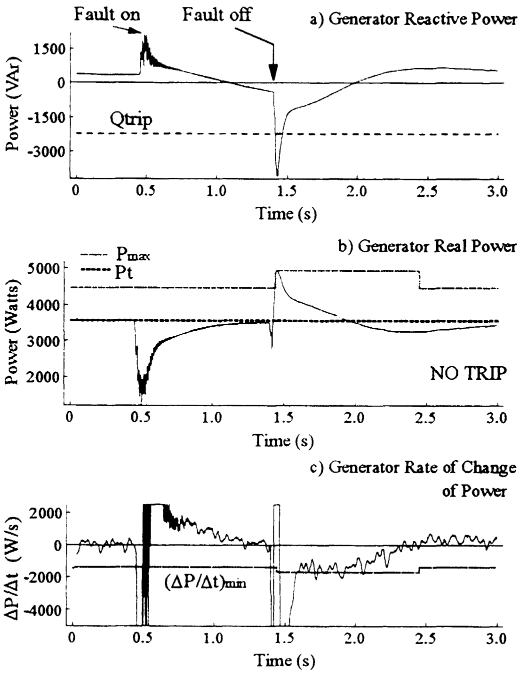


FIGURE 3 - 5 kVA GENERATOR 2 PHASE TO EARTH FAULT TEST.

The algorithm also successfully restrained for all of the other fault types tested.

Figure 4 shows the results to a test using the dynamic simulator. Initially the generator was operated at full power, it was then reduced to half rated operation. The condition monitoring part of the algorithm updated at a time of 3.75s on the record.

Inspection of the $(\Delta P/\Delta t)_{min}$ curve shows that until the update, it stayed at its high power level, resulting in the algorithm being de-sensitised for a small duration. This is unavoidable, but is of no great concern since in the event of a pole slip it would just result in the algorithm producing a trip signal delayed by a small time. At 4.75 s on the record the fault was placed on transformer bus, and removed again at 5.2s.

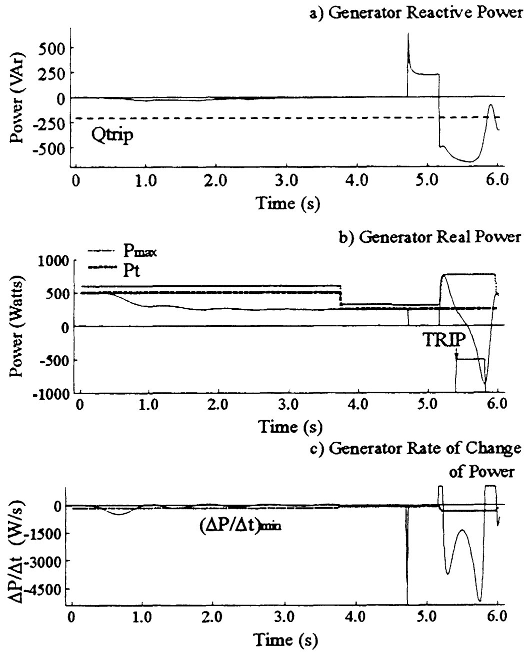


FIGURE 4 - 588 MVA GENERATOR POLE SLIPPING DUE TO A THREE PHASE FAULT.

On removal of the fault the generator's reactive power was less than *Qtrip*, satisfying the reactive criterion indicating that the load angle was above 90°. At the same time, the real power output is much greater than the nominal value before the fault.

This invoked the adaptive P_{max} part of the algorithm, which tracked the real power output up to its maximum value, and then held this value for 1 second before returning back to *1.25*Pt*.

This action resulted in $(\Delta P/\Delta t)_{min}$ falling to a lower level, thus desensitising the algorithm to the pending transient pole slip. The $(\Delta P/\Delta t)$ signal still fell below the trip setting $(\Delta P/\Delta t)_{min}$ for one cycle, and during this time the other two criteria were satisfied. A trip signal therefore resulted.

The algorithm successfully restrained for the power swing test, which produced a severe swing in load angle up to a value of 160°.

4. FIELD TESTS.

A series of field tests were conducted using a 625 kVA diesel generator connected via a transformer to the 11 kV network supply. In the most dramatic of the tests, a pole slip was induced by quickly ramping the diesel power at a rate faster than the generator controls could respond.

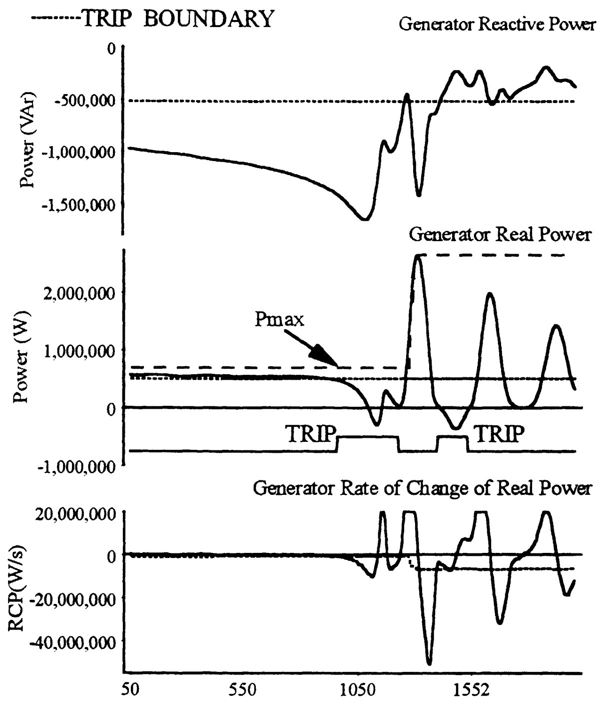


FIGURE 5. POWER BASED ALGORITHM RESPONSE TO 625 KVA DIESEL GENERATOR POLE SLIP.

Figure 5 shows the power based pole slipping algorithm's response to this test. The real power plot shows where the algorithm tripped, which for the first pole slip occurred just before 1000 ms on the record. Allowing for a circuit breaker operating time of 100 ms, this would have isolated the generator before the actual pole slip. The real power plot also reveals the potentially damaging effects of pole slipping, since the peak in power output after the first pole slip reaches 2.7 MW, five times rated power. By tripping before the pole slip occurred, the new algorithm would have avoided this dangerous surge in the power output. Due to the finite disturbance recording time, the transition from normal to underexcited generator operation was not captured.

5. CONCLUSIONS.

During laboratory model, computer simulation and field tests, the power based pole slipping algorithm has proven to be very successful in detecting pole slips while remaining stable during periods of other types of power system disturbances.

It offers the immediate advantage of detecting when the synchronous Dispersed Storage and Generation unit is committed to a pole slip rather than has actually slipped and therefore offers the opportunity of disconnecting the machine from the network before possible damage or major disturbance to the power system.

The relay's settings are determined by readily available generator data and thus the need for simulation studies is avoided.

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