Development of an impedance-based pole slipping algorithm

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This paper discusses the operation, design and simulation tests for an impedance-based pole slipping protection algorithm, it can be applied to hydro generators as well as other types of machine. The relay is able to detect the first and subsequent pole slips.

A power system shock may cause a generator rotor to oscillate, with consequent variations of current, voltage and power factor. If the angular displacement of the rotor exceeds the stable limit, the rotor will slip a pole pitch and the generator will lose synchronism with the rest of the system. Such a condition is commonly known as pole slipping or out of step. The generator must be isolated as soon as possible from the system before it is damaged or before wide spread outage occurs.

Conventional techniques employ the measurement of impedance utilising the generator's terminal voltage and current signals as inputs. Typically directional and blinder elements are used together with a mho element to obtain the desired relay characteristics.

Pole slipping protection characteristic and operation

The pole slipping protection characteristic consists of three parts (see Fig. 1). The first part is the tangent (tangent) characteristic, the second is a straight line referred to as the blinder that bisects the lens and divides the impedance plane into the left and right halves and the third is a reaction line which is perpendicular to the blinder. This reaction line can provide further discrimination between pole slipping of the generator and power swings of the system. The inclination of the lens and the blinder, $\beta$, is determined by the angle of the total system impedance. The equivalent impedance of the system and the step-up transformer determines the forward reach of the lens, $Z_a$, whereas the generator’s transient reactance determines the reverse reach $Z_b$. The width of the lens is varied by the setting of the angle $\alpha$. A reaction line, perpendicular to the axis of the lens, is used to distinguish whether the impedance centre of the swing is located in the power system or in the generator. It is set by the value of $Z_b$ along the axis of the lens, as shown in Fig. 1. The reaction line splits the lens into Zone 1 (below the line) and Zone 2 (above and below the line).

If the protection is running in the generating mode, the impedance is expected to be at the right hand side of the lens under normal load conditions. During a pole slip the impedance locus traverses across the right half and then the left half of the lens. The minimum time spent in each half of the lens can be set with timers T1 for the right hand side and T2 for the left hand side. The relay registers a pole slipping cycle when the locus finally leaves the lens. If the protection is running in the motoring mode, the relay operates in a similar way to the generating mode except the impedance locus traverses across the lens from the left half to the right half of the lens during a pole slip.

For a pumped storage application, the generator's operation can switch from generating mode to motoring mode and vice versa. Therefore, a facility can be provided for the protection to detect the normal running mode of the machine (generating or motoring) and to perform pole slipping detection in either mode or both.

Also, when a generator is running at low load, due to the presence of heavy system damping during a fault the generator can slow down and result in a motor like slip ('negative slip'). To detect this condition the 'pole slip mode' should be set to 'Both'.

Protection design using a state machine

In order to track the impedance locus under a pole slipping condition, a ‘state machine’ approach is adopted. There are four states 'Idle', 'Start', 'Confirm' and 'Detect') used to describe the movement of the impedance locus. Each state has one entrance and one or several exit terminus. Exit terminus fall into two categories; 'normal exit' and 'abnormal exit'. There is only one 'normal exit' which leads to the next state when the impedance locus moves into the desired region. Unexpected impedance movement will result in a return to the 'Idle' state or will be ignored depending on where the impedance stays.

The regions defined in the state machine model, R1, R2, R3, R4 for the 'Generating Mode' are shown in Fig. 2. For the 'Motoring Mode' the regions R1, R2, R3, R4 are the mirror of these regions about the blinder.

'Idle': This is the normal state when the measured impedance is the normal load impedance. The impedance locus of any pole slip should start from here. In this state the 'normal exit' is when the measured impedance moves from R1 to R2. Timer T1, which is used to time the duration of the impedance locus remaining in R2. It is started when this change is detected. In this state, impedance locus changes to R3 will be ignored.

If the impedance locus moves to R4 and 'Both' is selected in the 'Mode' setting, a flag is toggled indicating that the operating mode is changed from 'Generating' to 'Motoring'.

'Start': This is the state when the impedance locus stays inside R2. Normal exit is taken only if the impedance has stayed in R2 longer.

Fig. 1: Pole slipping protection using blinder and tangent characteristic.

Fig. 2: Regions and zones definition for the state machine (generating mode).
Zone 2 is the backup pole slipping stage and so all pole slips increment the Zone 2 counter. If the pole slip has completed the preset slip cycles setting a trip signal is given.

When the normal transition occurs, T2 is reset. If this is the first pole slip detected, a Reset Timer is also started. The Reset Timer is used to reset the counters for pole slips that are cleared by external protection.

Detected: This is the stage where the impedance locus has to complete its full cycle although the counter is updated in the previous confirm stage. Abnormal movements of the impedance locus in this stage will be ignored and this state is kept until the impedance moves to R1 indicating completion of a pole slip cycle. If a trip signal has not been given for this pole slip, only the Start Signals and the Zone 1 flag are reset in preparation for the next pole slip cycle. However, if a trip signal has been issued, then the trip signal and the counters are both reset.

In general, once the measured impedance has traversed all the ‘Stages’ in the normal exit sequence, a pole slip is confirmed. For a stable power swing or fault condition the measured impedance will not satisfy all the exit transition criteria.

Simulation testing

Extensive simulation tests have been performed to demonstrate the correct operation of the algorithm. Disturbance records were obtained from the relay, which show the states of all the internal digital signals during a pole slip cycle. The voltage and current signals can be converted into impedance loci and plotted against the relay characteristics. The simulation tests for the pole slipping protection were performed on the RTDS (real time digital simulator). The power system model simulated on the RTDS is shown in Fig. 3.

Different faults were applied for various durations to test the pole slipping protection feature of the relay. All the possible conditions that might be expected to cause pole slipping of a generator on the system can be adequately represented using the power system model shown in Fig. 3 and are described below.

Pole slip tests

The following system faults and operating conditions were applied to obtain pole slips:

Fig. 4: Pole slipping - generating AVR, 3ph local fault, load 60%.
• Two phase to ground fault.
• Three phase to ground fault.
• Field failure.

The system faults were applied at two different locations:

• Local - These faults were applied at the HV terminals of the generator transformer and were called local faults.
• Remote - These faults were applied at the far end of the transmission line connecting the generator to the rest of the system and were called remote faults.

At the above mentioned faults were applied at different machine loadings. Machine loadings of 20%, 50%, 80%, and 100% (or 95% where the system stability demanded) were simulated.

Fig. 4 shows a typical pole slip caused by a 3 phase local fault with the machine generating at 80% load with the AVR in service. Note that each marker on the impedance locus represents a 5 ms time interval.

Fig. 5 shows a pole slip caused by a 3 phase local fault with the machine generating at 20% load with the AVR in service. Due to the presence of heavy system damping during the fault, the generator slows down and results in motor like slip (negative slip). If the relay is set to detect generator slips only, then it will not recognize this condition as a slip. Therefore the relay setting 'Pole Slip Mode' should be set to 'Both'.

All the results are presented in graphical form consisting of the calculated A-phase impedance locus on the impedance plane.

Fig. 6 shows the impedance locus for a loss of field at 100% machine load. A sustained loss of field for several tens of seconds results in a periodic pole slip, and the relay operates correctly for each slip. The relay remains stable when there is no pole slip.

Stability tests for power swings

These tests verified that the pole slip element is stable during power swing conditions, confirming the validity of the algorithm. The following three test conditions were simulated:

• Power swing following a two phase to ground fault.
• Power swing following a three phase to ground fault.
• Power swing following generator excitation control failure.

Both local and remote system faults were applied with the AVR enabled and disabled.

Fig. 7 shows the impedance locus for a remote 3 phase fault at 20% machine load. The relay remains stable during this power swing event.

Stability tests for loss of prime mover

These tests verified that the pole slip protection element remained stable during a prime-mover failure that causes the generator to operate in a motoring state with high var export and very low active power import.

The extreme case was a generator operating at unity power factor exporting maximum power to the system before the prime-mover failure.

Fig. 8 shows the impedance locus during a loss of prime-mover at 80% loading. The relay remains stable during this power swing event.

Conclusion

This paper discusses the operation, design, and simulation tests for an impedance-based pole slipping protection algorithm. It can be applied to hydro generators as well as other types of machines. Directional and blinder elements are used together with a mho element to obtain the desired relay characteristics. Extensive simulation tests have been performed to demonstrate the correct operation of the algorithm.

References


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