SETTING AND TESTING OF POWER SWING BLOCKING AND OUT OF STEP RELAYS CONSIDERING TRANSIENT STABILITY CONDITIONS

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Abstract

This paper reviews the behavior of electrical systems when they are subjected to oscillations which can cause that one or more synchronous machines loose synchronism with each other. The paper makes a detailed reference to power swing blocking and out of step relays whose operation has to assure adequate protection under these conditions. A thorough procedure is discussed to set out of step relays based on transient stability studies. The procedure is illustrated with a case study using power system stability software and then the settings were implemented in a numerical relay for real testing.

1 Introduction

Electrical power systems are exposed to a variety of abnormal operating conditions such as faults, loss of generators, line tripping and other disturbances which can result in power oscillations and consequent system instability. Under these conditions appropriate relay setting is essential to assure proper protection, this is, the disconnection of generators that loose synchronism and the blocking of distance relays associated to HV lines, whose operation is not required. This topic is receiving especial attention after the blackout of August 14th, 2003, that affected severely millions of users in the Midwest and Northeast of the US Electrical system, when it was evident that many relay schemes did not perform appropriately.

Transient stability studies are aimed to determine if the system will remain in synchronism following major disturbances. The nature of these problems do not allow the linearization process to be used but the solution of nonlinear differential and algebraic equations by direct methods or by iterative step-by-step procedures.

Usually the time period under study is the first second following a system fault. If the machines of the system are found to remain in synchronism within the first second, the system is said to be stable. Multiswing stability problems must consider effects over an extended time period. Models of higher sophistication must be used to reflect accurately the machine behavior [1].

2 Transient Stability Concepts Review

Transient stability concepts will be reviewed with a simple lossless transmission line connecting two sources corresponding to a generator at a location S and an equivalent network at a location R. It is well known that the active power, P, transferred from the generator into the network can be expressed as:

$$P = \frac{Vs\ x\ Vr}{X} Sin\ \delta \qquad (1)$$

Where Vs is the sending-end source voltage magnitude, Vr is the receiving-end source voltage magnitude, δ is the angle difference between the two sources, and X is the total reactance of the transmission line that connects the two sources.

With fixed Vs, Vr and X values, the relationship between P and δ can be described in a power angle curve as shown in Figure 1. Starting from δ = 0, the power transferred increases as δ increases. The power transferred reaches the maximum value P_{MAX}, when δ is 90 degrees. After that point, further increase in δ will result in a decrease of power transfer.

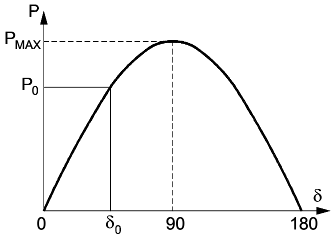

Figure 1 Power Angle Curve

During normal conditions, the output of electric power from the generator produces an electric torque that balances the mechanical torque applied to the generator rotor shaft. The rotor therefore runs at a constant speed with this balance of electric and mechanical torques. When a fault occurs, the amount of power transferred is reduced and so the electric torque that counters the mechanical torque. If the mechanical power is not reduced during the period of the fault, the generator rotor will accelerate proportionally to the net surplus of torque input. To better explain the physical behavior of a power system under faults or disturbances, consider the simple two line system of Figure 2.

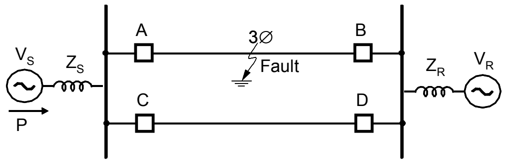

Figure 2 Electrical System used for the Illustration

If a three phase fault occurs at the upper line, the power output is reduced from point D to E, the rotor therefore accelerates and the surplus power starts increasing the angular displacement along the new power transfer curve to point F as indicated in Figure 3. When breaker A opens the power transfer function increases to point G. The rate of angular displacement is reduced but still increasing to point H when Breaker B opens in zone 2. The fault is then cleared, the power output goes to point J and a decelerating torque appears on the rotor because the electric power output at J is larger than the mechanical power input P_O. However, because of the inertia of the rotor, the angle does not go back immediately. Rather, the system then swings along the new power transfer function that is lower than the original because one line is now out, and reaches point K when the decelerating energy of Area II equals the accelerating energy of Area I. This is the so-called equal-area criterion..

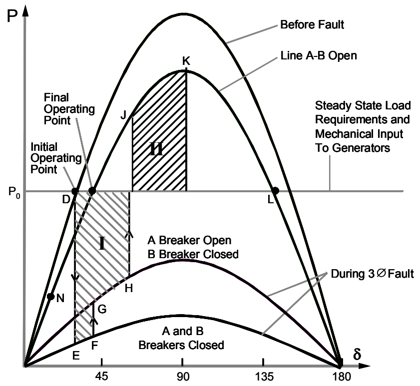

Figure 3 Transient Stable Condition

With sufficient damping, the angle difference of the two sources eventually goes back to a balance point. There is a critical angle for clearing the fault in order to satisfy the requirements of the equal area criterion mentioned above. If area II is smaller than area I at the critical angle, then further increase in angle δ will result in an electric power output that is smaller than the mechanical power input. Therefore, the rotor will accelerate again and δ will increase beyond recovery. When an unstable condition exists in the power system, one equivalent generator rotates at a speed that is different from the other equivalent generator of the system. Such a condition is referred to as a loss of synchronism or an out-of- step condition of the power system.

If such a loss of synchronism occurs, it is imperative that the generator or system areas operating asynchronously be separated immediately using out-of-step protection systems-OST identified as 78.[2]

3 Impedances Seen By Relays

During power system oscillations the voltage and current which feed the relay vary with time and, as a result, the relay will also see an impedance that is varying with time which may cause it to operate incorrectly. The equivalent circuit for an analysis considering two sources V_S and V_R is shown in Figure 4. Vector and impedance diagrams corresponding to the system of Figure 4, are shown in Figures 5 and 6 respectively.

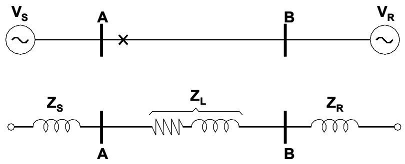

Fig. 4 Equivalent circuit for analysis of power system oscillations

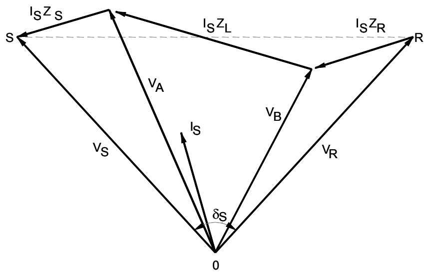

Figure 5 Vector diagram for system of Figure 4

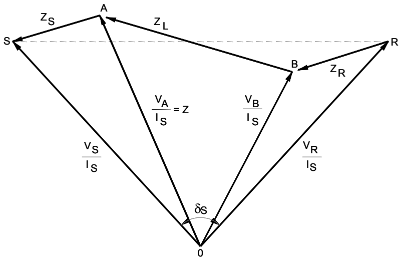

Figure 6 Impedance diagram for system of Figure 4

4 Out of Step Protection

The Out-of-Step function is used to protect the generator from running under out-of-step or pole slip conditions. There are different ways to implement Out of Step Protection [3]. One of the commonest types uses one set of blinders, along with a supervisory MHO element. As shown in Figure 7.

The pickup area is restricted to the shaded area, defined by the inner region of the MHO circle, the region to the right of the blinder A and the region to the left of blinder B.

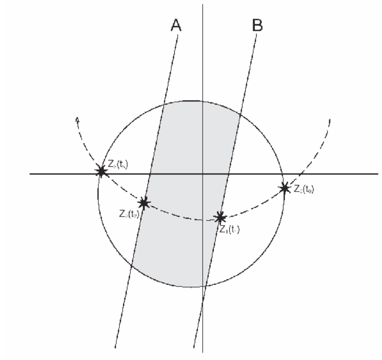

Figure 7 Out of step relay with one set of blinders

The following conditions have to be satisfied for operation of out of step relay using the blinder scheme:

- The positive sequence impedance must originate outside either blinder A or B.
- It should swing through the pickup area and progress to the opposite blinder from where the swing had originated.
- The swing time should be greater than the time delay setting

When this scenario happens, the tripping circuit is complete. The contact will remain closed for the amount of time set by the seal-in timer delay.

The setting of 78 elements is carried out with the following procedure that is illustrated on Figure 8:

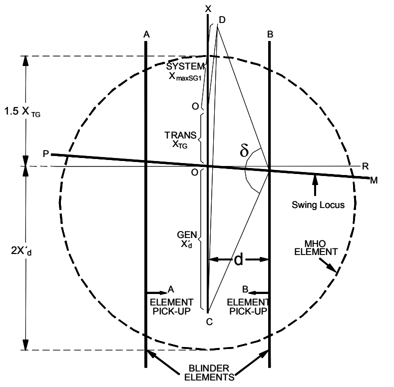

Figure 8 Procedure to set out of step relays

1. Determine values of X'_d, X_{TG} and $X_{\max SG1}$. The summation makes up the so called line of impedance.
2. Set the Mho unit to limit the reach to 1.5 times the transformer impedance in the system direction. In the generator direction the reach is typically set at twice generator transient reactance. Therefore the diameter of the MHO characteristic is $2X'_d + 1.5X_{TG}$.
3. Determine by means of several transient stability runs, the critical angle δ between the generator and the system. This happens at the point where the system just gets unstable. If a transient stability study is not available, this angle is typically set at 120°.
4. Determine the blinder distance d, which is determined with the following expression:

$$d = \left(\left(\frac{X'_d + X_{TG} + X_{\max SG1}}{2} \right) x \tan(90 - \delta / 2) \right) \qquad (2)$$

5. Determine the time for the impedance trajectory to travel from the position corresponding to the critical angle to that corresponding to 180°. This time is obtained from the rotor angle vs. time curve which is generated by the transient stability study, for the case just when the system experiences the first slip.

6. With the above value times two, determine the time taken by system to travel within the blinders. This gives the reference to set the out of step relay. [4,5,6]

5 Case Study of Transient Stability

5.1

Consider the power system of the Figure 11, corresponding to the Example 14.9 from the book 'Elements of Power System Analysis by William D. Stevenson [3]. This case is used to illustrate the procedure to determine the critical clearing time and the traveling time within the blinders of an Out of Step relay by means of a transient stability study. The other settings of the relay are rather straightforward as they depend on the reactances of the elements and will not be illustrated here. The transient stability analysis will be carried out considering a three-phase fault over line L_45, near node 4.

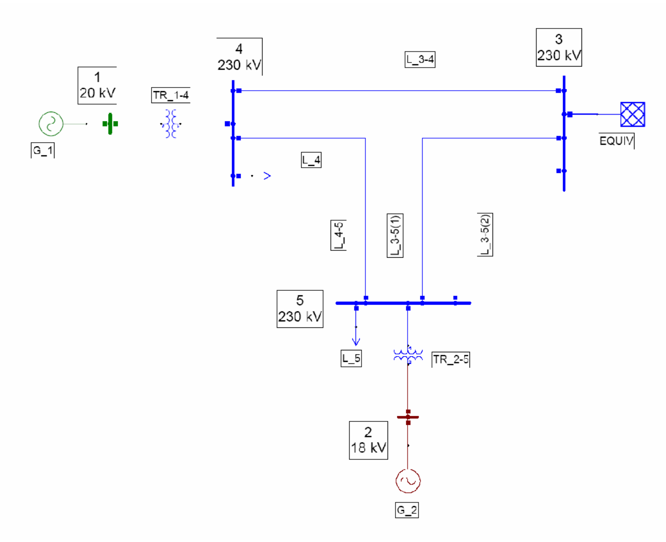

Figure 9 Power system for example

5.1 Considerations

The considerations to analyze the example are the following:

1. The fault inception will be considered at t = 0.5 s
2. Clearance times starting at t = 90 ms (Approx. 5 cycles) will be analyzed in consecutive steps of 10 ms.
3. For each case, the fault is removed with the consequent outage of the line.

5.2 Critical Clearing Time

Determining the critical clearing time is perhaps the most elaborate part of the entire setting process. To achieve this, several runs of the transient stability study have to be done to determine when the system looses synchronism or has the first slip.

5.3 Results

The transient stability analysis was made for a three-phase fault over line L_45, near node 4. The solution was obtained by using a software package called NEPLAN®[12]. The results corresponding to the load flow conditions prior to the fault are shown graphically in Figure 10 by the software package as follows:

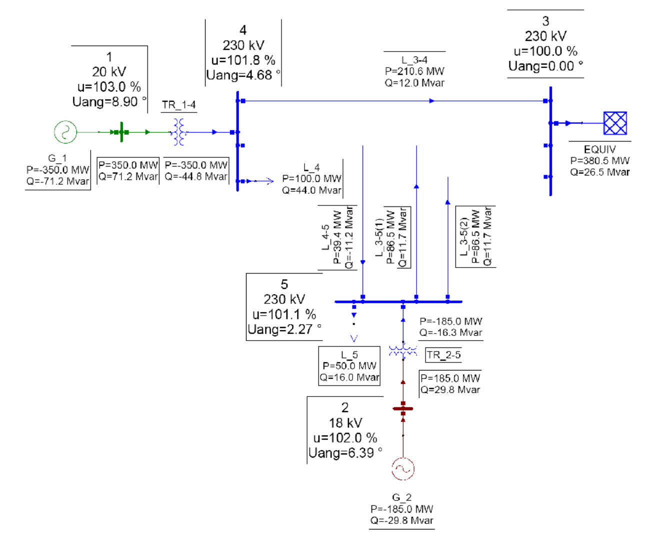

Figure 10 Load flow results

Different cases were run with clearing times starting at starting at t = 90 ms and increments of 10 ms in an iterative process until stability was lost. The results of three representative cases will be analyzed here with clearing times as shown in the following table.

Case	***Fault Clearance Time (ms)***
Case 1	90
Case 2	180
Case 3	190

Table 1: Fault Clearing Times

From the respective plots it is observed that in Case 1 with a clearing time of 0.09 s the system remains in synchronism. In Case 2, G_1 the system is still in synchronism with a clearing time 0.18 s. For case 3, G_1 the system looses synchronism when clearing time is 0.19 s. From the above it is clear that the critical time to clear the fault of the generator G_1 is equal to 180 ms after fault inception.

The rotor angles for the three cases are shown in Figure 11, from which it can be seen that the critical angle is approximately 140°. The time for the impedance point to travel from that critical angle to 180° is approximately 0.2 s. Therefore the traveling time within the blinders should be set at 0.4 s.

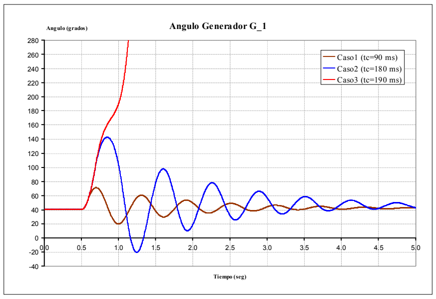

Figure 11 Rotor angle vs Time form the three cases considered

5.2 ANALYSIS OF R VS X DIAGRAMS

R vs X diagrams for the three cases show the trajectory followed by the impedance seen by the relay during the disturbances. When there is an oscillation in the generator which is stable, the point of impedance does not cross the line of impedance.

When there is an Out of Step in the generator, the point of impedance crosses the line of impedance of the system each time the slip is completed and the relay should disconnect the generator. Figure 12 shows the diagram R vs X for cases 1, 2 and 3. In the first two it is clear that the impedance point does not cross the line of impedance of the system. For case 3, the impedance point crosses the line of impedance indicating therefore that synchronism is lost and therefore Out of Step operation must be allowed.

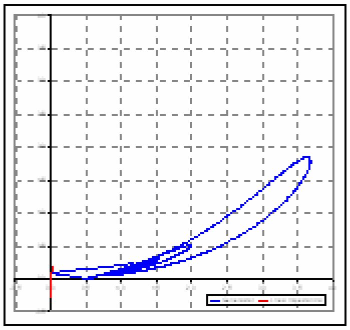

Figure 12-1 Diagram R vs X for case 1

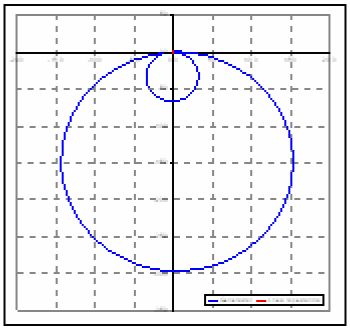

Figure 12-2 Diagram R vs X for case 2

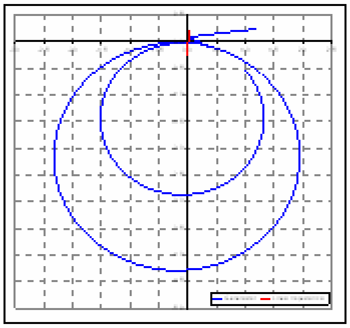

Figure 12-3 Diagram R vs X for case 3

6 Conclusions

- Transient stability studies are essential to determine the behavior of an electrical system subjected to oscillations following disturbances in the networks. Among other reasons, transient s Case 3 ıould be conducted to properly set out of step relays since they provide the critical angle and the traveling time of the impedance point within the blinders set.
- Out of Step relays are very important and reliable to determine truly slip conditions of synchronous generators.
- From the formulation it is clear that there are ways the protection system can mitigate the affect of the fault on the power swing which includes: fast clearing to minimize the time that the fault is reducing the transfer capability; use of pilot systems to clear both ends fast; use of breaker failure systems to reduce the worst case situation; implement single pole tripping to allow transfer of energy during breaker open time; implement high speed reclosing and load shedding whenever practicable.

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