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Out-of-step protection of generator using analysis of angular velocity and acceleration data measured from magnetic flux

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ABSTRACT

This paper presents a new flux-based method for out-of-step protection of synchronous generator. The available measured angular velocity and acceleration data from magnetic flux of the generator, at the location of the relay, are used to detect out-of-step conditions. An out-of-step condition can be distinguished in the point in which the polarity of the angular acceleration changes from a negative to positive value and the angular velocity is greater than the base angular velocity. The basic idea of the approach stems from the fact that the resultant magnetic flux rotates at synchronous speed and cannot change rapidly. In other words, this constant magnetic flux will not be affected by switching transients due to highly inductive characteristics of the machine. Finally, the simulation results verify the straightforward application of the proposed technique even for a multi-machine power system. Therefore, the proposed approach can be directly applied to an interconnected power system without any need to cumbersome network reduction methods. Furthermore, the proposed technique does not require any offline studies and overcomes some of the problems associated with the previous solutions.

1. Introduction

The North American blackout on August 14, 2003, has led to considerable number of researches on many aspects of system protection. One of the important and commonly misunderstood issues that have been addressed is power swing and out-of-step protection applied to the power systems [1]. The power system stability problem is a major concern in the planning and operation of electric power systems, and synchronous generators play a significant role in this issue. An unstable power system that loses synchronism may cause severe damage to the machine, interruption of electrical supply, and significant economic loss. Therefore, loss of synchronism detection is essential for the safe operation of the system. Loss of synchronism of a synchronous generator may occur as a result of loss of excitation or out-of-step conditions. In loss of excitation fault, the excitation system may be completely or partially lost due to some technical problems [2]. However, in out-of-step conditions; the protection system also detects loss of synchronism, but with the excitation system intact. In out-of-step condition, the power system loses synchronism due to a disturbance such as short-circuit faults, line switching, generator tripping, load shedding, etc. [3,4]. Depending on the disturbance severity, the power network may or may not return to a new stable situation. When the disturbance is serious, the fluctuations would not be damped out which leads to asynchronous operation of the generators. This phenomenon is called out-of-step condition [4,5].

The most popular and commonly used approaches for detecting out-of-step conditions are based on the measurement of positive sequence impedance at the relay location. In general, these approaches utilize a distance relay with blinders in the R–X plane and a timer. Regardless of stable or unstable swing, the distance relay is prone to interpret a power swing as a fault which is discussed in Fig. 1. The relay in Fig. 1(a) trips for the cases ‘b’ and ‘c’ as the impedance trajectory moves towards the operating zone. Sending a trip signal during the stable condition (case ‘b’) is not desirable. Therefore, assigning a time delay is usually utilized to overcome the possible maloperation of the distance relay. In this case, the power network returns to the new steady state condition. Thus, an out-of-step protection relay must be able to discriminate between a fault and a swing (stable or unstable). First, the blocking function must block relay during a stable or unstable power swing. Tripping function must then distinguish between stable and unstable power swings.

It must be mentioned that according to the power system configuration, loading conditions, the type of faults that often happen on the system and the desired performance, one of the blinder schemes, can be selected. The schemes can be classified as one blinder scheme, two blinder scheme, concentric characteristic schemes

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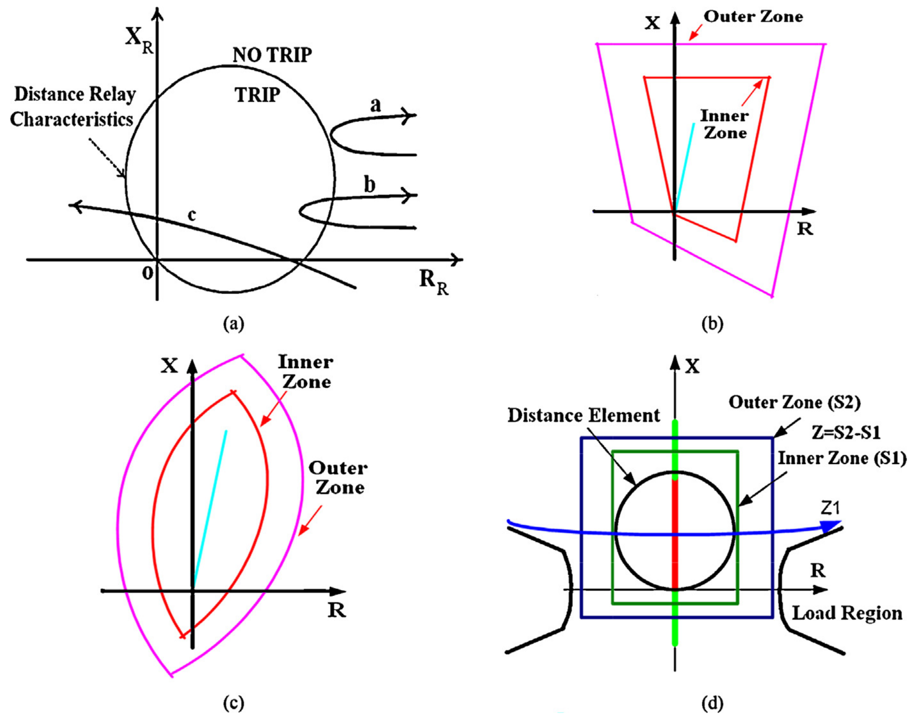

Fig. 1. Impedance-based techniques of out-of-step protection relay [1]: (a) operating characteristics of distance relay showing various power swings; (b) concentric quadrilaterals; (c) concentric lenticulars; (d) concentric rectangular.

(Mho, Polygon, Lenticular). Fig. 1(b)–(d) illustrate the concentric characteristic schemes used for out-of-step protection and it must be noted that the operating principle is the same for all cases.

During normal conditions, the impedance measured at the relay location is the load impedance, and its trajectory is away from the distance characteristics. During a fault occurrence, the impedance trajectory seen from the terminal of the generator travels immediately from the load impedance region to the location that shows the fault on the R–X plane. During a power swing condition, the calculated impedance moves slowly on the R–X plane due to the slip frequency of an equivalent two-machine system. Traditional detection methods for power swing condition, utilize the difference between the impedance rate of change in a fault and in a power swing condition to discriminate between a fault and a swing. In order to carry out this discrimination, one specific designer can usually place two concentric impedance characteristics '$S1$' and '$S2$', separated by impedance Z ($Z = S2 - S1$), on the R–X plane (see Fig. 1(d)). The time taken by the impedance locus to travel between the two concentric impedances ('$S1$' and '$S2$') is measured by the relay. This time is compared with the preset time to distinguish between a fault and a swing. If the impedance locus travels inner and outer characteristics in less than the pre-set time, the relay detects the case to be a fault. If the impedance locus passes the outer characteristic, but does not pass the inner characteristic, the case is a stable swing. Finally, an out-of-step condition is detected when the time it takes for the impedance locus to pass through both inner and outer characteristics is more than the pre-set time [1,4].

Setting the blinders (i.e. the inner characteristics '$S1$' and the outer characteristics '$S2$') and determining a pre-set delay are the main problems with these methods. The settings require some information about the rate of slip during the transient condition that depends on the accelerating torque and power network inertias. Another problem is that in heavily loaded long transmission line condition, the load region lies close to the operating characteristics of the relay and the settings of binders may overlap the setting of relay and normal load region. This overlap may cause the relay incorrect operation.

It can be clearly seen that, these methods need some information about the normal operation region, the system loading conditions, the possible swing frequencies, the fastest power swing and other system specific data. In other words, these methods need an extensive system stability studies for finding the settings and their complexity increases when applied to multi-machine networks. For a multi-machine network, the realization of these methods is not clear-cut and is not straightforward as a two area system. It is worth mentioning that, incorrect operation of these relays has been reported in recent works [1,6], when there is a significant change in system and transfer impedance values. Therefore, in order to enhance security and also overcome some of the problems associated with the impedance-based techniques, new methods have been introduced in literature.

In [1], the monitoring of the rate of change of swing center voltage (SCV) was found to be an effective technique to discriminate between stable and out-of-step swings. The disadvantage of this method is that for a multi-machine network, the voltage measured at relay location does not give a precise estimation of SCV. The method also needs extensive offline system stability simulations to set the rate of change of SCV (threshold value) [4]. Out-of-step detection method by mapping the equal area criterion conditions to the time domain is presented in [4]. Out-of-step conditions were identified using the accelerating and decelerating energies, which represents the area under the power-time curve. The recommended technique is simple and overcomes some of the problems associated with the previous methods. However, this identification is graphically done by point-by-point analysis directly in the time domain that may limit its application. A new out-of-step detection method using the state-plane representation of the generator speed and power angle is presented [6]. The energy function criterion for out-of-step detection in a complex power system has been proposed in [7]. However, due to its dependency to wide area information, its implementation becomes complex [4].