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Performance evaluation of impedance-based synchronous generator out-of-step protection in the presence of unified power flow controller

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ABSTRACT

Flexible ac transmission system (FACTS) controllers change the transmission line voltage and current signals measured with protection relays. These devices affect the operation of impedance-based relays and can lead to relays under/over-reaching. This study investigates the effects of a unified power flow controller (UPFC) as one of the most important shunt-series compensators on the synchronous generator out-of-step (OOS) protection. A detailed model of the UPFC is used for the purpose of the study and its performance has been simulated in three operational modes of the shunt-series compensator including static compensator (STATCOM), static synchronous series compensator (SSSC) and UPFC. The results show that all the three modes of the UPFC change the impedance trajectory and disrupt the diagnosis of the OOS protection. Moreover, an analytical approach is developed to eliminate the negative effects of the devices. The approach only requires the UPFC voltage and current synchro-phasor data to calculate the modified impedance. The results show that the presented method properly eliminates the negative effects on the OOS relay and prevents it from under-reaching in all the UPFC operation modes. The most important advantage of the modified algorithm is that it can be generalized to other types of FACTS devices.

1. Introduction

Power system stability is an important issue in the power system operation. In the normal operation of the power system all synchronous machines are in step with each other and operate at the same average speed. However, when faults occur in the system, the resulting disturbances cause oscillations in machine rotor angles and consequent power flow swing in the system. Depending on the severity of the disturbance, a power swing may evolve into a stable or an unstable power swing. In the unstable power swing, the system cannot return to synchronous operation. The unstable power swing and machine loss of synchronism are called out-of-step (OOS) condition [1]. The OOS condition causes cyclic variations in the currents and voltages of the effected machine, which are damaging the machine. Moreover, the condition may endanger the stability of the entire system [2]. To avoid such damages, a reliable generator protection scheme is necessary to detect the OOS condition. The conventional detection function of the OOS protection is based on analyzing the measured impedance at the R-X plane [3,4]. Some traditional methods of power swing and OOS detection such as concentric characteristic and blinder schemes, Rdot scheme, continuous impedance calculation, swing-center voltage were summarized in [5]. Among these methods, the blinder schemes have been more considered. The main advantage of this method is its simplicity. New approaches such as distributed dynamic state estimator [6,7], synchrophasor-based out-of-step relaying [8,9] and frequency based out-of-step protection [10] have been presented in recent studies. The main features of these methods are compatibility and strength against changes in power system configuration. However, these approaches are complicated and have a high computational requirement. One of the main problems with respect to the impedance-based techniques is the change of measured impedance due to the large disturbances [11] and the using of compensators in the transmission line.

Many publications considered the distance relay performance for different fault types/point with various FACTS devices [12–24]. Another studies investigated the effects of FACTS devices on the loss of excitation (LOE) protection of synchronous generator [25–29]. Results of these studies showed that the presence of FACTS devices causes a substantial delay in the performance of LOE relay. Only few articles have been published on distance relay performance for a compensated line during a power swing condition [30,31]. The authors in [30] simulated and compared the performance of two power swing detection algorithms with and without series capacitors. In [31], the impedance seen by a distance relay during power swing conditions in a compensated line with UPFC was investigated but any modified approach was

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not proposed.

In this study, the impact of UPFC is analyzed on the synchronous generator OOS protection. It should be noted; that the power swing characteristic/logic of distance relay is different from generator OOS characteristic/logic and must be evaluate, separately. According to authors' knowledge this issue has not been addressed in the literatures. To this end, a gate turn-off thyristor (GTO)-based detailed model of UPFC is used and different operation modes of the UPFC including shunt (STATCOM), series (SSSC) and shunt-series (UPFC) mode have been considered in the simulations. The main contributions of this study are:

1. The measured impedance by OOS relay is extracted based on generator internal voltage and external system voltages in the presence and absence of UPFC.
2. The performance of the OOS relay in the presence of UPFC during power swing condition is studied and the impact of SSSC, STATCOM and UPFC is investigated.
3. An modified approach is developed to correct the impedance deviation caused by the UPFC
4. The performance of modified approach is validated by simulation results

During power swing condition the impedance loci seen by the OOS relay without UPFC are circles [32]. The presence of UPFC changes the impedance path and causes the measured impedance deviate from circle Trajectory. Due to this deviation, it is possible; the OOS condition not to be detected and causes under-reaching of the OOS relay. Using the analytical investigation and simulation, a new modified approach is proposed to correct the impedance path. The performance of proposed approach is validated by the simulation results. Since the proposed approach considers the effects of all the UPFC operation modes on the OOS relay operation, it proves to be highly useful in power system protections.

The rest of this paper is organized as follows: Section 2 describes the generator impedance-based OOS protection. Section 3 introduces the principles about the UPFC performance and describes the different operating modes of the UPFC. In Section 4, the modified impedance-based OOS protection is presented. Section 5 presents the simulation results of the loss of synchronism in the presence of the UPFC. Section 6 investigates the performance of the modified approach and the results are addressed and analyzed. Finally, Section 7 concludes the study.

2. Synchronous generator OOS protection

During power swing in the network, OOS generators must be rapidly isolated from the power system not only to prevent damage to the generator, turbine and step up transformer, but also to prevent instability from spreading to other portions of the system. There are several schemes available for OOS protection, most of which detect a loss of synchronism by analyzing the measured impedance at the R-X plane. Two commonly used approaches to OOS protection are the mho element and the blinder scheme [1].

In order to assess the relay operation, the system shown in Fig. 1(a) is considered. In this system, the CT and VT of the relay are placed in the generator terminal and after step up transformer. In this figure, I_R, V_R, E_1, E_2 and V_{B1} are the relay current and voltage phasors, the internal voltage of generator, external system voltage and step up transformer output bus bar voltage, respectively. The impedance Z_1 is the sum of the generator and transformer reactance and Z_2 is the sum of the transmission line and external system impedances. The thevenin equivalent of the system is at right side of the Bus B1. Fig. 1(b) shows the block diagram of the impedance-based OOS relay. First, the voltage and current are sampled using the VT and CT. Then, the samples pass through the low pass filter to remove high frequency components. After analog-to-digital conversion, the voltage and current phasors are calculated with the full cycle discrete Fourier transform (FCDFT). The measured apparent impedance of the relay is obtained by dividing the voltage phasor into the current phasor. Finally, the impedance path is obtained by plotting the apparent impedance on the real-image plane.

In this study, we used the blinder scheme with the characteristic of Siemens 7UM62 protection relay shown in Fig. 2 [33]. The characteristic boundaries are determined by the setting parameters impedances Z_a, Z_b, Z_c and Z_d, which are given in Table 1. In this table $x_d^{'}$, X_{TR} and X_{sys} are transient reactance, transformer reactance and system reactance, respectively. Moreover, δ_{CRIT} is the critical rotor angle and must be determine by stability analysis such as equal area criterion and its range is 120–150 degrees. Based on Siemens 7UM62 manual $\delta_{CRIT} = 120$ is chosen. The polygon is symmetrical around its vertical axis. The power swing polygon is divided into two parts. Characteristic 1 represents the lower section of the rectangle and Characteristic 2 covers the upper hatched area. Depending on the electrical center of the power swing, or in the vicinity of the power station, the impedance trajectory passes from the Characteristic 1 or the Characteristic 2.

Due to the symmetrical nature of the power swing, the first condition for power swing detection is that the positive sequence component of the current exceeds an adjustable limit I_1 while the negative sequence current remains below an adjustable value I_2. Additionally, detection of an OOS condition requires that the impedance trajectory enters a characteristic from one side and exits from the opposite side (Cases 1 and 2). On the other hand, if the impedance trajectory enters and exits the same side, in this case, the power swing tends to stabilize (Cases 3 and 4).

The logic diagram of the out-of-step protection of 7UM62 is shown in Fig. 3 [33]. When an out-of-step condition is recognized, i.e. when the impedance vector has passed through a power swing characteristic, an annunciation is issued which also identifies the crossed characteristic. Additionally, a counter n1 (for characteristic 1) or n2 (for characteristic 2) is incremented. Out-of-step protection pickup is activated when a counter reaches to 1. A further out-of-step indication is set for an adjustable indication time period, each time a counter is incremented. After an adjustable holding time, the pickup resets to zero. The holding time is started a new each time a counter is incremented. A trip command is issued when the number of power swing polygon crossings has reached a selectable number. This command is maintained for at least the set time THOLDING. The minimum trip command duration Tmin TRIPCOM. does not start until the pickup has reset.

3. Principles of the unified power flow controller (UPFC) performance

The UPFC is a FACTS device that is primarily used for power-flow control and voltage regulation in transmission networks. In addition, it can be used to damp low-frequency dynamic oscillations (e.g., inter-area oscillations and subsynchronous resonance) and enhance transient stability. Fig. 4(a) presents a single-line diagram of a UPFC with its main components. The UPFC is composed of two shunt and series converters with coupling transformers and a common DC link between the converters. The simplified single-line diagram of the UPFC is shown in Fig. 4(b). Analytically, the UPFC can be considered as a voltage source with variable amplitude and phase angle. The corresponding vector diagram is shown in Fig. 4(c).

The UPFC is composed of three inter-connect subcircuits including series, shunt and DC link subcircuits. The series converter injects a voltage in series with the line which, in turn, modifies the voltage at terminal 2(V_2). According to the familiar Eqs. (1) and (2), the active and reactive power at the sending-end can be affected by controlling the magnitude and angle of V_2. In this way, by injecting V_{inj}, V_2 can take any values inside the circle of Fig. 3(c). The radius of the circle is given by the maximum magnitude of the injected voltage (V_{inj_max}).