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Evaluation of power transformer inrush currents and internal faults discrimination methods in presence of fault current limiter

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ABSTRACT

Due to increase in penetration of Distributed Generations (DGs) in power systems, fault current level is being increased, which results in some problems in the systems. Fault Current Limiters (FCLs) are attractive devices to tackle these problems for transmission and distribution systems. The utilized FCLs may have considerable impact on the signals used for differential protection of power transformers, which leads to mal-operation of these protections. It seems a comprehensive analysis is necessary for performance evaluation of differential protection algorithms in presence of FCLs. This paper deals with investigation of FCLs impact on power transformers' differential protection. The performance of some well-known differential protection algorithms for discrimination between internal fault current and magnetizing inrush current with and without presence of FCL are evaluated.

1. Introduction

Due to some economical, technical and environmental concerns, Distributed Generations (DGs) have been widely used in recent decades [1,2]. Some of the benefits of utilizing DGs in power systems are environmental power facilities, improvement of power quality [3], reliability, supplying loads in remote areas without access to the power system, reduction of transmission losses [4], etc. However, installation of DGs in power system tends to have some concerns related to voltage regulation, voltage flicker, voltage sag, and harmonics [5], which are dependent on the distribution system operating and DG characteristics. The mentioned concerns can be solved through extended distribution networks containing appropriate control systems and communication possibilities [6].

Also, increase in penetration of DG and electrical energy demand lead to rise of fault current level in power systems. The increased fault current level has several negative impacts on power system components, which are as follows [7–12]:

a. Results in large mechanical forces on the power system equipment.
b. The increased fault current level exceeds interruption capacity of circuit breakers.
c. Leads to loss of coordination of over-current protections.
d. Leads to false tripping of the healthy feeders.
e. Results in unwanted islanding.

Replacement of power system components such as transformers and circuit breakers with higher rating ones and using adaptive protection systems are two remedial strategies. However, utilizing Fault current limiter (FCL) is another attractive alternative solution [13–19]. FCL is one of promising devices which is capable of limiting fault current in fault condition and has no considerable impact on network in normal condition. In [13], FCL is applied in neutral line of power transformer in order to improve the sensitivity of differential protection. In [14], FCL is used to limit the effect of DGs on coordination of directional overcurrent relays. Different types of FCLs have been proposed, which can be classified into two categories based on their current limiting impedances, L-type and R-type. Both types have several advantages and disadvantages [15–17]. The effects of R-type and L-type FCLs on distance relay are evaluated in [18,19].

Since the FCLs are utilized to limit short circuit current within the first cycle after fault occurrence, the current and voltage waveforms and consequently the differential protection of power systems are affected. The affected input signals of the Digital Signal Processor (DSP) relevant to a differential protection may lead to mal-operation of this protection. So, a comprehensive analysis is required to investigate the effects of FCLs on the differential protections.

One of the main concerns for the performance of differential protections is mal-operation in magnetizing condition. In fact, magnetizing inrush current of power transformers may have similar attributes with internal fault currents. In addition to the energization, any abrupt changes of the magnetizing voltage may generate inrush current. For

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example, voltage recovery after external fault clearance and energization of a transformer in parallel with an already in service transformer may cause inrush current. Discrimination of inrush current from internal fault is one of the most challenging issues in this regard.

Plenty of algorithms have been proposed in order to discriminate internal fault from inrush currents. They are based on different approaches such as harmonic restraint [20–22], instantaneous inductance [23], waveform singularity factor [24], comparing the relationship between flux and current signals [25], absolute difference of incoming and consuming active power of power transformers [26], wavelet coefficients [27], and improved correlation algorithms [28,29].

A variety of methods for improving reliability and detection time of this protection are presented in [30–32]. An auto correlation function based technique has been proposed in [30] in this regard. In [31], criterion of the discrimination is captured by gradient of differential current. Another method which is based on variation feature of the fundamental current has been presented in [32]. An identification criterion is proposed in [33], which is based on normalized grill curve. A discrimination method based on least square technique is proposed in [34,35]. Also, the second harmonic components of differential currents have been used in [36,37] to identify inrush condition.

However, comprehensive studies are required to evaluate the performance of the differential protection algorithms in case of utilizing FCL in power systems. In this paper, sixteen techniques for discrimination of internal fault from magnetizing inrush currents including conventional and recently proposed methods are evaluated with and without presence of two types of FCL in the system. Different simulations are carried out to reveal effects of the FCL on the methods.

2. Solid State Fault Current Limiter

In this paper, a Solid State FCL (SSFCL) shown in Fig. 1 is utilized, which is presented in [14]. The SSFCL is composed of a bidirectional semiconductor switch, limiting impedance Z_{FCL}, a high voltage ZnO varistor to prevent overvoltage transient, and a parallel snubber to protect the switch. Under normal condition, the FCL provides a low impedance path in order to decrease losses and distortion by turning on the semiconductor switch. In case of fault occurrence, by turning off the switch, fault current is suppressed by the FCL's impedance. The fault current limiting element can be either a resistive or inductive impedance. In this study, both L-type and R-type SSFCLs are considered and their impacts on the differential protection algorithms are investigated..

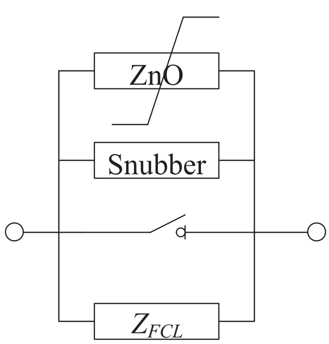

Fig. 1. Series switch-type SSFCL.

2.1. Internal fault current wave shape of power transformers

The power system, shown in Fig. 2, is simulated in PSCAD to evaluate the FCLs impact on the performance of the detection methods. The performance of the methods is evaluated with and without presence of the FCLs in the system by different simulations. Effects of both the L-type and R-type FCLs during internal faults are studied..

In the following, FCLs impacts on the differential current in internal fault condition are calculated.

$$I_{fault} = I_1 + I_2 \tag{1}$$

in which I_{fault} is internal fault current and I_1 and I_2 are HV and LV side currents of the power transformer. The HV side current can be calculated by

$$I_1 = \frac{V_1}{Z_{eq}} = \frac{V_1}{R_{eq} + jX_{eq}} = \frac{|V_1|}{\sqrt{{R_{eq}}^2 + {X_{eq}}^2}} \angle \tan^{-1}\frac{X_{eq}}{R_{eq}} \tag{2}$$

where, Z_{eq} is internal fault impedance seen from V_1.

From Eq. (2), one can conclude that L-type and R-type FCLs with the same impedance reduce current amplitude and change HV side current phase. However, in case of L-type FCL, due to inductive impedance of the power system, the AC component of fault current could be more limited than the R-type one with the same impedance. On the other hand, for the same limiting performance, the R-type FCL should have larger impedance. Fig. 3(a) shows that HV side current and consequently the internal fault current are more affected by the L-type FCL than the R-type one. Due to non-linear behavior of the inductance, a fracture on current waveform occurs in case of the L-type FCL. Various types of FCLs have different impacts on fault current amplitude and phase angle. Fig. 3(b) and (c) presents a comparison between an internal fault current with and without presence of the R-type and L-type FCLs in the system. Distortion of the current waveform in presence of the FCLs is obvious in the figures..

3. Evaluation of the discrimination methods in presence of the FCLs

To study the FCLs impact on the discrimination methods, a power system is simulated in PSCAD as shown in Fig. 1. The system includes a YNd, 30 MVA, 50 Hz, 63 kV/20 kV power transformer. The power system components are modeled accurately and their parameters are presented in the Appendix. Current and voltage signals of the simulated transformer are exported to MATLAB and the signals are processed using the algorithms. More than 1000 cases are simulated in this study. Simulation data for various scenarios are tested by changing the fault type, fault resistance, source impedance, and length of transmission lines. Furthermore, different energization angles, various winding connections of the power transformer, the transformer energization in internal fault condition, as well as different impedances and response times of the SSFCLs are considered. The sampling rate of the simulation is chosen 156 samples/cycle. With a suitable implementation of the transformer in PSCAD, the internal faults of the

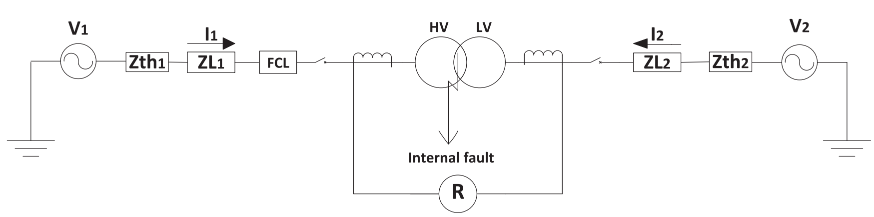

Fig. 2. Simulated power system.