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High-sensitivity stator fault protection for synchronous generators: A time-domain approach based on mathematical morphology

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ABSTRACT

This work presents an analytical methodology for synchronous generators stator faults protection. The proposed method is built on a differential protection relay strategy. A morphological filter is applied on the differential current providing real-time signal characterization. Unlike the traditional percentage differential relay, the proposed analytical methodology is able to detect all types of stator faults, including those close to the neutral end, which generates small differential currents due to the high impedance grounding of generator. Validation is done with OPAL-RT using a phase-domain synchronous machine model, which represents realistic operating conditions. The results of test cases highlights the method's dependability and security. Easy to implement models without hard-to-design parameters indicates the method's potential for real-life applications.

1. Introduction

SYNCHRONOUS generators (SG) are one of the most important and costly elements of power systems. Unlike other power system components, SGs need to be protected from several different types of faults and abnormal operating conditions, such as stator winding faults, overload, unbalanced operation, loss-of-excitation, loss-of-synchronism and motoring [1]. Currently, percentage differential protection is a common practice for SG [1] and power transformer protection [2]. Modern digital signal techniques and advanced model-based analytical methods may improve generator protection, especially from a potential stator fault. This type of fault may cause severe damage to the generator. The most common type of fault that SGs are subject to is ground faults in stator windings [3]. When SGs are grounded with high impedance, it is extremely difficult for differential protection to detect faults on stator winding since small fault currents are generated [1]. To overcome this problem, proposed solutions to protect 100% of winding suggests the simultaneous use of several protection functions, such as: percentage differential relays, neutral overvoltage relays and third harmonic schemes. This however may be costly and thus hinder real life applications in smaller SGs.

Considering such, several solutions aiming SGs protection schemes improvement, considering generator stator protection [4–10] have been proposed. Literature review highlights a common trend between proposed solutions. In such works, authors have focused on generator neutral and terminal third harmonic voltage characteristics use for fault detection. However, inherent limitations and significant disadvantages of third harmonic voltage-based protection solutions, such as the third-harmonic voltage level dependency on generator design and loading, have been reported [7,10–12].

Recently, Wavelet Transform [13,14], Neural Networks [15] and Fuzzy [16] based approaches for generator stator protection have been presented. Common assumptions are used in these works. Small laboratory generators or very simple SG models are used on problem formulation [13–18]. Hence, is not possible to see the behavior of the methods for different stator fault positions. The most of proposed works are tested for faults at generator terminals and it is considered as stator internal fault.

This paper presents an analytical methodology to protect generators against stator faults. The proposed analytical methodology is designed on a percentage differential relay strategy and tested in phase-domain synchronous machine model [19]. A Mathematical Morphological filter [20] and relay logic are proposed for signal characterization and fault detection, respectively. The main contributions of this method are:

- Only one protection function is able to detect single winding-ground fault, winding-winding faults (double and three phase faults) and winding-winding-ground (double and three phase faults);

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- Single winding-ground fault close to the neutral end are detected even if the generators has high impedance grounding;
- Solution may be applied for generators with effectively grounded, low-impedance or high-impedance grounded.

Still, simulation results show the generators protection reliability is also enhanced, since dependability and security are increased. Validation is made with an OPAL-RT simulator [21]. Using a refined synchronous machine model [22], which is incorporated into OPAL-RT's Hypersim, several fault and non-fault conditions are investigated.

The remainder of this paper is organized as follows. Section 2 presents the problem statement. Section 3 presents the Mathematical Morphology operations used in this work. The proposed analytical methodology is presented on Section 4. A case study is presented in Section 5. Section 6 includes the conclusions derived from this work.

2. Problem statement

SGs stator winding faults may cause severe damage to the windings and stator core [12]. Single winding to ground fault is the most common insulation failure and may result in a simultaneous burning of the iron and welds laminations. Generator grounding determines the ground fault protection type [12]. High impedance grounding is commonly used for generator grounding, especially when there is connection to a step-up transformer [1]. High impedances may be inserted directly between the generator neutral point and the ground or through a distribution transformer loaded with secondary resistance. When this grounding type is applied, the ground fault current is limited to between 5 and 15 A [12] and thus the generator differential relay may not be able to detect all ground faults, especially those near the neutral connection [1]. On the other hand, phase-phase faults, which are less common and are not limited by the grounding impedance, can be detected by the generator differential protection [1].

In the past, it was thought that a fault on an unprotected portion of winding, close to the neutral connection, would not produce significant damage to SGs. However, experience has shown that damaging faults can occur near this location [12]. Still, an undetected fault near the neutral connection of the generator will bypass the grounding and the ground-fault relay. Thus, if a second ground fault occurs in the same phase near the generator terminal it would also be undetectable, since the differential relay would also not operate [12].

In the late 1970s, a major European manufacturer [20] introduced a third-harmonic neutral undervoltage relay (27TN) aiming to enhance SGs stator protection. This relay, together with the traditional overvoltage protection, (59G) would provide stator ground fault protection over the entire stator winding. The basic idea of the third harmonic neutral undervoltage strategy is that when a generator stator ground fault occurs near the neutral connection, the third-harmonic voltage, which is measured across the neutral grounding resistor, is reduced to a small value. Otherwise, the terminal third harmonic voltage does not decrease. These features are used in several proposed solutions [4–10] to detect SGs near to neutral connection ground faults, named SGs "dead zone".

The drawback of third harmonic characteristic based schemes is that the level of third harmonic voltage that is present on a given generator depends on several operation conditions. These include the construction characteristics of the generator itself, the SG size, the generator terminal capacitance and the parallel operation condition. Still, there are SGs that generates small third harmonic voltages on which this strategy is unable to be applied [12]. Moreover, there have been a number of works that discuss relay setting through third-harmonic voltages at generator neutral. Reports highlight significant errors, making this an unreliable protection strategy [11,12].

An alternative solution for SGs stator ground protection is the neutral injection scheme [12]. With this strategy, a low power ac signal is applied at the neutral point using a transformer in series with the grounding transformer. This injected signal is usually a low-frequency voltage signal, typically at 12.5 Hz, 15 Hz or 20 Hz. This scheme provides complete ground fault protection during startup and shutdown. The drawback of using this scheme is that it must be taken out when the machine is offline for safety reasons and its cost is relatively high. Moreover, this strategy will not detect an open circuit in the grounding transformer or its secondary circuit [12].

3. Morphological operators

Mathematical Morphology (MM) is a nonlinear signal transformation tool that is applicable to non-periodic transient signals [20]. The mathematical calculation involved in MM includes addition, subtraction, maximum and minimum operations. Hence, morphological operators are suitable for real-time applications, such as generator protection. In addition, MM works exclusively in time domain with several reported applications on de-noising signals and images [20].

In the signal processing field, the main function of morphological operators is to extract relevant characteristics of a signal. This extraction is done by the interaction between the signal and another function called "*Structured Element*" (SE). SE shape is a key factor for the application's success and depends on the characteristics of problem [23].

The basic operations in MM are called dilation and erosion. Let *f(n)* and *g(m)* be the input signal and the SE, respectively, defined in the domains, $D_f = \{x_o, x_1, \dots x_n\}$ and $D_g = \{y_0, y_1, \dots y_m\}$, respectively with $n > m$, where n and m are integers. The dilation of signal *f(n)* by SE *g (m)*, denoted by (f⊕g) is defined as (1).

$$y_D(n) = (f \oplus g)(n) = max\begin{cases} f(n-m) + g(m), \\ (n-m) \in D_f, m \in D_g \end{cases} \tag{1}$$

The erosion of signal *f(n)* by SE *g(m)*, denoted by (f⊖g) is defined as (2).

$$y_E(n) = (f \ominus g)(n) = min\begin{cases} f(n+m) - g(m), \\ (n+m) \in D_f, m \in D_g \end{cases} \tag{2}$$

Based on dilation and erosion operators, several other operators such as opening and closing can be defined [23].

Several MM applications in power systems have been reported recently. To date, MM has not been applied for the purpose of generator protection. Ref. [20] presents a discussion about MM applied as a filtering tool for power system signals. For power system applications, the morphological operators opening and closing, which are defined by (3) and (4), respectively, are often used [20] and applied in this work.

$$y_O(n) = (f \ominus g) \oplus g(n) \tag{3}$$

$$y_C(n) = (f \oplus g) \ominus g(n) \tag{4}$$

In order to filter the noise from signals, [20] recommends averaging the dilated and eroded waveforms and the opened and closed waveforms. We will call the latter open-close-median (OCM) filter. The process is described as:

$$y_{OCM}(n) = [(y_O)(n) + (y_C)(n)]/2 \tag{5}$$

Still, a sudden change in the shape of signal due to fault or other disturbance may be detected by a dilation-erosion difference filter (DEDF), or an opening-closing difference filter (OCDF) defined by Eqs. (6) and (7), respectively.

$$y_{DEDF}(n) = (f \oplus g)(n) - (f \ominus g)(n) \tag{6}$$

$$y_{OCDF}(n) = (y_O)(n) - (y_C)(n) \tag{7}$$

4. Analytical methodology

The proposed strategy aims to detect SG stator faults. It is built on the percentage differential relay [1,12] and uses MM operators [20].