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On-line stator ground-fault location method for synchronous generators based on 100% stator low-frequency injection protection

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ABSTRACT

Locating stator-winding ground faults accurately is a very difficult task, especially in high-impedance grounded generators. Through the conventional measurements of power plants, obtaining the precise location of these defects in on-line operating conditions is not possible, because the fault resistance is unknown. This paper presents a general algorithm for locating stator-winding ground faults in on-line operating conditions, based on the measurements provided by the 100% ground-fault low-frequency injection protection, and other available measurements. Some simplifications are applied to the general algorithm, and a simplified method is also presented for generators with especially low capacitance-to-ground, whose implementation in modern protective relays is more simple. The location through the general algorithm, and the simplified algorithms, has been validated by simulation and experimental tests, for several fault resistance values at different points of the stator winding. These algorithms assure an acceptable accuracy for a wide range of fault resistance values and locations, without the need of any additional equipment.

1. Introduction

Electrical protections are currently a primary concern not only for maintaining the reliability of the power system, but also for assuring the safe operation under faulty conditions. In power plants, protective systems are vital for guaranteeing the safety of the personnel and for minimizing the damage on the power components and equipment during any type of events.

One of the most common defects of power synchronous generators is the stator-winding ground fault [1]. The consequences of this type of faults entirely depend on the generator grounding scheme [2]. If the generator is grounded through a low impedance, the fault current may be very high [3]. In this type of grounding scheme the damage caused by a solid ground fault at the generator terminal could be very severe, since the stator winding is solidly short-circuited [4]. The defect in this case is easy to locate because the damage caused by the defect is visible.

On the other hand, medium and large sized synchronous generators are grounded through a high impedance, whose value is generally set in order to limit the neutral current. In case of solid ground-fault at the generator terminal, this current is typically limited to 5 A or 10 A [5]. This limits the damage in the stator winding, nevertheless it makes the fault location less visible, even if the rotor is extracted.

The most basic stator ground-fault protection scheme is based on the measurement of the neutral voltage (59N) [6] or the neutral current (51N). Since stator ground faults cause the appearance of a neutral circulating current (and therefore a neutral voltage), any ground fault may be detected by the measurement of any of these variables [7]. However, the setting of the trip threshold to zero is not recommended for this scheme, since the presence of any transient neutral current may cause an unwanted trip command. This kind of protection scheme is generally called "95% stator ground-fault protection", attributable to the portion of the stator winding that they protect.

For the protection of the remaining 5% of the stator winding, any of the "100% stator ground-fault protection" schemes are used [8,9]. One of the most extended schemes is based on the measurement of the third-harmonic component of the neutral voltage (27NTH) [10]. The magnitude of this component depends mainly on the value of the capacitance-to-ground of the generator stator winding and other components such as the generator breaker or the step-up transformer. However, the third-harmonic component also depends on the operating conditions of the generator [11,12]. According to this, the operation of 27NTH is normally blocked during the start-up process, as well as during low active or reactive power operating conditions [5], in order to avoid unwanted trip commands.

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As a consequence of this limitation, another extended solution is the low-frequency injection scheme (64S). It is based on the injection of a low-frequency voltage signal (typically 12.5 Hz, 15 Hz or 20 Hz) in the grounding impedance through a band-pass filter. This protection obtains the equivalent impedance by measuring the low-frequency current, which changes during ground faults. Although this scheme is expensive, it is becoming extensively used, since it is able to be kept enabled when the machine is off-line [5]. This protection scheme is becoming a very active research topic [13–15], mainly because there are no unwanted trips through this scheme. An additional feature of this protection is the accurate measurement of the equivalent resistance, from which the fault-resistance value can be obtained.

Nowadays, after the detection of a ground fault, the generating unit is removed from service. Once the insulation level is checked, and the existence of the ground fault is confirmed, the complete rotor has to be extracted just for location purposes. Then, the ground fault has to be located. This operation may become really difficult, especially in high-impedance grounded generators, in which the maximum neutral current is limited up to 10 A. This low fault current does not damage the stator core, and it makes impossible the visual location of the insulation failure. Then, the fault is located by using different methods. Some technicians inject high-value current through the faulty winding and the iron core in order to visually detect the fault. This high current could damage the iron lamination insulation. Other methods of fault location include non-damaging techniques, which consist of dividing the stator winding into two parts and checking the insulation level of each one. Thereafter, the part of the winding with low level of insulation is again divided into two parts, and both of them are checked again. In this way, through the division of the stator winding in several parts, the ground fault can be located. This process of the location and repair of the fault can take several days and it is quite expensive. If some information about the location of the fault was provided, the time of the repair would be reduced drastically. On the other hand, in some particular cases the ground fault is even more difficult to locate, due to the insulation failure being present only at rated voltage of the winding. Then, the fault location would have to be obtained by the use of high voltage tests.

Although the detection of the stator ground faults is extensively studied [16–20] and solved, the location of the defect along the field winding is currently being addressed in many contributions, not only for large synchronous generators [21,22], but also for other types of electrical machines, such as wind generators [23]. In this paper, an algorithm for on-line location of ground faults in generators with low-frequency 100% stator and 95% ground-fault protections is proposed. Firstly, the measurements of the neutral voltage and current (95% ground-fault protection) are evaluated as a fault locator (Simplified Method "A") in Section 2 which provides unacceptable results. Secondly, In Section 3, a high-accurate location method is proposed. It uses the equivalent resistance provided by the 100% ground fault low-frequency injection protection, the neutral current (or the voltage) and the system parameters, to obtain the fault resistance value, and thus the location of the fault. Finally, some simplifications are applied to the general algorithm in order to obtain Simplified Method "B", which is applicable to synchronous generators with especially low capacitance-to-ground. The implementation of this simplified method in protective relays would be easier. These methods have been evaluated by simulation and experimental tests, and the results are described in Sections 4 and 5, respectively. By the use of the novel on-line location method presented in this paper, modern protective systems may be able to provide both the value of the fault resistance and the location of the ground fault during the trip, which will make possible detecting isolation failures that only appears with the generator at rated voltage and will drastically reduce the repair time after the rotor extraction.

2. Theoretical approach of ground-fault location in stator windings

In synchronous generators grounded through a high-value impedance, the stator ground-faults are generally detected by using a neutral overvoltage protection (59N), or neutral overcurrent protection (51N). In some cases, this protection is installed together with a 100% ground-fault protection scheme, which covers 5–10% of the stator winding that is closer to the neutral point. In Fig. 1, the simplified scheme of a power plant is shown, where the general scheme of 59N is represented. In this figure, a ground-fault is represented in phase A, where R_f is the fault resistance, I_f is the fault current, U_n is the generator phase voltage, and x represents the exact location of the ground fault, from 0 pu or 0% (Neutral, N) to 1 pu or 100% (Terminal, A). This ground fault causes the appearance of a neutral voltage (V_N), and a circulating neutral current (I_N), measured by the previously described protections. In large size generators, several capacitances-to-ground have to be taken into account, such as the equivalent capacitance-to-ground of the stator winding (C_g), and C_z, which includes the capacitance-to-ground of the generator breaker, the generator step-up (GSU) transformer, the auxiliary transformer and the bus bars, among others.

In power plants, the measurements of this scheme (Fig. 1) which can be obtained are I_N, V_N, U_n, and the terminal voltage (V_A). R_N is the grounding resistance, which is represented in the primary winding of the grounding transformer, although the installation of this resistance in the secondary winding is also common. The value of R_N is typically obtained as the resistance necessary to limit the neutral current to 10 A (5 A is also used), in case of a solid ground-fault at the generator terminal. According to this, a ground fault is detected when the value of I_N is higher than the 51N setting threshold (whose value is generally set to 5% of 10 A), or when the value of V_N is higher than the 59N setting threshold (whose value is generally set to 5% of U_n). In both cases, the upper 95% of the stator winding is protected. Lower setting levels are not recommended because of the possibility of unwanted trip commands [1].

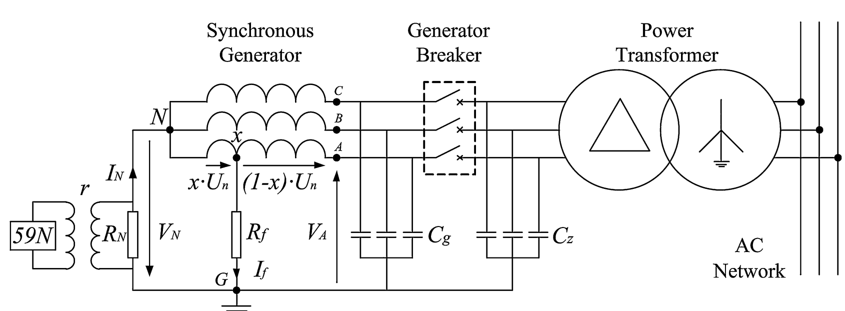

Fig. 1. Simplified scheme of a power plant with a synchronous generator grounded through a high-value resistance equipped with 95% ground-fault protection (59N).