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Turn-to-turn fault protection technique for synchronous machines without additional voltage transformers

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***Abstract*—This paper presents a novel protection technique for the detection of inter-turn faults in synchronous machines. It is based on the calculation of voltage in the stator windings from the usual phases and neutral voltage, typically available in all generator protection relays. The existing turn-to-turn protection mechanisms require additional voltage transformers. The main contribution of this technique is that it can be implemented without using any additional voltage transformers. This technique has been successfully tested in a special synchronous machine with taps in the stator windings, where turn-to-turn faults have been created.**

Keywords— Power Generation Protection, Synchronous Generator, Turn-to-turn Fault,

I. INTRODUCTION

Synchronous machines are extremely important devices in power systems. Following the earth fault, the turn-to-turn fault, also known as inter-turn fault, is one of the most common internal faults in electrical generators. The turn-to-turn fault is a short circuit between some turns of the same phase of a stator winding. The fault occurs due to eventual insulation degradation and ageing. The rotating magnetic field induces a circulating current in the shorted turns loop and produces excessive heat, causing important damage in the machines.

The detection of inter-turn faults is a very active research topic in synchronous machines [1]-[2], in power transformers [3], in permanent magnet synchronous motors [4]-[6] in brushless dc-motors [7] and of course in asynchronous machines [8]-[10]. This interest is due to the very fast evolution of this fault from an incipient stage to a catastrophic machine breakdown.

In synchronous machines, the stator earth fault protection does not detect turn-to-turn fault, as there is not current flowing to the ground [11].

Moreover, the stator differential protection does not detect turn-to-turn faults within the same phase-winding of the generator [12]. The reason is that the current produced by the inter-turn fault flows in the close circuit loop created by the shorted turns, thus it does not create any difference between the current in the neutral and phase side of the winding, as shown in Fig. 1.

In the case of machines with two or more circuits per phase, the differential split-phase relaying scheme may be used to detect a short circuit between turns [13]. In other types of machines, it is more challenging to detect them and the stator is often left unprotected against inter-turn faults. In such cases only the earth fault may be detected.

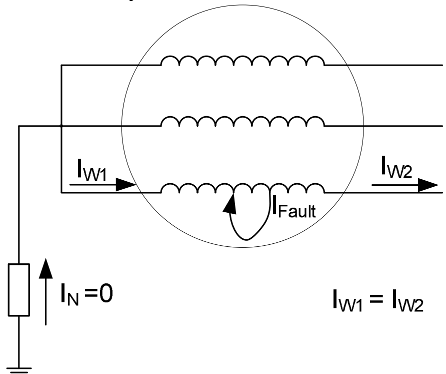

Fig 1. Current distribution in a inter-turn fault in a synchronous machine.

II. REVIEW OF EXISTING TURN-TO-TURN FAULT PROTECTION METHODS

Mainly, there are two methods to detect the turn-to-turn faults in synchronous machines. The first one is based on the comparison of the current in the different branches of the winding, while the other is based on the comparison of the winding voltage in the three phases, as it will be explained later in this section.

A. Generator differential turn-to-turn protection (Split phase)

This technique is possible for generator cases with multi-turn coils and two or more windings per phase. It is based on the current comparison of the different stator windings of the same phase, as illustrated in Fig 2.

In the case of normal operation, the currents in the different branches of the same phase should be identical. On the other hand, if a turn-to-turn fault happens then the protection will defect a differential current between the windings and it will trip the generator [13].

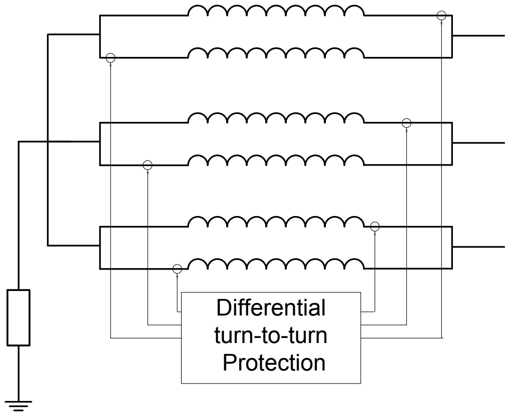

Fig 2. Generator differential turn-to-turn protection (Split phase).

B. Residual windings voltage

This technique could be used for any type of generators with single or split phase. The inter-turn protection is provided by measuring the residual voltage of the 3 phase windings.

In the case of a healthy machine, the induced voltages in the three phases are identical. However, in the case of a turn-to-turn fault in one phase, the voltage in this phase will present lower amplitude as the number of effective turns will be reduced.

The main operation principle of the turn-to-turn protection is the comparison between the voltages across the windings. For this purpose, it is normal practice to install three additional voltage transformers (VT) connected between the neutral and the phases [14]-[15], as shown in the Fig. 3.

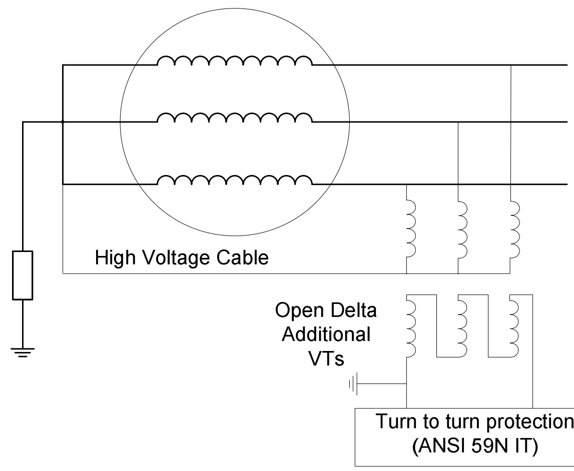

Fig 3. Turn-to-turn protection (ANSI 59N IT) with three additional Voltage Transformers.

The primary windings of the voltage transformer measure the generator windings voltages. The secondary windings are connected in open delta, so the addition of the three windings voltages is obtained. In normal operating conditions the 1st harmonic of the resultant voltage should be null. Similarly, the resulting sum of higher harmonics located at odd multiples (excluding the triplets) of the supply frequency should be also zero. On the other hand, the 3rd harmonic and higher triplet harmonics should be removed by the protection relay.

It is also important to point out that, the connections to the neutral point and the voltage transformer should be performed with a high voltage cable because in case of ground fault, the voltage in the generator neutral should be equal to the winding voltage.

Another possible configuration to avoid the installations of the high voltage cable and the three additional VT´s is shown in Fig 4. In this configuration it is required to install additional secondary windings in the phase to ground VT´s, and an additional secondary winding in the neutral.

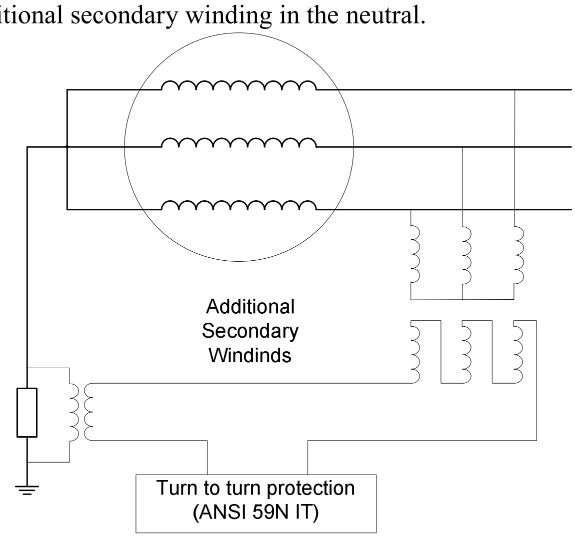

Fig 4. Turn-to-turn protection (ANSI 59N IT) with four additional secondary windings.

The neutral displacement voltage should be used to make the voltage seen by the relay zero in case of ground fault. According to [14] this configuration has limited sensibility. The ratio of the neutral transformer and the phase to ground transformer should be coordinated to get the addition of the three windings voltages. It is important to avoid the saturation of the voltage transformers.

III. The Proposed Turn-to-turn Fault Protection Method

The main idea presented in this paper relies on a new technique for detecting the inter-turn faults, while using the usual voltage transformers installed for a multifunction protection relays, that is three voltage transformers connected between each phase and ground and the one voltage transformer between the neutral and ground. So, no additional voltage transformers are required.

This algorithm requires to measure the neutral (V_{NG}) and the phase (V_{AG}, V_{BG} and V_{CG}) to ground voltages. This configuration, represented in Fig 5, the required voltages are widely available at any multifunction generator protection relay.

The proposed method is described in detail below.

A. Synchronous machine voltage generation

Firstly the generator phase to neutral voltages (V_{AN}, V_{BN} and V_{CN}), corresponding to the winding voltages, should be calculated. This is achieved by the subtraction of the neutral to ground voltage (V_{NG}) from phase to ground voltages (V_{AG}, V_{BG} and V_{CG}). That is according to the expressions (1), (2) and (3) below:

$$V_{AN} = V_{AG} - V_{NG} \quad (1)$$

$$V_{BN} = V_{BG} - V_{NG} \quad (2)$$

$$V_{CN} = V_{CG} - V_{NG} \quad (3)$$

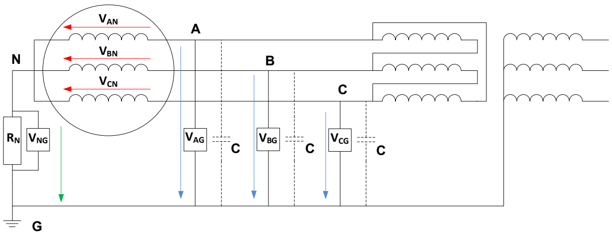

Fig 5. Terminals, windings and neutral voltages of a synchronous generator.

B. Fundamental voltage under normal conditions

In normal conditions, the voltage generated by the machine at the fundamental frequency (50 or 60 Hz) is always balanced, that is, the sum of V_{AN}, V_{BN} and V_{CN} is theoretically zero ($3V_{0N} = 0$ in equation 4)

$$V_{AN} + V_{BN} + V_{CN} = 3 \cdot V_{0N} \quad (4)$$

The zero sequence voltage of the windings voltages ($3V_{0N}$) may have third order harmonic voltage, so for the purpose of this protection, only the fundamental component will be taken into account. Fig 6 shows the proposed method's strategy algorithm.

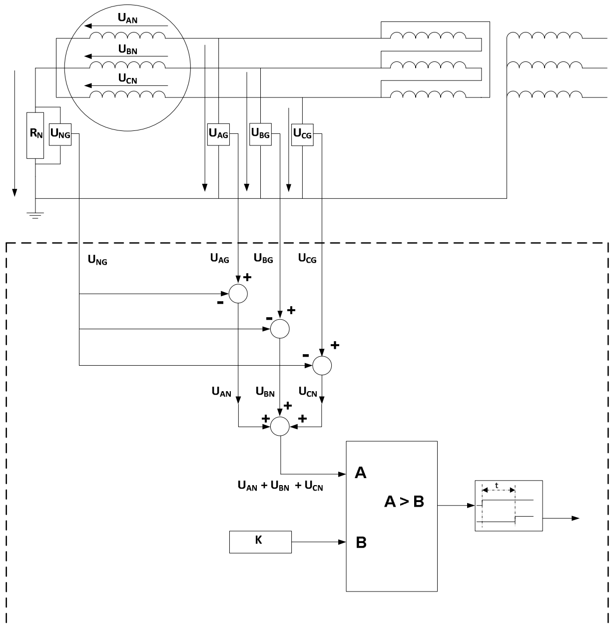

Fig.6. Proposed turn-to-turn protection strategy scheme.

C. Fault detection criteria

In case of a turn-to-turn fault in one phase, the voltage along this winding decreases. Therefore the voltage $3V_{0N}$ will be non-zero (ideally). However in practice, it will have a small value due to inherent asymmetries. So, if the voltage $3V_{0N}$ is greater than a certain threshold value (k), it can be concluded that there is a turn-to-turn fault. This setting may be a safe percentage of the nominal voltage (i.e., 2%). This represents the same sensibility as other commercial protection relays [14]. The time delay for generator tripping should be adjustable in the real protection.

IV. EXPERIMENTAL SETUP

The tests were performed on a salient pole 5kVA, 400V synchronous machine (Fig. 7). Detailed data on the machine and its windings are in Table I.

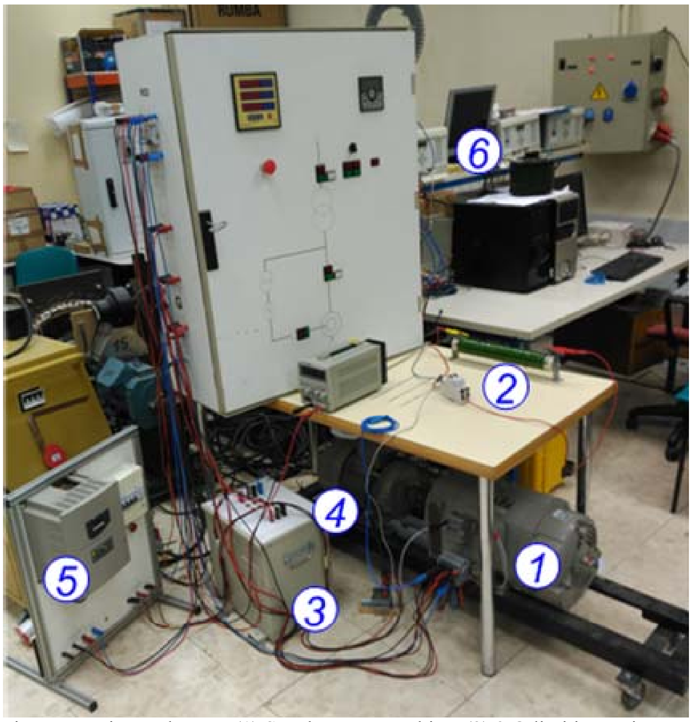

Fig.7. Experimental setup. (1) Synchronous machine, (2) 3 Ω limiting resistor, (3) Main transformer, (4) Asynchronous motor, (5) Frequency converter and (6) Protection relay.

TABLE I
SYNCHRONOUS MACHINE DATA USED IN THE EXPERIMENT

Rated apparent power	5 kVA
Rated voltage (± 5%)	400 V
Frequency	50 Hz
Pole pairs	2
Rated speed	1500 rpm
Rated Power Factor	0.8
Number of slots	36
Turns per pole and phase	63
Parallel branches	1

The phase C of the stator winding of this synchronous machine has been specially manufactured to allow for the testing of inter-turn faults at different winding locations (thus altering the fault level severity), as shown in Fig. 8. The other two phases, A and B, are manufactured as in a standard machine. Six different taps are available in phase C: four taps along the stator winding phase and the two endpoints of the winding. Taps correspond to 2%, 4%, 6% and 8% of the windings turns. So, it is possible to perform inter-turn faults of 2%, 4%, 6% and 8% fault level severity.

The generator is driven by an asynchronous machine fed by a frequency converter. The main generator transformer is a 5 kVA 400/400 V and the vector group is YNd11. The generator side is delta connection, no connected to ground, and while the net side is start connection with the neutral rigid connected to ground, as in the large generation units.

The testing of the generator under the turn-to-turn faults has been performed with an additional 3Ω resistor in series with the shorted turns, to limit the short current in the fault loop up to 8 A. In this way the machine is not damaged due to excessive local overheating.

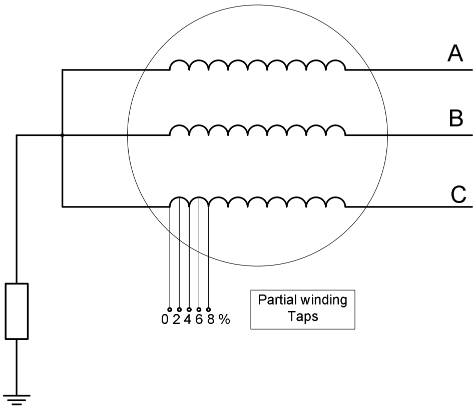

Fig 8. Internal connections of the synchronous machines of the experimental setup.

V. EXPERIMENTAL RESULTS AND ANALYSIS

Using the experimental machine described in the previous section, various tests were performed with 2, 4, 6 and 8 % turn-to-turn fault severity levels.

All inter-turn fault tests have been executed with the 3Ω limiting in series with the faulty turns resistor, in order to keep the machine windings unharmed at no load condition and when the generator is connected to the grid.

A. Turn-to-turn fault at no-load operation

Firstly, the synchronous machine has been tested at no-load. The short-circuits were performed at time 2s. The result from the application of the proposed method for a 4% turn-to-turn fault is presented in the following Fig. 9.

The voltages of the two generator phase windings are of similar amplitude. However, the voltage of the faulty phase C decreases, as expected.

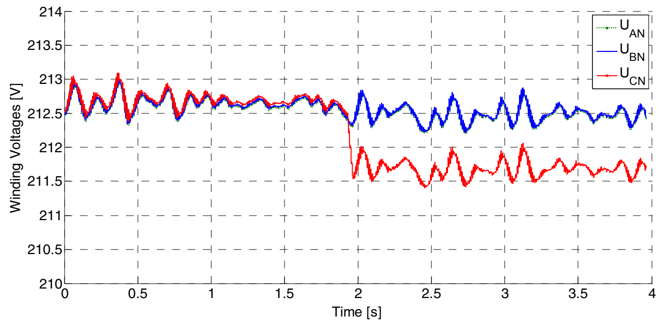

Fig. 9. Winding voltages in a 4 % turn-to-turn fault at no load conditions.

The full results summarizing all tested cases are displayed in Table II.

TABLE II
ZERO SEQUENCE WINDING VOLTAGE IN CASE OF TURN-TO-TURN FAULT AT NO LOAD CONDITION WITH 3Ω LIMITING RESITOR

Turn-to-Turn Fault	***$3V_{0N}$ [V]***	***$3V_{0N}$ [%]***
2 %	0.11	0.05
4 %	0.82	0.38
6 %	2.45	1.14
8 %	4.69	2.34

B. Turn-to-turn fault under load operation

Similar tests were performed after the synchronization of the machine to the grid. The results are different as the grid determine the voltage level. In this case, the turn-to-turn fault corresponding to 2 % could not be detected.

The total results of the tests under load are summarized in Table III and the record of the case where the fault severity level has been 6% is shown in Fig. 10.

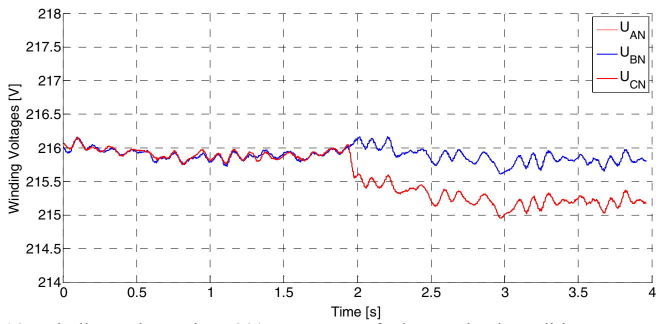

Fig.10. Winding voltages in a 6 % turn-to-turn fault at no load conditions.

TABLE III
ZERO SEQUENCE WINDING VOLTAGE IN CASE OF TURN-TO-TURN FAULT. SYNCHRONOUS MACHINE CONNECTED TO THE GRID WITH 3Ω LIMITING RESITOR.

Turn-to-Turn Fault	***$3V_{0N}$ [V]***	***$3V_{0N}$ [%]***
2 %	≈ 0	≈ 0
4 %	0.25	0.11
6 %	0.55	0.25
8 %	1.46	0.67

The obtaining results, even with the limiting resistor, verify this technique for inter-turn detection. If the tests were performed without limiting resistor the results would be better.

VI. CONCLUSIONS

The main contribution of the paper is the introduction of a new technique for turn-to-turn protection of synchronous generators, which does not require the additional transformers as in the existing protection schemes.

The basis of the detection of the turn-to-turn fault is the addition of the three stator winding voltages. Each winding voltage is calculated from the measured phase to ground and neutral to ground voltages. The monitoring of the required voltages is available in any commercial generator protection scheme nowadays. This implies a remarkable simplification of the protection system and a consequent cost reduction.

Measurements performed in a laboratory environment with a 5kVA synchronous generator have proven the reliability and success of the proposed inter-turn fault diagnostic method, even under the influence of a non-zero, in series with the faulted turns, resistance.

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