FUZZY BASED ROTOR GROUND FAULT LOCATION METHOD FOR SYNCHRONOUS MACHINES

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ABSTRACT
This paper presents a fuzzy rule based on-line rotor ground fault location method for synchronous machines with static excitation systems, which, combined with rotor ground fault protection, can detect and locate faults in the rotor. Synchronous machine field winding is fed by rectifiers through an excitation transformer. The main contribution of this technique to locate the position of the ground fault in the rotor winding online, reduce the repair time. The system is based on the analysis of the ac and dc components of the excitation voltage and the voltage measured in a grounding resistance located in the neutral terminal of the excitation transformer. This technique has been validated through computer simulations.

KEYWORDS: *AC generator excitation, fault location, power generation protection, synchronous generator excitation.*

I. INTRODUCTION

The use of protection devices in power systems is absolutely necessary in order to safeguard them against short circuits, overloads and, in general, abnormal operations, or faults. The protection system in generating units is especially important since it must reliably guarantee the power supply as per IEEE Standard C37.102 [1].

Some of the most common malfunctions in synchronous generators, such as vibrations and unbalanced stator voltages, are caused by ground faults in the rotor.

Generally, the initial ground fault does not cause any damage to the machine, because this circuit is usually ungrounded. However, the probability of a second fault increases after the first one since it establishes a reference for voltages induced in the field, thereby increasing the stress to ground at other points on the field winding. If this second fault occurs, the field winding will be partially short circuited, producing unbalanced fluxes in the machine, with the consequent vibrations and unbalance in the stator voltage.

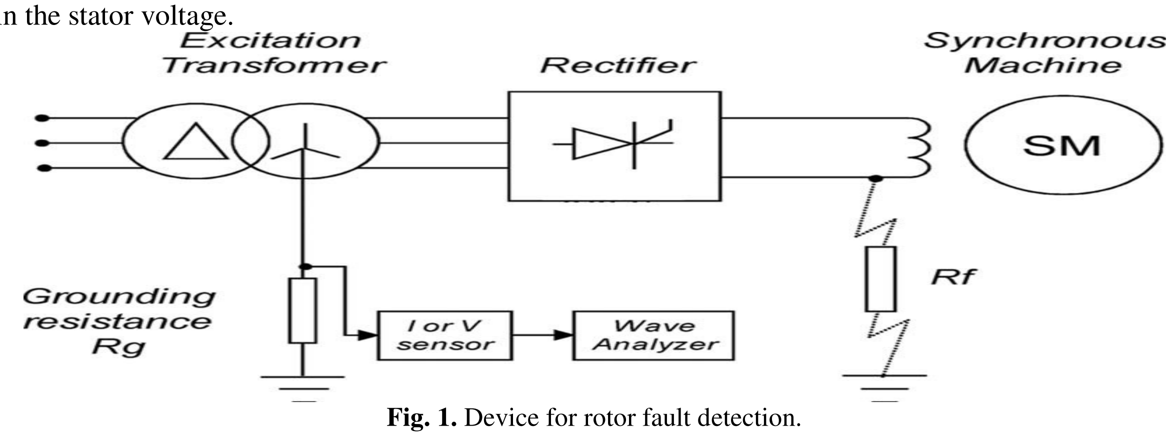

Fig. 1. Device for rotor fault detection.

Most rotor ground fault detection devices for synchronous generators are based on detecting abnormal values in certain electrical variables, such as the stator no-load voltage [2], or the air gap flux [3], so they can only detect double faults.

To achieve the early detection of the initial failure of the rotor to ground before severe damage occurs in the generator, authors presented in [4] a detection technique for synchronous generators with static excitation systems, where the excitation field windings are fed by an excitation transformer through a rectifier. Fig. 1 shows a scheme of the proposed technique

This technique exhibited two important advantages when compared to current fault detection systems.

1) It could discriminate between a ground fault on the ac or the dc side of the excitation circuit.

2) It did not need any additional injection source to detect the fault, because the proposed detection technique is supplied by the power network itself.

This technique required a Wye secondary in the excitation transformer for the rectifier power supply. In this situation, the proposed technique requires a high-value grounding resistance. Otherwise, if the system is fed by a transformer with delta secondary winding, an artificial neutral will be required (i.e., an earthing transformer or zig-zag impedance).

In any case, once detected, locating the fault can be a long and laborious process, especially with multipole synchronous generators. When the fault is on the rotor winding, the connections between poles must be opened in order to locate the ground fault. Except for some cases [6], in order to determine whether the fault is on the rotor winding or in the external buses and dc source, the machine has to be removed from service.

This paper presents a fuzzy rule based rotor ground fault location method for synchronous machines applicable to the fault detection system presented in [4].The fuzzy rule is based on the value minimum and maximum variation of V_{dc},V_{ac},R_f,V_{fdc},V_{fac} due to the effect of fault at different position of winding. The variation of values is studied from the paper [5]. This new system eliminates the current need to disconnect all poles to locate the fault. Moreover, having available information about the position of the ground fault in the excitation winding could save time in the generator repair process. This fact is of particular interest in the case of hydro generators because of the feasibility of removing one pole without requiring a complete rotor extraction.

We aim to make a contribution to the field of fault location in synchronous machines, where there are already developments in ground fault location for the stator winding [7], in fault location between the core laminations [8] and even in insulation fault location is using partial discharges [9].

The subject of rotor fault location in electrical machines has been extensively studied in the case of induction machines, where there are very significant contributions in the detection of broken bars, running the machine in transient state [10],[11] and even in magnetic saturation conditions [12], and its combination with the effects of eccentricity[13]. However, with a few exceptions [6], there are not many contributions to rotor fault location methods for synchronous machines. This is the field that will be covered in this paper.

This section II presents the principles of the proposed method. Then, Section III analysis the results of the simulations obtained by applying the proposed method. Finally, section IV concludes with the main contributions of the proposed technique.

II. PRINCIPLES OF THE ROTOR GROUND FAULT LOCATION METHOD

This procedure for rotor ground fault location was developed with the analysis of numerous laboratory tests, which followed the development of a previous rotor ground fault protection technique presented by the authors in [4]. The rotor ground fault protection technique was based on the analysis of the ac component of the voltage at the grounding resistance. But also a dc component appears in the grounding resistance in case of earth fault in the field winding. The procedure proposed in this paper will use both ac and dc components to locate the rotor ground fault.

The neutral of the excitation transformer is grounded, so the dc voltage supplied by the rectifier has a ground reference. In case of normal operation, the voltage between the midpoint of the field winding and ground is zero. Moreover, the voltage between the positive brush and ground is half the voltage supplied by the rectifier (Vfdc/2), in a similar way the voltage at the negative brush has the same amplitude but negative polarity ($-Vf$dc/2). The distribution of the voltage to ground is linear along the field winding. For a general position in the field winding X (%), the voltage between this point and ground can be obtained as presented in (1) as VT . This voltage relationship is illustrated in Fig. 2

$$V_T = V_{fdc}(X - 50/100) - \quad (1)$$

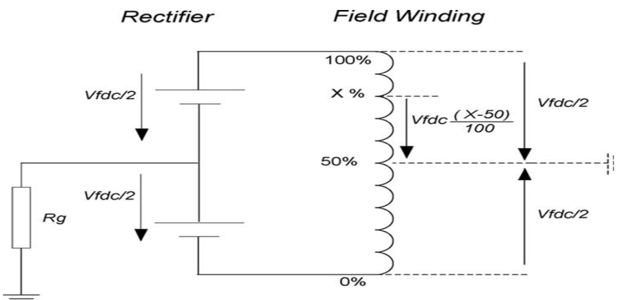

Fig. 2. Excitation dc equivalent circuit.

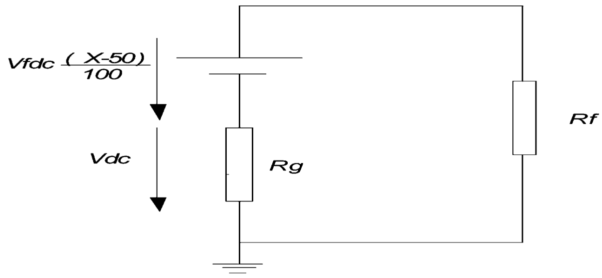

Fig. 3. Equivalent circuit for rotor ground fault dc current calculation for any rotor position X (%).

The dc current that flows from the field winding to earth, in case of earth fault, is calculated using Thevenin's theorem. Then, the equivalent circuit between any point of the field winding and earth consists of a voltage source and a resistance. The voltage source corresponds to the voltage in open circuit, according to (1). On the other hand, the resistance of this equivalent circuit be approximated by the grounding can resistance Rg, as this resistance is much higher (around 5 kΩ, to limit the ground fault current) than the resistances of the field winding, the transformer or the rectifier. Finally, the dc equivalent circuit for any rotor position X and the fault resistance is presented in Fig. 3. Hence, the dc current depends on the position of the rotor earth fault and the fault resistance.

The principle behind this method is the relationship between the dc voltage component in the grounding resistance V dc and the position of the fault along the field winding. It is important to realize that the voltage measurements available with the machine online are the ac and dc components of the field winding voltage and the voltage in the grounding resistance in the event of a fault.

A. Relationship between V dc and Fault Position

The dc component of the voltage in the grounding resistance is related to the rotor fault position. The amplitude of V dc is maximum, with positive polarity, when the fault occurs in the negative terminal, which will be considered as the start of the winding (0%). If, on the other hand, the fault occurs in the positive terminal, which is at the end of the winding (100%), V dc has the same amplitude, but the polarity is negative. In contrast, V dc is negligible for faults at the midpoint of the winding (50%).

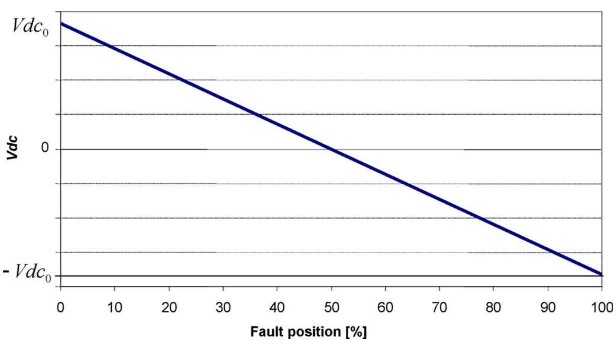

Fig. 4. V dc-Fault position relationship.

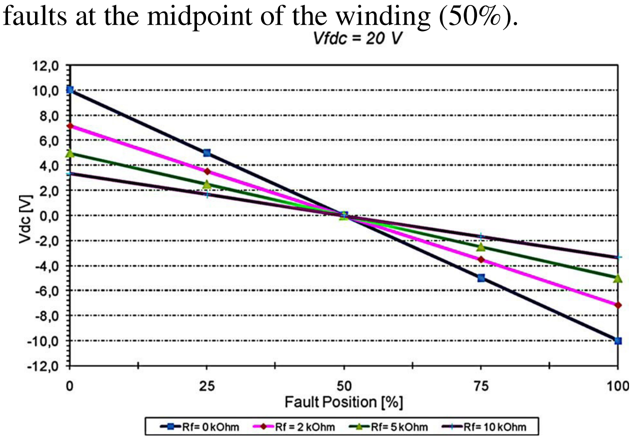

Fig. 5. V dc-Fault position relationship for different Rf.

The value of V dc for different fault positions and a particular fault resistance Rf is shown in Fig. 4. The maximum value is referred to as V dc0.

The maximum value of the dc component V dc0 depends on the value of the fault resistance Rf and the value of the dc component of the excitation field voltage Vfdc.

B. Estimate of the Fault Resistance Rf.

In order to estimate the fault resistance Rf, the ac components should be used. In a similar way, the ac current that flows from the field winding to earth depends on the ac component of the excitation

voltage *Vf*ac and the fault resistance *Rf*. The equivalent ac circuit is composed by a voltage source and impedance.
The voltage source corresponds to the ac component of the excitation voltage *Vf*ac, and the impedance corresponds to the ground resistance *Rf*. In this case, the ground fault position does not affect the value of the current.

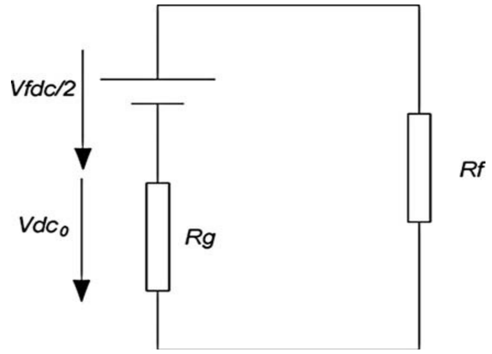

Fig. 6. Equivalent dc circuit for *V* dc0 calculation.

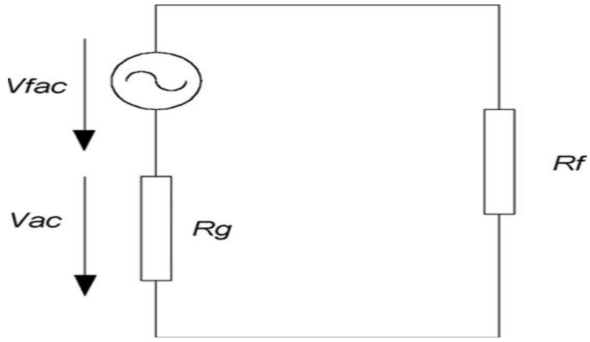

Fig. 7. Equivalent ac circuit for *Rf* calculation.

After analyzing numerous tests, it was determined that the fault resistance *Rg* could be reasonably estimated using this ac equivalent circuit, as shown in Fig. 7.
The dc and ac equivalent circuits, as shown in Figs. 6 and 7, are checked using all test measurements, where the fault resistance *Rf* and the rotor fault position *X* are known in advance.
Therefore, the fault resistance *Rf* can be estimated according to the following expression:

$$R_f = R_g\left(\left(V_{fac} / V_{ac}\right)-1\right)$$

C. Fuzzy Rule.

The fuzzy rule is based on the value minimum and maximum variation of V_{dc},V_{ac},R_f,V_{fdc},V_{fac} due to the effect of fault at different position of winding.
If (fdc is PS) and (dc is PS) and (rf is NVB) the (output1 is 60) (1)
If (fdc is PS) and (dc is PS) and (rf is NB) then (output1 is 80) (1)
If (fdc is PS) and (dc is PS) and (rf is NS) then (output1 is 100) (1)
If (fdc is PS) and (dc is PS) and (rf is mf4) then (output1 is 0) (1)
If (fdc is PS) and (dc is PS) and (rf is PS) then (output1 is 20) (1)
If (fdc is PS) and (dc is PS) and (rf is PB) then (output1 is 40) (1)
If (fdc is PS) and (dc is PS) and (rf is PVB) then (output1 is 50) (1)
If (fdc is NB) and (dc is NB) and (rf is mf4) then (output1 is 0) (1)
If (fdc is NS) and (dc is NS) and (rf is mf4) then (output1 is 0) (1)
If (fdc is NS) and (dc is NS) and (rf is PS) then (output1 is 20) (1)
If (fdc is Z) and (dc is Z) and (rf is PVB) then (output1 is 50) (1)
If (fdc is PS) and (dc is PS) and (rf is PB) then (output1 is 60) (1)
If (fdc is PB) and (dc is PB) and (rf is PB) then (output1 is 80) (1)
If (fdc is PB) and (dc is PB) and (rf is NS) then (output1 is 100) (1)
If (fdc is z) and (dc is NB) and (rf is mf4) then (output1 is 0) (1)
If (fdc is z) and (dc is NS) and (rf is PS) then (output1 is 20) (1)
If (fdc is z) and (dc is Z) and (rf is PB) then (output1 is4 0) (1)
If (fdc is z) and (dc is PS) and (rf is NVB) then (output1 is6 0) (1)
If (fdc is z) and (dc is PB) and (rf is NB) then (output1 is 80) (1)
If (fdc is z) and (dc is NB) and (rf is PVB) then (output1 is 50) (1)
If (fdc is z) and (dc is NS) and (rf is NS) then (output1 is 100) (1)
If (fdc is PS) and (dc is NB) and (rf is mf4) then (output1 is 0) (1)
If (fdc is PS) and (dc is NS) and (rf is PS) then (output1 is 20) (1)
If (fdc is PS) and (dc is Z) and (rf is PB) then (output1 is 4 0) (1)
If (fdc is PS) and (dc is PS) and (rf is NVB) then (output1 is6 0) (1)
If (fdc is PS) and (dc is PB) and (rf is NB) then (output1 is 80) (1)

If (fdc is PS) and (dc is NB) and (rf is PVB) then (output1 is 50) (1)
If (fdc is PS) and (dc is z) and (rf is NS) then (output1 is 100) (1)
If (fdc is PB) and (dc is NB) and (rf is mf4) then (output1 is 0) (1)
If (fdc is PB) and (dc is NS) and (rf is PS) then (output1 is 20) (1)
If (fdc is PB) and (dc is Z) and (rf is PB) then (output1 is 4 0) (1)
If (fdc is PB) and (dc is PB) and (rf is NVB) then (output1 is6 0) (1)
If (fdc is PB) and (dc is PS) and (rf is NB) then (output1 is 80) (1)
If (fdc is PB) and (dc is PS) and (rf is PVB) then (output1 is 50) (1)
If (fdc is PB) and (dc is PS) and (rf is NS) then (output1 is 100) (1)

D. Rotor ground fault location block diagram.

To summarize the complete rotor fault location procedure, we include the rotor location block diagram in Fig. 8. The algorithm steps for estimating the rotor fault position are as follows.

1) The measurement of the excitation voltage *Vf* and grounding resistance voltage *V* yields their ac and dc components *Vf*ac, *Vf*dc, *V* ac, and *V* dc, respectively.

2) The ground fault resistance *Rf* is estimated from the ac components which is already calculated.

3) Based on the values of Rf, Vfdc, Vdc specific fault position is calculated using Fuzzy logic controller.

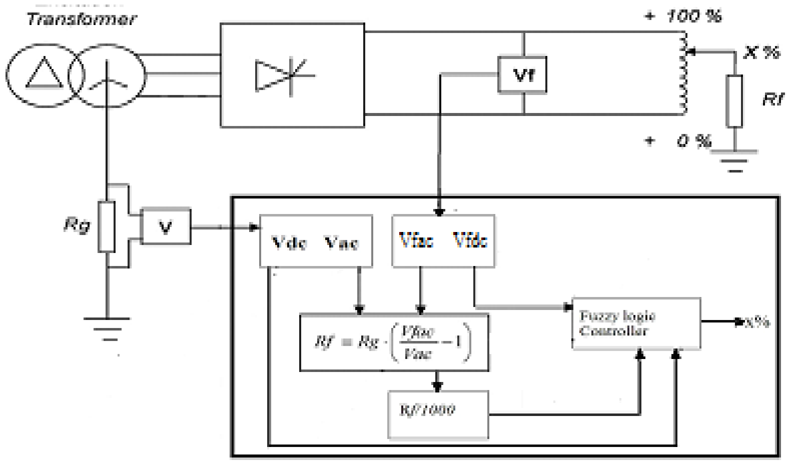

Fig. 8. Rotor fault location device layout.

The proposed rotor ground fault location method was simulated using the MATLAB/Simulink Power Systems software. The simplified schematics of the MATLAB simulation are shown in Fig. 9, representing a 5-kVA synchronous machine and its excitation system, similar to the machine used in the experimental tests. Detailed data on the simulated devices can be found in Tables I and II.

In the simulation, the excitation transformer is modelled as a three-phase voltage source; the rotor windings of the synchronous machine are modelled with ten sets of resistances, inductances, and capacitors; finally, the rectifier is modelled with a three-phase thyristor-controlled rectifier bridge. In the example, the excitation transformer neutral grounding resistance is a 5kΩ resistance.

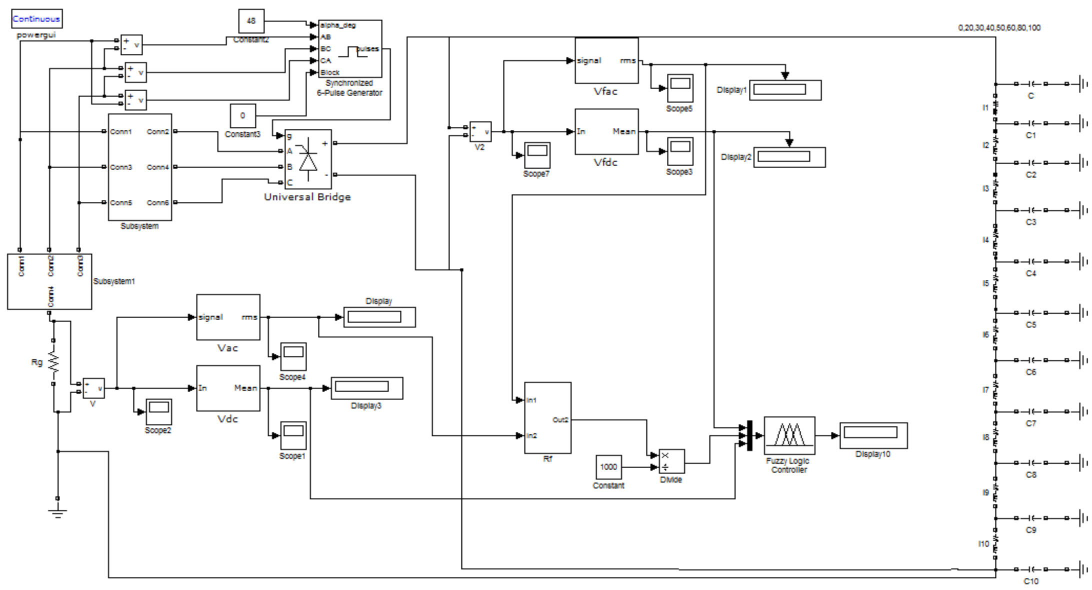

Fig. 9. Simplified schematics of the excitation system for rotor ground fault location simulation

TABLE I
CHARACTERISTICS OF SYNCHRONOUS GENERATOR USED IN THE EXPERIMENT

Rated apparent power	5 kVA
Rated voltage (± 5%)	400 V
Frequency	50 Hz
Pole pairs	2
Rated speed	1,500 rpm
Rated Power Factor	0.8
Measured rotor capacitance	157 nF
Rated Excitation Voltage	22.1 V
Rotor resistance	10.5 Ω
No load excitation Voltage	8.7 V

TABLE II
SYNCHRONOUS GENERATOR STATIC EXCITATION SYSTEM TECHNICAL DATA

Excitation transformer	
Winding connection	Dyn
Ratio	400/25 V
Rated power	200 VA
Grounding resistance	
Resistance	5 kΩ
Thyristor bridge	
Operation mode	Fully controlled
Maximum output voltage	33 V
Minimum firing angle	15 °

III. Simulation Result

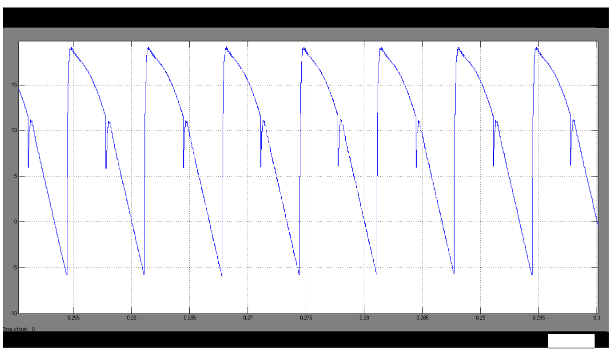

Fig. 10. Voltage waveform measured at the grounding resistance for a fault at 0% winding position with $Rf = 0$.

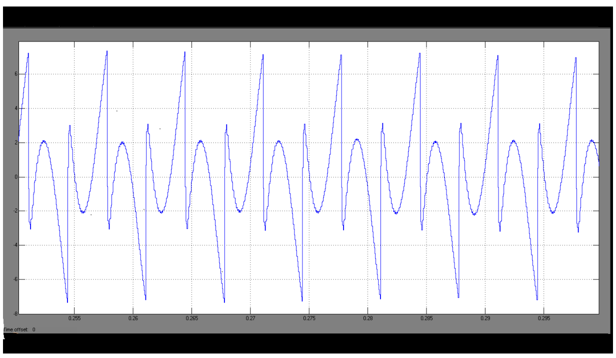

Fig. 11. Voltage waveform measured at the grounding resistance for a fault at 50% winding position with Rf =0.

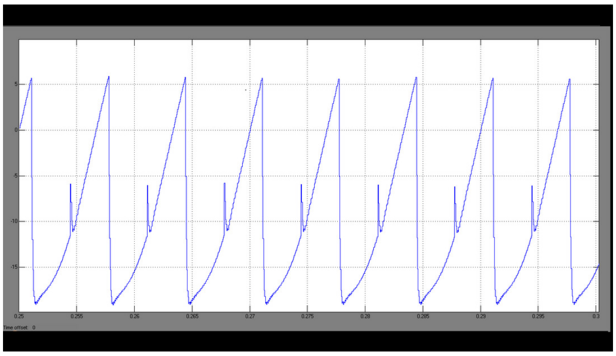

Fig. 12. Voltage waveform measured at the grounding resistance for a fault at 100% winding position with $Rf = 0$.

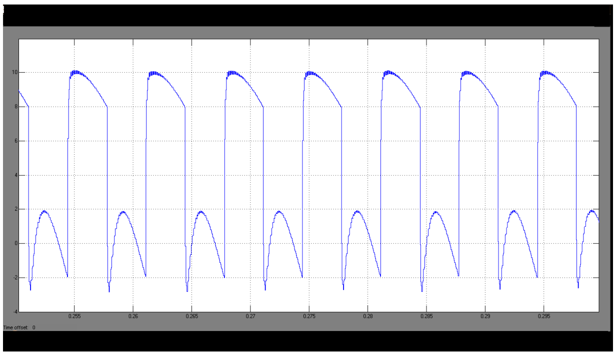

Fig. 13. Voltage waveform measured at the grounding resistance for a fault at 0% winding position with Rf = 5kΩ

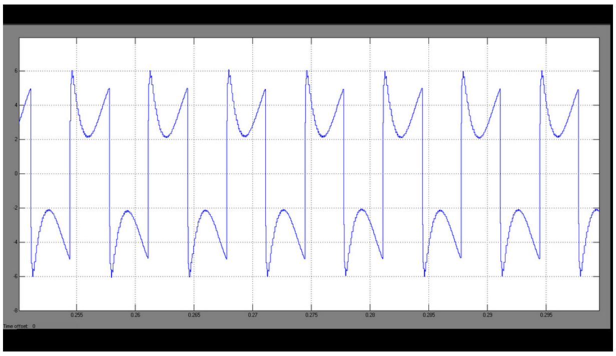

Fig. 14. Voltage waveform measured at the grounding resistance for a fault at 50% winding position with $Rf = 5$kΩ.

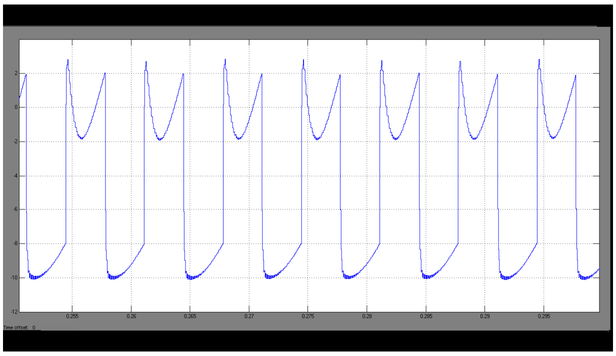

Fig. 15. Voltage waveform measured at the grounding resistance for a fault at 100% winding position with $Rf = 5$kΩ.

Figs. 10–12 show the voltage in the grounding resistance for a fault in the negative brush (0%), midpoint (50%), and positive brush (100%), respectively. A zero fault resistance and a field voltage of 20 V dc (corresponding to a firing angle of 48◦) are used for the simulations.
The simulations at the same conditions, but using a fault resistance of 5 kΩ, are included in Figs. 13–15. As expected, the values are lower than in the previous case without fault resistance.

IV. CONCLUSION

The method is able to locate the fault with the machine online. Moreover, it offers a significant improvement over the detection technique proposed by the authors in [4].
The fuzzy controller locates the position of fault in the rotor of synchronous machines faster due to the pre programmed laboratory value. In practical application it reduces the time needed for calculation. It directly determines the fault position in rotor winding.
The main advantage of this technique is that it contributes valuable information on the fault position before tripping the generator. It is possible to incorporate it easily into actual rotor ground protection systems.
Having information on the position of a ground fault in the excitation winding saves time in the generator repair process.

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