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Fault Diagnosis Based on ANN for Turn-to-Turn Short Circuit of Synchronous Generator Rotor Windings

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ABSTRACT

Rotor winding turn-to-turn short circuit is a common electrical fault in steam turbines. When turn-to-turn short circuit fault happens to rotor winding of the generator, the generator terminal parameters will change. According to these parameters, the conditions of the rotor winding can be reflected. However, it is hard to express the relations between fault information and generator terminal parameters in accurate mathematical formula. The satisfactory results in fault diagnosis can be obtained by the application of neural network. In general, the information about the severity level of the generator faults can be acquired directly when the faulty samples are found in the training samples of neural network. However, the faulty samples are difficult to acquire in practice. In this paper, the relations among active power, reactive power and excitation current are discovered by analyzing the generator mmf with terminal voltage constant. Depending on these relations, a novel diagnosis method of generator rotor winding turn-to-turn short circuit fault is proposed by using ANN method to obtain the fault samples directly, without destructive tests.

Keywords: *Generator, Rotor Winding, Turn-to-turn Short Circuit, ANN, Diagnosis*

1. Introduction

The statistical material form China Electric Power Research Institute indicated that the rotor winding turn-to-turn short circuit is a common electrical fault in a generator [1,2]. However, minor turn-to-turn short circuit will not affect the normal operation of generator unit, so it is often ignored. But if this fault develops, something serious will appear, such as remarkable increasing of rotor current, higher temperature of winding, deceasing of reactive power, distortion of voltage, vibration of generator unit and many other mechanical faults. Therefore, estimation of the early signs of failure severity and its develop trends can be made based on the identification of the fault's early signals, and this task has gradually become important in condition-based maintenance of generators [2,3].

At present, there have been many scholars studying in the monitoring of rotor winding turn-to-turn short circuit worldwide [2–5]. Albright proposed differential search-coil test method: Its diagnosing effect is good for a generator under on-load and three phase short circuit, but one-time location is difficult to make under load and it is not sensitive to minor turn-to-turn short circuit. Russian scholar B. T. Carsman proposed to detect turn-to-turn short circuit based on the circulating current in stator parallel branch, but this method depends on the structure of stator winding. Travelling-wave method based on online diagnosing technique for rotor winding turn-to-turn short circuit is immature. The alternating impedance method and loss method are often-adopted in experiment, but the method can not give an accurate conclusion in monitoring miner rotor winding turn-to-turn short circuit all the time. Further more, it is difficult to realize with the affection of the factors like slot wedge etc. [6–8].

This paper analyses the fault mechanism and mmf (magnetomotive force) for generator rotor winding turn-to-turn short circuit. It discovers that when the machine terminal voltage is in the condition of constant, there exist certain relations among active power, reactive power and field current. Thus it finds a kind of experiment on the electrical engineering which does not need to carry on a destructiveness experiment, but can obtain fault sample. And then it makes use of artificial neural network to carry out fault diagnosis for generator rotor winding turn-to-turn short circuit.

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2. Causes of Rotor Winding Turn-to-Turn Short Circuit

The causes of rotor winding turn-to-turn short circuit mainly include manufacture and operation. For example, the mounting of rotor end winding is not firm; spacer block becomes loose; the trimming of leading wire soldered joint is not good; there are remaining metal scales inside rotor protective ring; the dynamic forces such as centrifugal force cause displacement deformation of high-speed rotating rotor winding; the choking of rotor winding causes local overheating, which makes turn-to-turn insulation to burn down.

Otherwise, while the generator is operating or converting from the static state to the dynamic state, due to the abrasion of the turn-to-turn insulation or the relative dislocation caused by the relative motion between the turns in rotor, the turns may contact each other. When this fault has developed to a certain extent, the turn-to-turn shot circuit will happen. As a result of the emergence of this, the Effective magnetic field of generator will decrease, and the generator reactive power will be affected. Those lead to imbalance in the magnetic circuit which causes vibration, and then “monopole potential” and “monopole current” will be produced to magnetize the generator shaft seriously. In addition, partial over heating in fault point may be extended to grounding fault in rotor windings.

3. Mmf Based Analysis of Electromagnetic Characteristics of Generator Rotor Winding Turn-to-Turn Short Circuit

3.1 Analysis of Mmf under Rotor Winding Turn-to-Turn Short Circuit

Spatial distribution of mmf in rotor windings is shown in Figure 1 Just like Figure 1(b), while the generator units are operating normally, the spatial distribution of Mmf is trapezoidal-like, ignoring the minor intermittent of mmf which is caused by the grooves. The mmf will loss partially, while short-circuit happens in rotor windings. This kind of loss will result in partial loss of shorted magnetic pole, so that the average and amplify of shorted magnetic pole will decrease as shown in Figure 1(c). Therefore, the spatial distribution of mmf in the turn-to-turn short circuit can be considered as that in demagnetization. So the equivalent effect of short-circuit can be considered as a mmf with the opposite direction adding on the main mmf of short circuit.

The mmf of rotor winding under normal condition is represented by F_0, the mmf caused by short-circuited turns is represented by ΔF, after short circuit, the rotor mmf is $\vec{F}' = \vec{F}_0 - \Delta\vec{F}$, smaller than the former value.

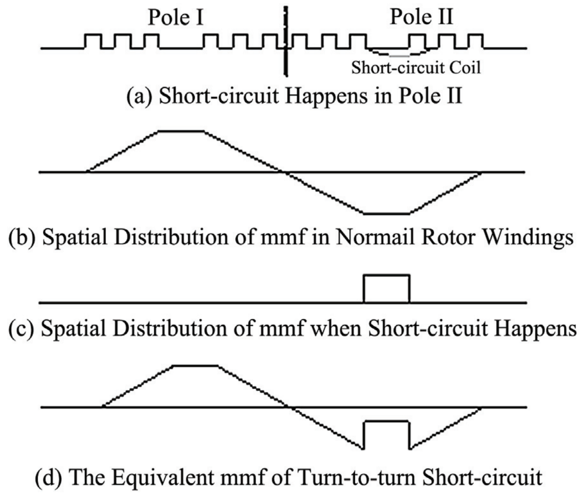

Figure 1. Spatial distribution of mmf in rotor windings

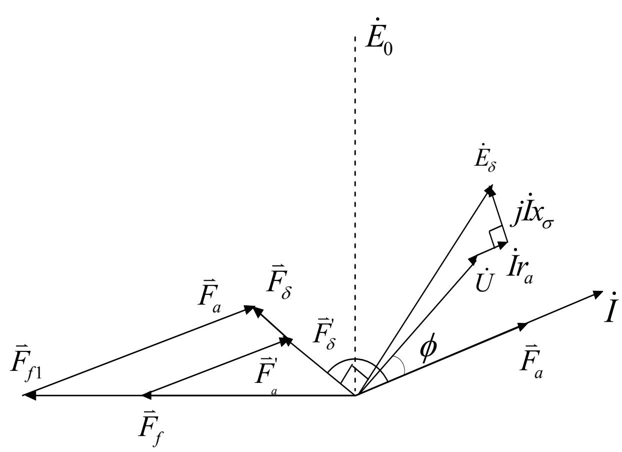

Figure 2. Magnetic-electronic potential vector of generators considering saturation

The mmf-emf vector diagram of non-salient poles generator considering saturation is shown in Figure 2.

The air-gap mmf fundamental component $\vec{F}_\delta$ is established by exciting mmf fundamental component $\vec{F}_{f1}$ and ar- mature reaction mmf fundamental component $\vec{F}_a$, i.e.

$$\vec{F}_\delta = \vec{F}_{f1} + \vec{F}_a \tag{1}$$

Reduced to the exciting mmf wave, it can be got:

$$\vec{F}'_\delta = \vec{F}_f + \vec{F}'_a \tag{2}$$

where, $F_f = w_f I_f$, w_f is the turn number of rotor winding; I_f is exciting current; the phase angle of

$$F_a = \frac{1.35 w_1 k_w I}{p}$$

in time-space vector diagram is the same as I, w_1 is the series number of stator winding phase, k_w is the coefficient of stator winding.

Suppose terminal voltage U, active output P and reactive output Q are invariants, then stator current I and power factor angle φ become invariable. And x_σ has little relation to the saturation level. $\dot{E}_\delta = \dot{U} + \dot{I}(r_a + jx_\sigma)$. Then the angle between $\dot{E}_\delta$ and $\dot{I}$ is unchangeable. So that the angle between $\bar{F}_\delta^{'}$ and $\bar{F}_a^{'}$ will not change. Because of this, $\bar{F}_f$ is unchangeable. If the working condition of a generator before and after rotor winding fault remains unchanged, in order to satisfy the air-gap composite flux condition, I_f will increase, but $w_f I_f$ does not change, from this it can be see: the relation between U, P, Q, I_f not only manifest the state of the rotor winding, but also reflects the effective turn number of the rotor winding.

3.2 Impact of Exciting Current on Rotor Winding Turn-to-Turn Short Circuit Diagnosis

The relation between U, P, Q, I_f can manifest the state of the rotor winding. The exciting current i_{f0} of a generator under normal operation can be calculated by the mathematical Equation, and then compared with measured exciting current i_{fc}, the existence of rotor winding turn-to-turn short circuit can be determined, furthermore the calculation of relative deviation $\alpha\% = \frac{i_{fc} - i_{f0}}{i_{f0}} \times 100\%$ can be used to estimate the severity of the fault.

4. ANN Diagnosis Method for Generator Rotor Winding Turn-to-Turn Short Circuit

Recently it is mainly according to the measurement of the generator terminal parameters which namely generator active power P, reactive power Q, the generator terminal voltage U, current I, field voltage and other generator parameters, uses a formula calculation to acquire the field current I_{f0} which operates under normally flows, and then compare the measurement of actual electric current $I_f^{'}$ with I_{f0} to diagnose rotor Winding Turn-to-turn Short Circuit fault of generators.

This kind of method needs to consider the influence of magnetic field saturation, and it needs accurate mathematics model and the parameter of generator in the meantime. The parameter of generator will also have variety change along with the operating way and the variety change of operating conditions. The accuracy of online recognition is not very high, therefore there exists a certain error margin.

The artificial neural network (ANN) does not need accurate mathematics model and the detailed parameters of generator, and it has no interference to the operation of generator in the meantime. It only needs to measure the generator terminal parameters accurately, and depends on a great deal of training samples. Through sufficient network trains, diagnosis can be directly carried out of the faults operated under dissimilar ways. By having faulty sample, we can not only diagnose the faults, but also estimate the seriousness of short-circuit.

The terminal voltage U of generator is generally a rated voltage, which could be supposed to be constant. According to the analysis of the basis generator magnetic field, certain P, Q will correspond to certain F_f, namely certain of $w_f I_f$. So the relation of P, Q and I_f can reflect the turn-to-turn short circuit fault, with the generator parameter P, Q, I_f as the ANN importation, and circles of turn-to-turn short circuit have the percent of total number of full circles α % as the output.

The key of the fault diagnosis which carries on with ANN to is to obtain the train samples. The selection of normal samples can take in various samples in normally operation in the P-Q diagram of generator, but in the actual power station for guaranteeing the "ergodicity" of samples, we could detect the generator parameters with long hours at normal operation conditions.

In order to estimate the severity of generator faults and the number of short-circuit turns, the faulty samples of generators are needed. Relatively speaking, to acquire the samples of the generators under normal operation condition is still easy, but to obtain generator fault samples is usually very difficult. The general method is to do a destructive experiment in dynamic simulation laboratory, short connecting several turns of the rotor windings of generator factitiously. This kind of method can barely be carried out on the engineering.

This paper uses the method of balancing the mmf to obtain fault sample of the generator under turn-to-turn short circuit of rotor winding. Suppose turn-to-turn short circuit fault occurs to generator at the rated condition, before and after the short-circuit, P, Q, U are constant. By analysing the magnetic field we can know the magnetic field $w_f I_f$ will maintain constant, and suppose the short-circuit turns of the total rotor winding number is α %, after the fault, the field current is:

$$I_f = \frac{1}{1-\alpha\%} I_{fN} \tag{3}$$

where, I_{fN} —the rated value of the field current.

Changing the number of short-circuit turns, we will get a series of faulty samples. And also we can acquire faulty samples under different operation conditions.

5. Simulation

To verify the credibility of this method, we can adopt cultural heritage [9] generator parameters, see Table 1; and then take its normal operating samples. The rated operate conditions of the fault sample can be seen in Table 2. In Table 2, α % is the short-turns as percentage of the total rotor winding turns number. We can carry out network training, and then carry out fault diagnosis; the fault samples can be seen in Table 3. From Table 3, α%(actual) is the factitiousness number of short-turns as percentage of the total number of rotor winding turns in dynamic simulation laboratory. a%(emulation) is the number of short-turns simulated by computer as percentage of the total number of rotor winding turns.

The back propagation artificial neural network(BP) is used here, and the active function adopts S type function. The BP network adopts 3 layers. As it is shown in Figure 3, the first layer has three importation nodes, hide layer has four nodes, and exportation layer has one node. The generator parameters contain active power, reactive power, exciting current, and all these parameters are normalized values. Table 3 shows the results simulated by MATLAB. According to this, the actual results confirmed the BP network diagnoses.

In a word, this method has realized the direct acquisition of fault's seriousness and the solution of fault samples' acquisition which are difficult to get.

In particular process, the current I and the terminal voltage U of stator windings are measured by CT (Current Transformer) and PT(Potential Transformer), and the exciting current I_f is measured by current converter. Here, select the CT and PT used to measure system parameters as the measure equipment. The generator capacity and voltage level decide the selection of them. And the hall current converter produced by Swiss company LEM is used to measure I_f in rotor winding. The parameters I and U are used to calculate both the active power P and reactive power Q.

After training, this method is applied to all kinds of load. By measuring I and U of normal generator in all running states, we can obtain the corresponding P and Q by calculating. The training of ANN needs P, Q and I_f to obtain the relationship among the parameters(P, Q and I_f) in all the running states.

5. Conclusions

While ANN is applied to the fault diagnosis of generator, the most difficult part is the acquirement of the fault samples among training samples. This paper analyses generator turn-to-turn short circuit of rotor winding fault and according to the certain operation of generator, namely active power P, reactive power Q, terminal voltage U keep constant, and the field current I_f in reases, but the mmf $F_f = w_f I_f$ maintains constant.

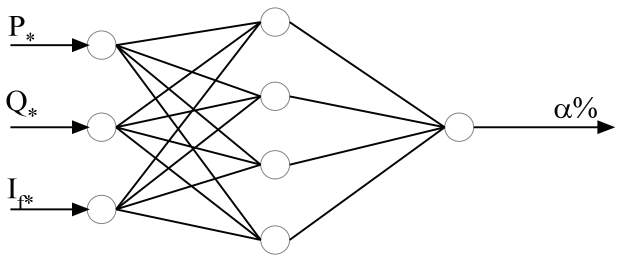

Figure 3. Schematic diagram of ANN

Table 1. Parameters of synchronous machine

Model number	MJF-30-6
Rated Voltage/V	400
Rated Current/A	43.3
Power Factor	0.8
Rotor Current/A	2
W_f **/turn**	100

Table 2. Diagnostic patterns in neural training

P(*) Active Power	Q(*) Reactive Power	I_f (*) Exciting Current	α % Short-turn Number as Percentage of Total Winding turns Number in Rotor
1	1	1.053	5
1	1	1.111	10
1	1	1.25	20
1	1	1.429	30

Table 3. The comparison between the output of the neural network and the actual output

P(*) Active Power	Q(*) Reactive Power	I_f (*) Exciting Current	α%(actual) Short-turn Number as Percentage of Total Winding Turns Number in Rotor	α%(emulation) Short-turn Number as Percentage of Total Winding Turns Number in Rotor
0.42555	0.51906	0.963	1.21	2.56
0.4295	0.5102	0.9771	3.91	4.86
0.4289	0.5054	0.99832	6.07	7.00
0.4325	0.5001	1.02026	10.06	9.48
0.4309	0.4899	1.06012	12.93	13.32
0.4168	0.4678	1.0765	14.83	15.50

Faulty samples are obtained through direct calculation, turn-to-turn short circuit fault of rotor winding is diagnosed by making use of artificial neural network, and we could obtain seriousness level of fault information directly. That method can avoid damage experimenting and it is convenient in engineering.

The shortcoming of this method is that it could not locate the faulty position. After diagnosing and confirming the existence of the fault, if we assist it with other ways such as traveling wave method, location of fault can be carried out.

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