Detection of Broken Damper Bars of a Turbo Generator by the Field Winding

J. Bacher[1]

[1] Institute of Electrical Machines and Drive Technology
E.M.A, University of Technology Graz
Kopernikusgasse, 8010 Graz (Austria)
phone:+43 316 8738601, fax: +43 316 8737244, e-mail: Bacher@ema.tugraz.at

Abstract. This paper completes the existing Diagnosis Systems of synchronous machines. In order to avoid break downs caused by broken damper bars, a method to diagnose such failures is presented. The main idea of this method is the separation of pole voltages of the field winding according to its polarity. By it, the difference of the pole voltages can be determined. This difference voltage is caused by the noise field of the missing damper bar because the main field of a symmetrical built machine disappears in the difference voltage. The broken damper bar is fixed on the rotor and the field winding is fixed, too. Moreover, the difference voltage depends as well on the position of the missing damper bar as on the distribution of the field winding. In the case of a distributed field winding, the damper bars under the edges of each pole can be detected exact. In order to check the bars in the middle of each pole additional measuring coils of each bar are needed. These coils work according to the measuring method of the field winding. The theoretical ideas are checked by measurements at a special adapted test machine.

Key words

Diagnostic system, turbo generator, field winding, broken damper bar.

1. Introduction

Increased reliability, variable maintenance intervals and minimised downtimes of electrical machines are results of an online diagnostic system. The requirement criterion of a synchronous machine in a power station is the reliability. As a result, all critical components of the machine must be checked by a life cycle analysis. The requirements of an online diagnostic system are a high service reliability of the machine and a low cost construction of the online diagnostic system.

A lot of critical components such as the three phase stator winding and the field winding and bearings are monitored by a modern diagnostic system. In this paper a method to detect broken damper bars of a complete damper cage in a turbo generator is described. Therefore the machine must be loaded asymmetrical or the operation must be transient. Because during these two operation states the built in damper cage works.

The primary aim of the built in damper cage in a synchronous machine is to minimise the negative sequence of the rotating field to zero. This idealised condition leads to an armature reaction of the positive sequence of the rotating field, because the negative sequence is damped to zero. So the machine is only loaded by the positive sequence of the rotating field. But we know that the negative sequence of the magnetic field can be never damped to zero, because of the leakage inductance of the damper winding.

More often than a defect damper cage is caused by an overloaded machine or a defected construction of the built in damper cage. Such defects lead for a moment to one broken damper bar. One broken damper changes the original damper bar current distribution in the machine. In other words the current of the broken damper bar flows in the both closed neighbouring bars. The frequency of the interference field is the same as the frequency of the negative sequence of the field related to the rotor.

Now broken damper bars can be detected by the interference field. As stated above, this interference field becomes visible when the damper cage works within limits. These limits are determined by a loaded test. In other words a broken damper bar can only detected by an interference field.

To detect the interference field caused by a broken damper bar two methods are used. Both methods are known from diagnostic systems of asynchronous machines. First, the interference field can be detected by the use of air gap windings. But the mounting of air gap coils is expensive. Second, faults are detected by the frequency spectrum of the Fourier analysed stator currents. But the second method isn't really a practical method.

A turbo generator with a distributed field winding made a new method possible. And this method is described in this paper. This method bases on the induced voltages of the interference field in the field winding. Due to the fact that the broken damper bar is fixed to the rotor, only the edge bars under each pole pitch can be detected. The bars in the middle of each pole are undetected.

The central point of this method is a very easy implementation to an existing diagnostic system of machines because only one additional slip ring must be mounted. Therefore the interference field can be filtered out from the main field.
The detection of a broken damper bar is nearly independent of the loading conditions of the machine.

2. Determination of the interference field distribution

A. The spatial field distribution

The faulty behaviour of a machine can be described by the summation of an error-free machine and by a machine with only the error [2]. The amplitude of the interference current is determined by the fact that the current which flows through the broken damper bar is zero. This means that the interference current is equal to the original bar current with an inverse sign. If the bar with the number 3 is broken the caused interference field is given in Fig. 1. Here the air gap is idealised, this means that the slotting effects are neglected.

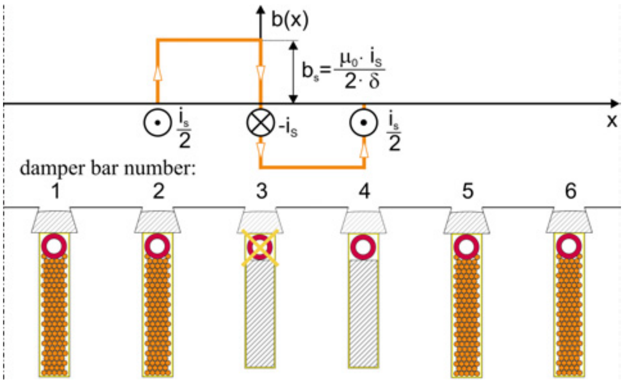

Fig. 1. Idealised interference field distribution

The slotting effects are taken into consideration by the next figure. The increased air gap is caused by the opened rotor and stator slots. This air gap field distribution is valid for a defined rotor position and at a moment.

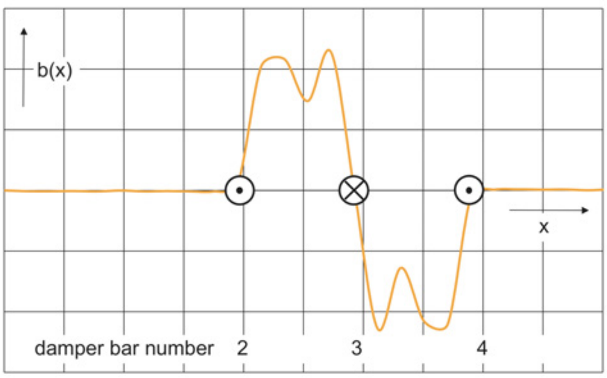

Fig. 2. Real interference field distribution

Compared with Fig. 1 the stator and rotor slotting effects can be seen well.

B. Characteristics of the interference field

The spatial interference field distribution depends most on its frequency and with it from the slip frequency. In a synchronous machine the slip of the negative sequence of the rotating field is 2. This is equivalent to an interference field which is pulsating with double power frequency.
Furthermore the spatial field distribution depends on the ohmic resistance and the self- and leakage inductance of the damper cage. And both electrical values depend on the one hand of the construction of the damper cage. The spatial field distribution in Fig. 2 bases on a high ratio between the self- and leakage inductance of the damper cage and its ohmic resistance. For it the splitting of the magneto motive force (MMF) into parts of the damper cage ring and bars. As a result, the limiting condition between an uniform field distribution along the rotor circumference and a field distribution in Fig. 2 is given in (1)

$$s \cdot \omega \cdot \mu_0 \cdot \frac{\pi \cdot D_i \cdot l_{Fe}}{N_3 \cdot \delta} \ll R_{bar} \qquad (1)$$

3. Voltage induction into the field winding of a synchronous machine

A. The spatial field distribution

In turbo generators the field winding is distributed. In order to get a sine-shaped excitation curve the rotor slots must be two thirds wrapped. The test machine is two pole and it has 24 rotor slots. So, we see, that one pole pitch has 6 slots and 4 out of these 6 are wrapped (Fig. 1).
The distribution of the field winding is important due to the fact that the induced voltage into the field winding by the interference field causes by the integration of the magnetic flux density within the field winding. Full facilities of the interference field distribution within one pole pitch are given in Fig. 3.

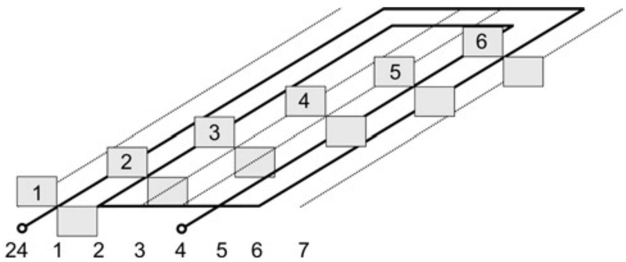

Fig. 3. Idealised interference field distribution

The field distribution is idealised as in Fig. 1. Now, let me give two classic examples. First, the damper bar with the number 2 is defect. The field winding of one pole pitch is the sum of two coils. One is in slot 1 and slot 6 with w_a turns and the other one is in slot 2 and slot 4 with w_a turns, too.
Both are serial connected. The negative half of the interference field distribution is within both coils but the

positive half is only within coil 2. The total flux within the field winding of one pole is described by (2):

$$\phi_{S2} = \mu_0 \cdot \frac{i_S}{2 \cdot \delta} \cdot w_i \cdot \tau_N \cdot l_{Fe} \quad (2)$$

Second, the damper bar with the number 3 is defect. We can see, that the interference field is complete surrounded by both coils. As a result the total flux is zero and no voltage can be induced into the field winding of the pole. This fact means that only such damper bars which are broken within the pole ends can be detected by the field winding. The damper bars number 1, 2, 5 and 6 can be detected by this system. The bars 3 and 4 can be detected by additional measuring coils. The number of the detectable damper bars in a synchronous machine depends on the number of wrapped rotor slots, on the number of pole pairs and on the number of rotor slots.

B. The time dependence of the interference field

The frequency of the interference field caused by a broken damper bar is equal to the frequency of the negative-sequence field. The behaviour of the first harmonic of the flux density of the interference field is given in (3):

$$B_{(x,t)} = B_{\max} \cdot \sin\left(\frac{x}{\tau_N} \cdot \pi\right) \cdot \sin\left(\omega_{inverse} \cdot t\right) \quad (3)$$

C. Voltage induction

In order to analyse the induced voltage into the field winding, the serial connected field winding must be divided into their pole pairs. So, the induced voltage caused by the negative-sequence field is eliminated and the rest of the induced voltage is caused only by the interference field. If the machine is free from defects the induced voltage into the field winding is zero.

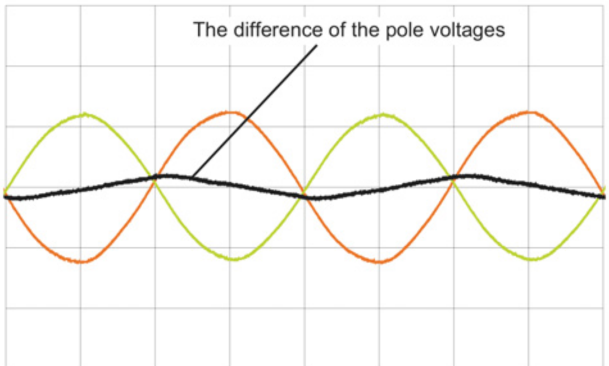

Fig. 4. The difference voltage of the pole voltages when the bar with the number 1 is broken

Fig. 4 shows the induced voltage into the field winding when the damper bar with the number 1 is broken. The two higher curves mark the induced voltage divided into the north and south poles of the machine. In the case of a symmetrical machine when no damper bar is broken the difference of these voltages must be zero. In Fig. 4 one damper bar is broken. As a result the difference voltage of the pole voltages is given by the last curve. The time position of the resulted curve depends on the position of the broken damper bar in reference to the spatial position of the field winding, because both are fixed to the rotor. The amplitude of the curve depends only on the current of the broken damper bar, before it is broken. This is valid when the interference field distribution base on Fig. 1. Fig. 5 shows the sum of the pole voltages. This curve is the result when all poles of the field winding are serial connected as usual.

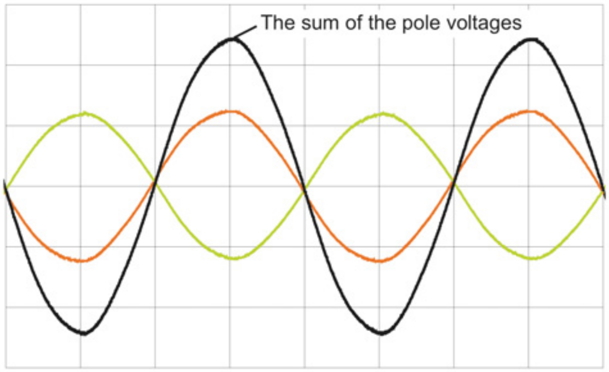

Fig. 5. The sum voltage of the pole voltages when the bar with the number 1 is broken

There is no information about a defect damper bar in the analyse of the sum of the pole voltages neither in the amplitude spectrum nor in the frequency spectrum. This is because the effects of one broken damper bar is to small and the produced interference field is averaged along the whole circumstance. The ratio between the sum of the pole voltages and the difference of the pole voltages is nearly 10. The curves in Fig. 4 and Fig. 5 base on a standstill test of the defected model machine. This means that the stator is supplied by a three phase system and the rotor stands still. Further the field winding is open-ended. A result of the open-ended is the missing reaction of the field winding to the stator.

The negative-sequence field in the machine induces into a closed field winding a voltage with the first harmonic, the fourth harmonics, the sixth harmonics etc. This is, because the field winding is uniaxial. But if the field winding is open there are no higher harmonics in the induced voltage. This means that the sum of the pole voltages contains only the fundamental frequency. Its amplitude is independent of the failure in the machine. The influence on the sum of the pole voltages caused by a broken bar is almost non-detectable.

In the case of the difference of the pole voltages the amplitude depends strong on the failure of the machine. The dominant voltage of the difference pole voltage is the second harmonic too. Higher harmonics are negligible.

4. Measuring

A. The measuring equipment

In order to measure each pole pair voltage separately an additional slip ring is required.

Fig. 6 shows the winding diagram of the field winding.

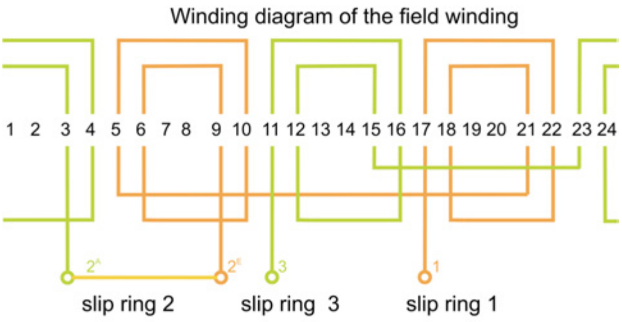

Fig. 6. Winding diagram of the distributed field winding of the test machine

The measuring circuit is given in Fig. 7. The synchronous machine operates isolated and the DC machine is the prime mover of the synchronous machine. The test machine is asymmetric loaded. The different of the pole voltages is measured by an oscilloscope.

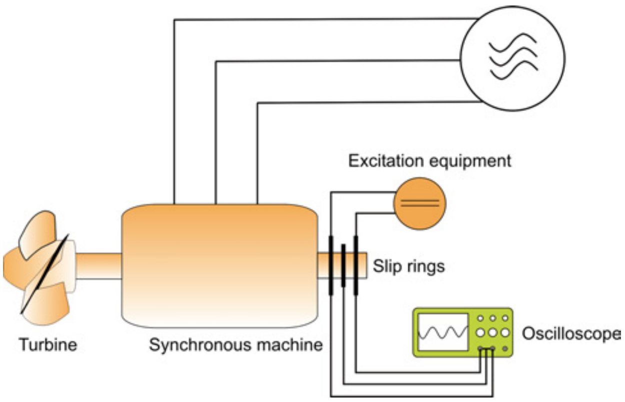

Fig. 7. The measuring circuit of the test machine

B. The evaluation of the measurements

First the synchronous machine is speeded up to the rated speed by the DC machine. Then the synchronous generator is asymmetric loaded by a three phase variable resistance. This means that each phase is loaded different. The relative asymmetric load varies between 3% and 25 %. In general, when the negative-sequence field can be detected in the pole voltages the interference field caused by a broken damper bar can be detected, too. This means that a 3% asymmetric load is needed to detect broken damper bars.

5. Results

A. The sum of the pole pair voltages

Here two different cases are analysed. First, the machine is free from defects and second, on damper bar is broken in the test machine.
At the beginning, the sum of the pole pair voltages are measured (Fig. 8). There are two curves in this figure. One curve presents the error free machine and the other curve marks the machine with a broken damper bar. Because of a clear presentation one curve is time shifted. From Fig. 8 can be derived that both curves are identical. This means that a broken damper can't be known by these curves.

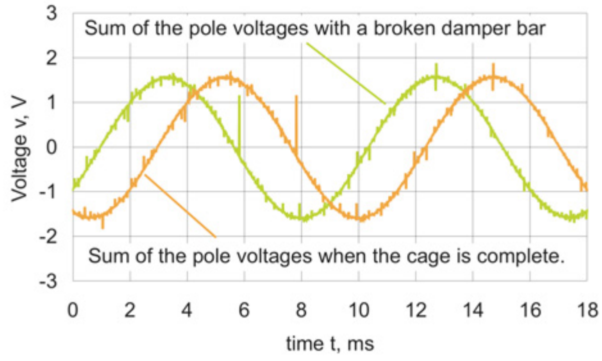

Fig. 8. The sum of the pole voltages when the machine is error free and when the machine has a broken bar.

As a result both curves are analysed by a Fast Fourier Transformation. The first order is equivalent to the mains frequency (50 Hz). From Fig. 9 we can learn that only this frequency is dominant. The other harmonic orders can be neglected. In both cases the amplitudes are nearly the same. So, it is true that the effects of a broken damper bar in synchronous machines can't be detected by the sum of the pole voltages.

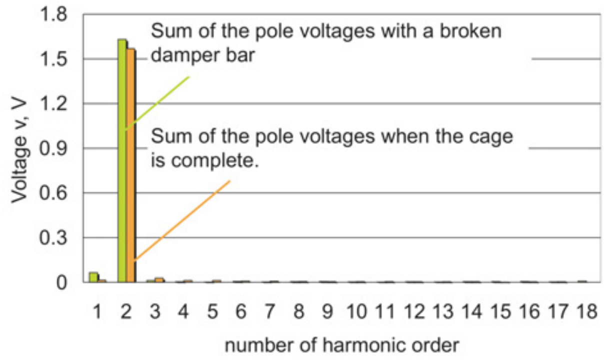

Fig. 9. Fourier analysed sum of the pole voltages

B. The difference of the pole pair voltages under asymmetric load

The difference of the pole voltages is presented in Fig. 10. On the one hand there is the curve of the error-free machine and on the other hand one damper bar is broken. It can be derived that the error-free machine doesn't produce a difference voltage.
By way of contrast, the machine with the broken damper bar produces a measurable difference voltage. Now the synchronous machine is asymmetric loaded and the machine works in the lock mode.
This fact can be derived from the curves in Fig. 10 too, because the influence of the slot ripples gets visible. Furthermore the effects of a connected uniaxial field winding are given in Fig. 10.

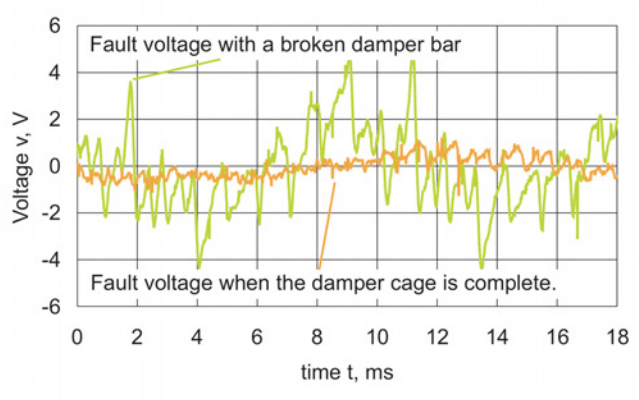

Fig. 10. The difference voltages of an error-free machine and a defected machine when the machine works in the lock mode.

The Fourier analysed voltage curves are shown in Fig. 11. First, all harmonic numbers of the difference voltage when the machine is free of defects are nearly zero, because the analysed voltage is almost zero. But for the difference voltage of the machine with a broken damper bar it resulted in an interest harmonic spectrum (Fig. 11). This harmonic spectrum is equal to the spectrum of a synchronous machine without an additional built in damper cage.

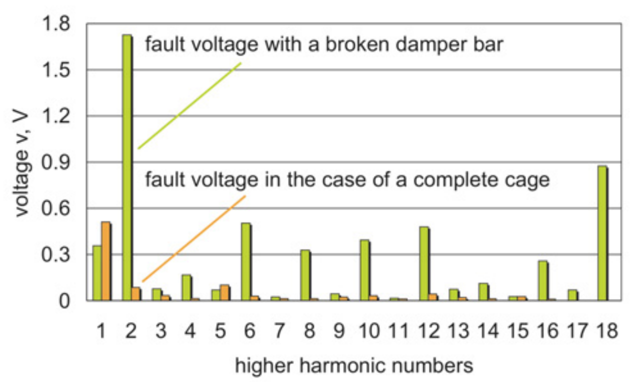

Fig. 11. Fourier analysed difference voltage of the synchronous machine (error-free and defected)

The second harmonic order bases on the frequency of the excitation field. As stated above, in the case of a broken damper bar is the excitation field of the interference field the negative-sequence field. Now, the field winding is closed. This means that their ends are connected to an excitation equipment. So, the negative-sequence field can't be compensated by the field winding because it is uniaxial. As a result the fourth harmonic, sixth harmonic, eight harmonic, etc. appearance in Fig. 11. The other harmonics are rotor slot harmonics which are given by (4).

$$\nu_N = i \cdot \frac{N}{p} \cdot \pm 1 \tag{4}$$

The harmonic numbers caused by the rotor are 10, 12, 14, etc..

6. Conclusion

An online diagnostic system of electrical machines with large power is important. Among the reduction of the maintenance intervals the reliability of the machine will be increased by such a system. Today a great number of critical components of a machine are monitored by an online diagnostic system. But not all are monitored. One critical component of an asynchronous and a synchronous machine is the built in damper cage in the rotor. There are methods to determine broken damper bars in the rotor of an asynchronous motor. But there are no methods for a synchronous machine. So a new method to detect broken damper bars in a synchronous machine is given in this paper. The presented method becomes valid in the case of a dynamic run of a synchronous machine and in the case of an asymmetric load of a synchronous generator.

A broken damper bar produces an interference field which is fixed to the rotor. This field induces a voltage in the field winding which is fixed to the rotor too. It is obvious to use the field winding as measuring winding, because the induced voltage caused by the broken damper bar is small and the field winding is next to the fault. But as stated before, the field winding must be divided into two parts. One part consists out of all poles which are positive and the other part consists of all negative poles. Further the construction of the measuring system is very simple, because only one additional slip ring at the rotor of the test machine is used. The difference of the two measured voltages can be analysed by a conventional two channel oscilloscope.

A disadvantage of the new method is that not all damper bars can be detected, because the field winding and the failure is fixed to the rotor. The number of bars which can be detected depends on the rotor slots, the pole pairs and the design of the field winding.

References

[1] K. Bonfert, Betriebsverhalten der Synchronmaschine, Bedeutung der Kenngrößen für Planung und Betrieb elektrischer Anlagen und Antriebe, Springer, Berlin, Göttingen, Heidelberg (1962), pp. 125-127.

[2] W. Deleroi, "Der Stabbruch im Käfigläufer eines Asynchronmotors, Teil 1: Beschreibung mittels Überlagerung eines Störfeldes", Archiv für Elektrotechnik 67, pp. 91-99, 1984.

[3] A. Einsele, "Über die Verteilung der Ströme in den Dämpferwicklungen von Turbogeneratoren mit Massivläufern", Elektrotechnische Zeitschrift Jahrgang 73, Vol. 6, pp. 173-176, 1952.

[4] H. Jordan, W. Schmitt, "Über den Einfluß fehlender Stäbe auf das Verhalten von Kurzschlußmotoren ", AEG Mitteilungen, Vol. 9/12, pp. 57-65, September/Dezember 1942.

[5] R. Richter, Elektrische Maschinen, Synchronmaschine und Einankerumformer, Zweiter Band, Birkhäuser, Basel/Stuttgart (1953), pp. 50-51.

[6] G. Müller, Theorie elektrischer Maschinen, VCH, New York / Basel / Cambridge / Tokyo (1995), pp. 91-104.