A Performance Analysis of a Hydrogenerator In The Case of Field Short-Circuit Using FEM

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Abstract. The maintenance of synchronous generators is very significant for the energy production. Being aware of the performance of a synchronous machine during different kinds of faults, such as phase to phase, phase to ground or field short-circuits, could provide useful information about their protection. A short-circuit in the field excitation is not a common fault, but it is severe enough to create high oscillations to both electrical and mechanical magnitudes (field, stator and damper currents, rotor shaft torque, load angle etc). Such kind of faults is difficult to examine and provide experimental results because of the kinds of generator used for energy production. The size of these machines, either hydrogenerator or turbogenerator, is enormous for experimental laboratory studies. Another important issue that arises is the difficulties in the accurate calculation of the damper currents during transient operation. The Finite Element Method analysis gives solution to this kind of problems, as it can calculate as well the damper, stator and field currents as the electromagnetic field distribution inside the air gap.

Key words

Damper currents, field excitation short-circuit, Finite Element Method (FEM), hydrogenerator, transient behaviour

1. Introduction

The last decades the use of renewable sources for energy production is rising rapidly. Despite the increase of the renewable energy systems, the power produced by hydrogenerators remains an important source of energy production. The maintenance of these machines is very significant, as a disconnection from the grid due to electrical faults could create serious problems to the power production. Being aware of the machine's performance during a field short-circuit, we can achieve useful information about the electromagnetic torque oscillation, the damper and stator currents and the affection of these oscillations to the field current.

In this paper the effects of a fault in the excitation supply of a salient pole synchronous generator is investigated. We consider that this fault happens when the machine operates at full load and is connected to the 50 Hz grid. In the literature several types of fault have been studied [1]-[4], but not this fault and under this certain operation. During this transient operation are all the currents, the electromagnetic torque, the load angle and the radial magnetic flux component inside the air-gap of the generator have been investigated.

The advantage of the finite element analysis, comparing to other methods, is that some of the abovementioned magnitudes can be calculated and observed more precisely and easily through the steady-state and transient operation. The damper currents of the machine exist at both steady-state and transient operation due to the saliency of the machine [5]. These currents could cause serious damage to the insulation of the damper cage, as they get high values during the fault. These kinds of currents are produced because of the fault which causes the electromagnetic torque oscillations. These oscillations have serious affection on the load and applied torque of the rotor shaft and lead the machine to pole slip.

During the simulation the mechanical torque of the rotor shaft is controlled by a PI-Controller in order to obtain more accurate and precise results. Although the machine speed is controlled to keep it equal to the synchronous one, a consideration about fixed constant speed leads to non-accurate results. This happens because by constant speed the machine can't lead to pole slip.

The study of the magnetic flux distribution during transient operation is very significant in the comprehension of the hydrogenerator electromagnetic behaviour. The finite element method provides the tool to analyze these magnitudes and examine their affection to the machine behaviour.

2. Modelling of the system

A. The PI-Controller

To obtain more accurate and realistic results of the simulated machine transient behaviour, a controller for the mechanical applied torque was inserted in the programme. Fig.1 presents the basic structure of the PI-Controller for the mechanical torque, when the machine is connected to the grid.
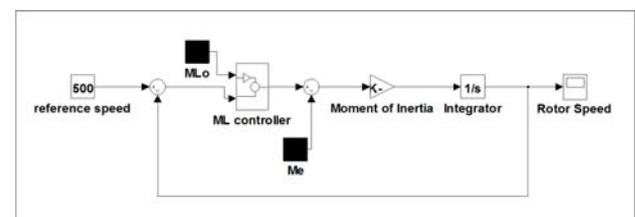

Fig. 1. The PI-Controller

The controller described above is based on the following equations:

$$M_e = M_L + J \frac{d\Omega}{dt} \qquad (1)$$

$$M_e = p\left(i_{sq} \cdot \Psi_{sd} - i_{sd} \cdot \Psi_{sq}\right) \qquad (2)$$

where:

M_e : Electromagnetic Torque

M_L : Load Torque

J : Moment of Inertia

Ω : Rotor Speed

i_{sq} : quadrature stator current

i_{sd} : direct stator current

Ψ_{sd} : direct stator flux

Ψ_{sq} : quadrature stator flux

The purpose of the controller is to modify the applied torque on the rotor shaft in keeping the rotor speed constant and equal to the synchronous. After the connection of the machine with the grid the speed is held constant by the grid, so the controller in this case changes the load torque and the active power according to the needs of the grid.

B. The Finite Element Method

Fig. 2 presents the finite element mesh of the one third of the simulated machine. The mesh consists of 13736 elements and 28185 nodes. As it can be seen in this figure, the size of each element is smaller in the areas near the air-gap, while in the area outside of the air-gap is bigger.
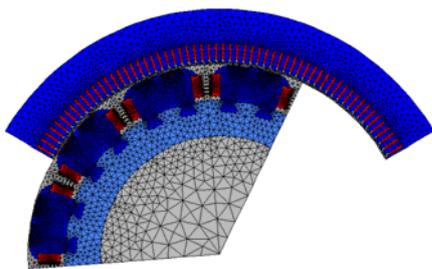
Fig. 2. The Finite element mesh

The solver used for this kind of analysis is the 'Rotating Machine Analysis', which is a transient eddy current solver, extended to include the effects of rigid body motion, to obtain the results in real time as well for the steady-state as for the transient operation. In this kind of analysis, the rotating regions rotate by an angle corresponding to their angular speed and the transient time-step. At each new position of the rotor the mesh in the air gap reforms to make a contiguous mesh. This kind of analysis has more benefits comparing to the static one as we additionally can study the machine behavior during transient operation. A linear analysis was used as the

consideration of linear magnetic flux characteristic is close to the reality.

C. Machine Data

The simulated machine is a 200 MVA salient pole synchronous generator. The machine consists of 12 poles and has a synchronous speed of 500 revolutions per minute. The stator winding consists of three parallel branches in order to reduce the stator current [?]. During the simulation the least symmetrical model of the generator was used, which is the one third of the machine. Symmetries lower than 120˚ couldn't be considered because the symmetry of the stator for the one branch covers a circumference equal to 120˚. The fault happens at the supply of the excitation, therefore there was no need to simulate the whole machine, as during this fault the field has the same distribution either for the symmetrical model or the whole machine. Fig .3 presents the cross-section of the hydrogenerator with the field lines superimposed.
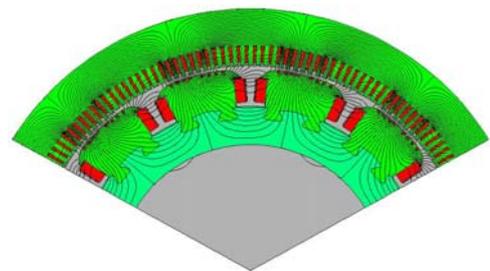
Fig. 3. The electromagnetic field lines

D. The Field Excitation Short-Circuit

The fault that is investigated in this paper is a short-circuit in the field supply, while the machine operates at full load connected to the 50 Hz grid. In order to simulate this kind of fault a switch was inserted parallel connected to the excitation supply (Fig. 4). This switch was represented by a resistor R_s, which is 1e9 Ω when the switch is off (steady-state operation) and 1e-9 Ω when is on (at the time of the fault).
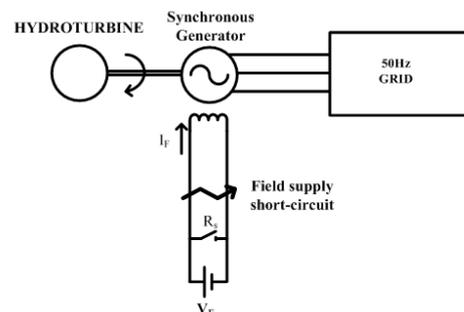
Fig. 4. Field excitation short-circuit

E. The Damper Cage Circuits

In order to calculate the damper current waveform during steady-state and transient operation the damper cage circuits were taken into account. In Fig. 5 the structure of the damper cage is presented.
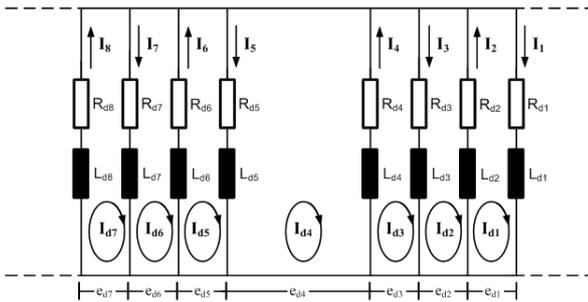

Fig. 5. The damper circuits

The current in each damper bar is calculated using the current in every damper loop. The existence of the damper current in the steady-state operation is caused by the induced voltage e_d [?] according to the equation (3):

$$e_d = \frac{d\Phi_d}{dt} \tag{3}$$

where Φ is the magnetic flux.
The current of each damper bar is given by the next equation:

$$i_\nu = (-1)^{\nu+1} \cdot \left(i_{d_\nu} + i_{d_{\nu+1}}\right), \tag{4}$$

where $i_{d\nu}$ and i_ν are the currents of the damper loop and damper bar respectively and $\nu=1…96$ the number of each damper bar.

3. Simulation Results

A. Electromagnetic Flux

During the transient operation of the simulated machine a distortion in the radial flux of the electromagnetic field appears. Fig.6a presents the radial flux component of the electromagnetic field for the case of the healthy operation and for two cases after the fault. The first one is 0.5 second after the beginning of the fault and the second one 9 seconds after the fault. In addition, in Fig. 6b is shown the harmonic analysis of the radial flux for the above mentioned cases.

As it can be clearly seen the distortion in the electromagnetic flux appears just after the beginning of the fault (0.5 second) and continues during the whole transient operation. The harmonic components in the third case are lower than the respective values in the other two cases. This is caused because the electromagnetic field is totally distorted and its distribution changes a lot.

This modified form is the reason that the harmonic components are decreased. The absence of the flux created by the excitation supply modifies the field inside the air-gap. After the fault this field is created by the stator voltage from the grid.
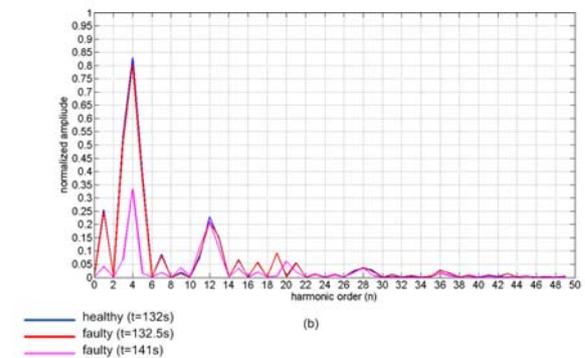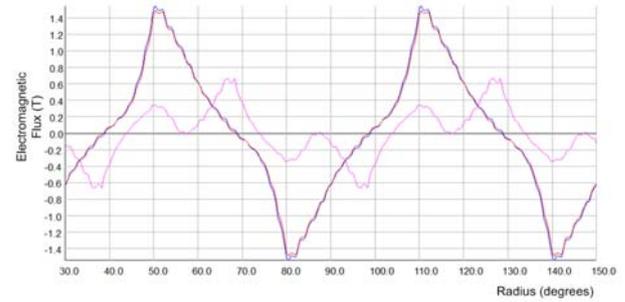

Fig. 6. a) Radial flux component
b) Harmonic analysis of radial flux component

B. Electromagnetic Torque

The operation of the machine during steady-state and transient cases is determined by the performance of the electromagnetic torque. In Fig. 7 the waveform of this torque is presented.
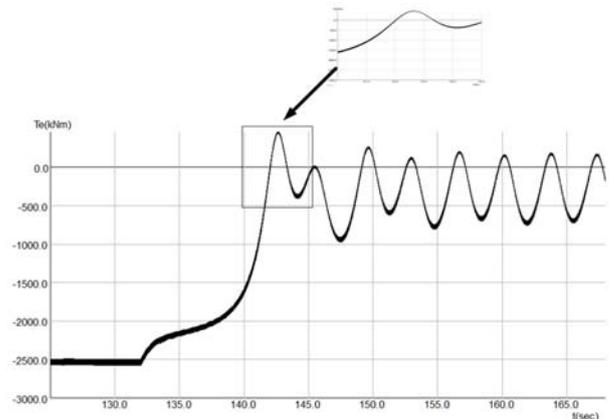

Fig. 7. The waveform of the electromagnetic torque

Before the short-circuit the generator operates at nominal load, the negative sign indicates that the machine operates as a generator. At the time of 132 seconds happens the short circuit in the field supply. Just after that the torque begins to rise reaching positive values

almost ten seconds after the fault. As there is no supply in the field winding there is no electromagnetic field and as a result the machine operation changes from generator to motor, but it doesn't keep this operation permanently as it happens under the consideration of constant speed [8]. At the time of 141sec high oscillations in the electromagnetic torque appear. These oscillations lead the machine to pole slip, while there is a continuous alternate power exchange from the generator to the grid. An important issue that arises is that the machine starts to pulsate between positive and negative values, couldn't being able to keep the motor performance. This kind of oscillation denotes that there is a respective oscillation of the load angle of the machine. As it can be seen in Fig. 8 the generator led to pole slip 7 second after the short-circuit and the disconnection from the grid is essential.
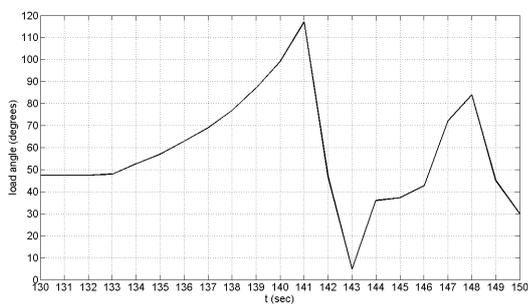

Fig. 8. The load angle oscillation

C. Stator Currents

Great affection appears in the stator currents during the transient operation of the machine. Fig. 9 presents the rms value of the current of the phase A at the healthy steady-state and faulty operation. The stator currents are symmetrical so there is no modification among them, while the performance of each phase is the same.
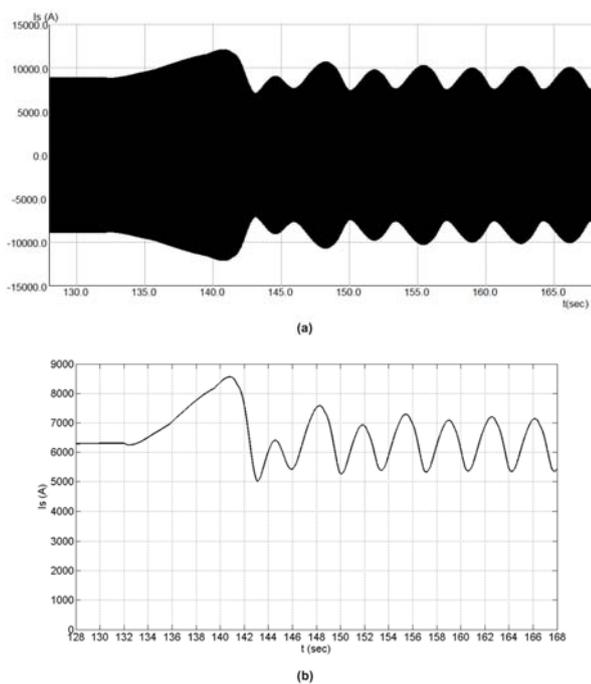

Fig. 9.   (a) The stator current waveform
            (b) The rms value of the stator current

At the steady-state operation the rms value of the stator current is 6300 A. Just after the time of the fault there is a rise of the amplitude that reaches the value of 8450 A, only 9 seconds after the beginning of the short-circuit. This rise of 36% is in absolute values equal to 2150 A and is high enough to cause serious damage to the winding insulation. It exists due to the fact that the machine begins to change operation mode from generator to motor and the stator current depends on the stator supply and not on the induced voltage from the field winding. This is the reason why the stator current oscillation is proportional to the respective oscillation of the electromagnetic torque.

D. Field Currents

High disturbances appear in the waveform of the field current during the transient operation of the generator. Fig. 10 shows the waveform of the field current before and after the short-circuit in the field supply.
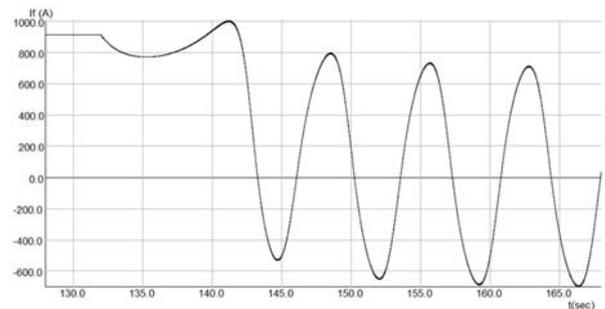

Fig. 10. The waveform of the field current

During the time interval of the fault a reduction of the field current appears. This situation lasts almost 3 seconds, where the amplitude becomes 772 A. This is the mean value of the field current as there is an oscillation of the amplitude (Fig. 11) that is caused by the distorted electromagnetic field.

At the steady-state operation this oscillation is 0.12 %. This percentage is in absolute values almost 1.14 A, as the amplitude of the current is 914.16±1.14 A. This oscillation remains during the transient operation and is rising reaching 0.36%, a value that is equal to 3 A.

The rotor current doesn't nullify, despite the fact that the field supply is short-circuited. After the reduction of the first 3 seconds there is a rise that reaches almost 1000 A, where the machine has been led to pole slip. After that a high oscillation appears and the current is getting positive and negative values as well. This is caused by the induced voltage from the stator to the rotor, as the current produced by the field supply is zero.
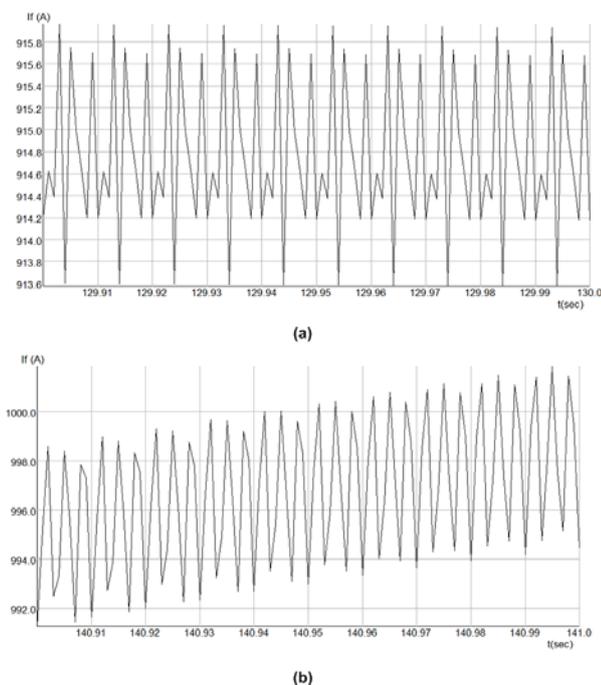
Fig. 11. The field current oscillation a) steady state
                                     b) transient operation

E. Damper Currents

Table I presents the mean and peak values of the damper current for each bar of the first pole of the machine at the healthy steady-state operation. Due to symmetry the respective values of the other poles is the same.

Table I.-Mean and peak values of the damper current

CONDUCTOR NUMBER	MEAN VALUE (A)	PEAK VALUES (A)
1	-6.7	390
2	-2.85	276
3	-1.325	252
4	-0.8165	338
5	0.635	450
6	0.635	425
7	2.36	470
8	5.77	560

In healthy steady-state operation the damper currents maintain a periodical form with a mean value not greater than 7 A. This form is as expected due to the pole saliency. The magnetic field is distorted and, as a result, induced current appears in the damper bars. This oscillation of the damper current has a stable frequency that is twice the frequency of the stator voltage. This is the same with the respective frequency oscillation of the electromagnetic torque [6]. Also, the peak value is relatively high on account of the very small resistance of the damper ring [7]. For example an induced voltage equal to 45 mV produces a current that is almost 450 A. The resistance of the damper ring in this machine is R_d=0.14 mΩ. Fig.12 presents the damper current waveform for the two neighbored damper bars during the steady-state and transient operation, while in Fig. 13 are

shown the mean current of each damper bar for the respective cases.

Just after the fault there is a rise in the damper current of each damper bar. The modification is almost the same for all the bars but the maximum amplitude differs for each one. The absence of the field supply and the oscillations of the rotor shaft lead to these kinds of currents.
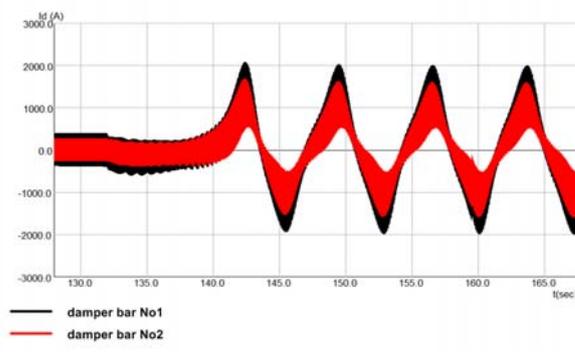

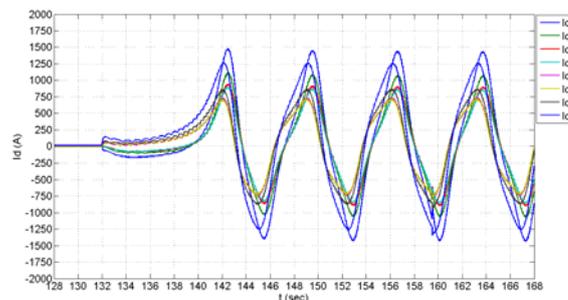
Fig. 12. The damper current waveform

Fig. 13. The mean values of the damper current

Table II presents the mean values of the damper current two and ten seconds after the beginning of the fault.

Table II.-Mean values of the damper current for two different times

CONDUCTOR NUMBER	MEAN VALUES (A) / MODIFICATION (t=134 s)	MEAN VALUES (A) / MODIFICATION (t=142 s)
1	-170.69 (2447%)	1198.05(17780%)
2	-107.68(3685%)	887.91(31055%)
3	-81.32(6037%)	758.15(57119%)
4	-79.8(9673%)	744.36(91065%)
5	23.69(3630%)	710.3(111758%)
6	24.87(3816%)	695.51(109429%)
7	40.31(1608%)	837.21(35375%)
8	74.14(1185%)	1237.24(21343%)

As it can be clearly seen high currents appear after the fault. These currents reach values that are in some cases 180 times greater than the respective at steady-state operation. Except from the high oscillations of the rotor shaft that are caused during the transient operation, these extremely high currents may create severe problems in the damper cage and the damper bars insulation as well.

Fig. 14 presents the field lines at the time of 134 sec where is shown how the distorted field lines affect the damper currents.
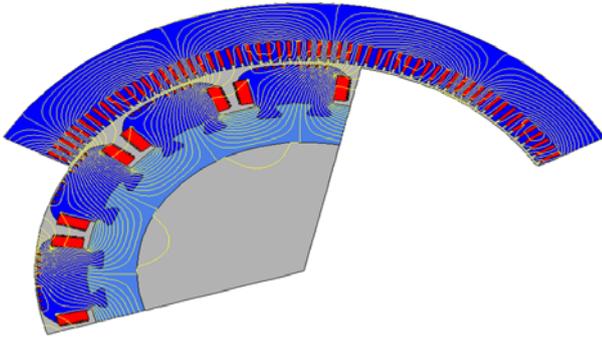

Fig. 14. The distorted field lines

As it is presented in Table II, the distortion for each damper current is not the same. The currents with the higher mean value are distorted less than the respective with the lower one. This distribution remains during the transient operation and as a result the damper bars 1,2 and 7,8 are affected more by these high currents. This phenomenon appears as the induced voltage at the damper cage is not uniformed in the whole circumference of the air-gap.

4. Conclusion

A short-circuit in the field supply has serious affection in the performance of the synchronous generator. The machine needs only 7 seconds to pole slip and high pulsation in the electromagnetic torque appears. This performance affects the rotor shaft and the stability of the grid as well.

High disturbances appear in both stator and field currents. Except from the sudden rise of the stator current before the pole slip, high periodical pulsation in this current appears.

On the other hand the field current doesn't nullify, as the field supply does, but it reduces before the pole slip and after that starts to oscillate between positive and negative values. Finally, high damper currents appear which are unequal in each pole. This waveform of currents could harm the damper cage if the fault won't be cleared immediately.

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