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SIMULATION ANALYSES OF AUTONOMOUS INDUCTION GENERATOR UNDER VARIOUS LOADS

Summary. The paper presents results of a computer-aided simulation of a self-excited induction generator in an autonomous operation regime under various loads. The simulations were performed for both the symmetrical and unsymmetrical resistive loads and for three-phase rectifiers. Moreover, the simulation of a single-phase short circuit was made, too.

Key words: induction generator, Diesel engine, generating aggregate

1. INTRODUCTION

Knowledge of an induction generator response to various kinds of loads is the way to understand the generator behaviour in customary service conditions. Two potent al approaches are possible to obtain that knowledge:

- measurement of the induction generator under required operation conditions or
- modelling and simulation analyses.

In order to measure the induction generator it is necessary to arrange the suitable working place, equipped with a generator, a set of various loads and a respective measuring system. It is clear that the cost of all those components is high.

Computer-aided modelling and simulation of technical devices and dynamic systems is one of frequently used tools to analyse their operation. On the basis of simulation results it is possible to understand function of those devices and systems in deeper details and to obtain reasonable knowledge about their real performance.

The paper summarizes results of the simulation analysis of a self-excited induction generator, loaded by both selected linear and non-linear electric circuits. The generator is driven by a speed-controlled Diesel engine.

2. MODEL OF A GENERATING AGGREGATE

In general, a simulation model of the generating aggregate consists of two fundamental parts:

- a Diesel-engine model and
- an induction-generator model.

The Diesel-engine simulation model (see Fig. 1) consists of a fuel-pump model FP, of an injection-limiter model IL and of a simple non-linear engine-cylinder model EC [1]. Engine torque T_e is a non-linear function of both the engine angular speed ω_e and the fuel injection portion d_f, given by the static torque-speed characteristic - $T_e = f(\omega_e, d_f)$. Mechanical inertia of the engine is

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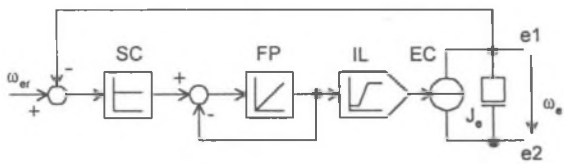

Fig. 1. Simulation model of a Diesel engine
SC-speed controller, FP-fuel pump, IL - injection limiter, EC - engine cylinder

represented by the mass moment of inertia J_e. The engine angular speed ω_e is controlled by a feedback control loop through a type P speed controller SC, the reference speed input is ω_{er}.

The simulation model of the induction generator is a non-linear model in terms of transformed *dq0* coordinates [2, 3]. As the generator rotor winding is supposed to be symmetrical, its model is expressed in terms of dq coordinates only. On the other hand, the model of the generator stator winding is formulated in terms of *dq0* coordinates in order to make possible to analyse unsymmetrical load cases, when the sum of stator currents does not equal zero. The output of the generator model is transformed to the natural coordinate system abc. The equivalent circuit diagram of the induction-generator model is drawn in Fig. 2. Condenser J_g and resistor b_g represent a rotor mass moment of inertia and speed-dependent losses, respectively.

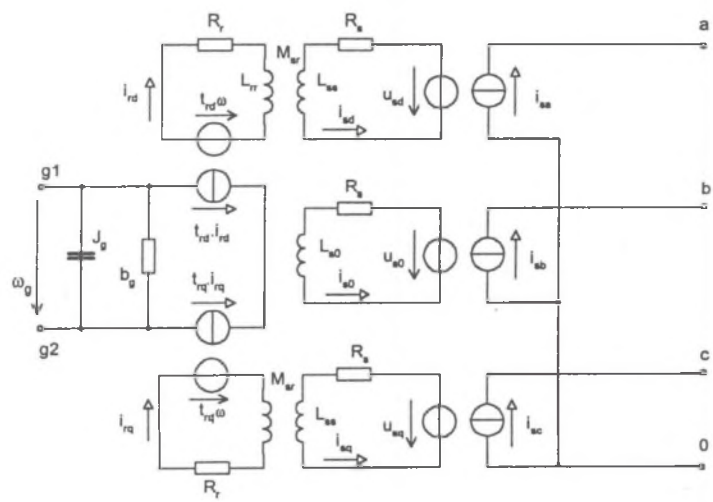

Fig. 2. Simulation equivalent circuit of an induction generator

3. SIMULATION ANALYSIS

The above mentioned models were used to perform the simulation analysis of the generating-aggregate responses to the following kinds of the generator loading:

1) no-load,
2) linear resistive loading,
3) non-linear loading (three-pulse and six-pulse rectifiers) and
4) short-termed single-phase short circuit.

The simulated generating aggregate consists of the following parts (Fig. 3):

a) speed-controlled Diesel engine - P_e = 5,6 kW at 3000 r.p.m., J_e = 0,24 kgm^2,
b) two-pole induction machine as a generator - P_g = 2,5 kVA, 3x230/400 V, J_g = 0,0015 kgm^2,
c) bank of 3 exciting condensers 90 μF in Y-connection.

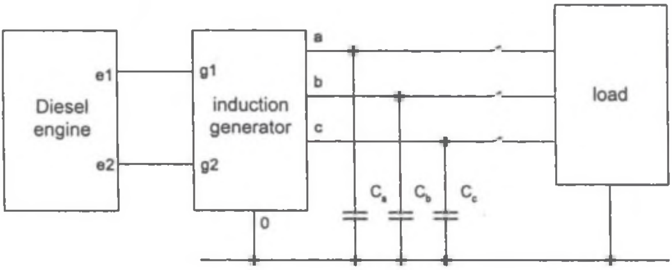

Fig. 3. Simulation model of a generating aggregate

Respective loads are connected to the generating aggregate by means of 3 switches after it has achieved the no-load steady state.

When analyzing simulation results the main attention was paid, among others, to responses of the following physical quantities:

- driving torque T_e of the Diesel engine and electromagnetic torque T_g of the generator,
- waveforms and values of generator phase voltages U_i and
- magnetizing current I_{magn}.

At the start of each simulation experiment the speed of the generating aggregate was always adjusted to 2960 r.p.m. (ω_e = 310 s^{-1}) and all exciting condensers were loaded to the voltage of 100 V. The reference speed of the speed controller SC was 3050 r.p.m. (ω_{er} = 319 s^{-1}) to generate the output-voltage frequency close to 50 Hz. Due to these initial conditions a transient process has appeared at the beginning of each simulation experiment (see responses in the next parts). The engine torque T_e increased to the value of approx. 20 Nm and than it decreased to the value of approx. 2 Nm, corresponding to the no-load operation of the generating aggregate. The generator started to excite spontaneously due to initial charges in the bank of exciting condensers, i.e. magnetizing current I_{magn}, output phase voltages U_i and generator torque T_g continuously increased.

3.1. No-load and resistive-load operation

The no-load operation of the generating aggregate was characterized by output phase voltages of 230 V, phase currents of 6,5 A and magnetizing current of 9,6 A.. Engine torque T_e and generator torque T_g were in balance at 2 Nm, the generating aggregate speed was close to 3050 r.p.m.

When the symmetrical resistive load in Y-connection was connected to the running generating aggregate, the generator torque T_g jumped to a new higher value and engine torque T_e increased aperiodically to a new value balanced with torque T_g in accordance with dynamic properties of the driving engine (Fig. 4). The output phase voltages decreased through approx. 12 %. It was caused by smaller value of the magnetizing current I_{magn} (Fig. 5). The output voltage frequency was slightly less than 50 Hz due to the generating-aggregate speed drop.

If the same resistive loads per phase were connected to the generator in a selected time sequence, the induction generator would "produce" an oscillating electromagnetic torque T_g (Fig. 6). The frequency of those oscillations was the second multiple of the generated voltage frequency, i.e. approx. 100 Hz. Similar oscillations were visible at the response of magnetizing current I_{magn} (Fig. 7). After the last resistor of the load had been connected to the generator the oscillations disappeared.

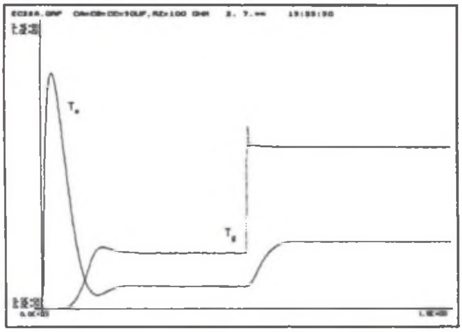

Fig. 4. Symmetrical resistive load - torques responses

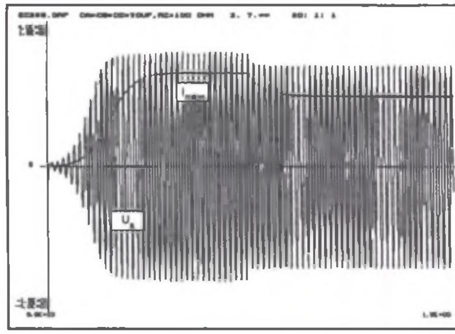

Fig. 5. Symmetrical resistive load - phase voltage and magnetizing current responses

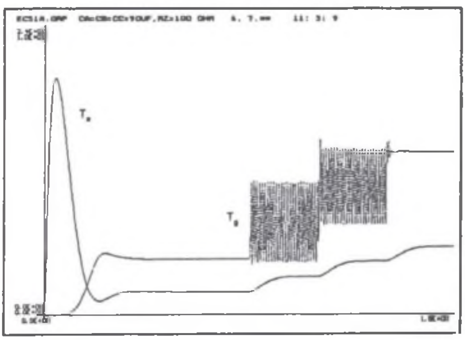

Fig. 6. Symmetrical load switched-on in sequence – torques responses

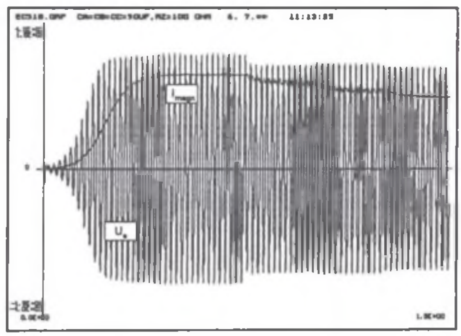

Fig. 7. Symmetrical load switched-on in sequence – phase voltage and magnetizing current responses

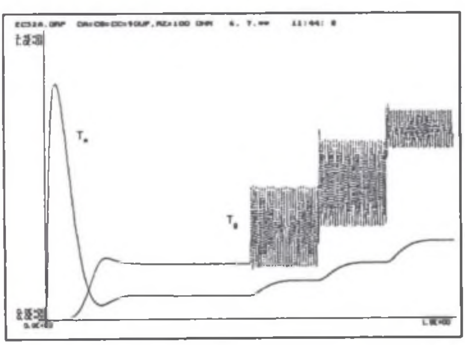

Fig. 8. Unsymmetrical load switched-on in sequence – torques responses

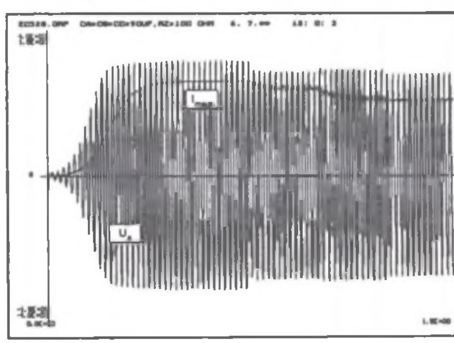

Fig. 9. Unsymmetrical load switched-on in sequence – phase voltage and magnetizing current responses

The connection of an unsymmetrical resistive load (different resistors in individual branches) to the induction generator in the same time sequence was simulated, too. In this case the oscillations of both the torque T_g and the current I_{magn} never disappeared (Figs. 8 and 9).

Nevertheless the waveforms of all generated phase voltages and currents remained sinusoidal, as it is visible on shapes of current-to-voltage trajectories in Figs. 10 and 11.

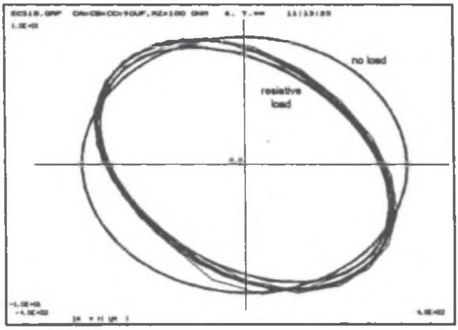

Fig. 10. Unsymmetrical resistive load - current-to-voltage trajectory of phase *a*

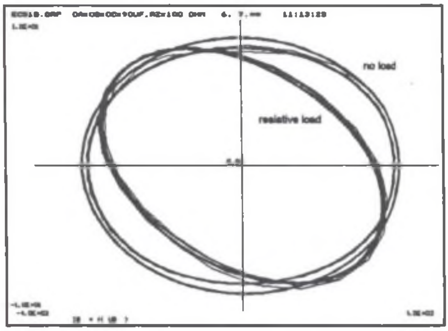

Fig. 11. Unsymmetrical resistive load - current-to-voltage trajectory of phase *b*

3.2. Loading with rectifiers

In order to understand better an interaction between the self-excited induction generator and non-linear loads, the operation of the generating aggregate under rectifying load was simulated. Models of two three-phase diode rectifiers were applied:

a) half-wave rectifier and

b) full-wave rectifier.

Each of them was loaded by a linear RL-circuit without counter-voltage.

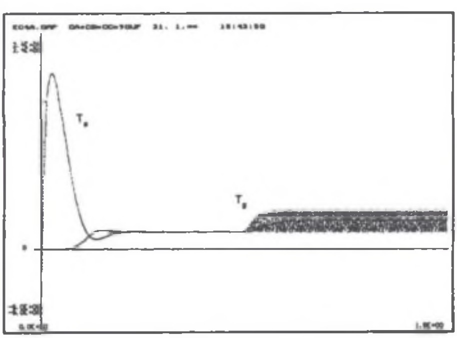

Fig. 12. Half-wave rectifier - torques

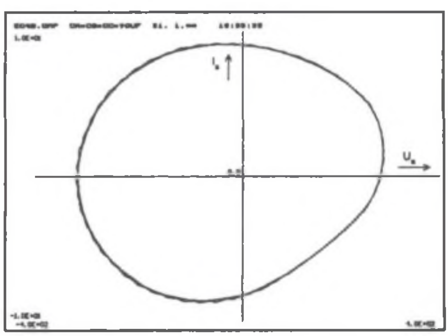

Fig. 13. Half - wave rectifier – current – to - voltage trajectory

The simulated responses of both torques T_g and T_e for the case of the half-wave rectifier are shown in Fig. 12. It is visible that the generator torque T_g oscillated with a high intensity at a frequency of the third multiple of the generated-voltage frequency. The generator output phase voltages were sinusoidal, while the waveforms of the phase currents were distorted, as it is clear from the current-to-voltage trajectory in Fig. 13.

In the case of a full-wave rectifier the oscillations of generator torque T_g were not so intensive and distortions of the phase currents were practically negligible (Figs. 14 and 15).

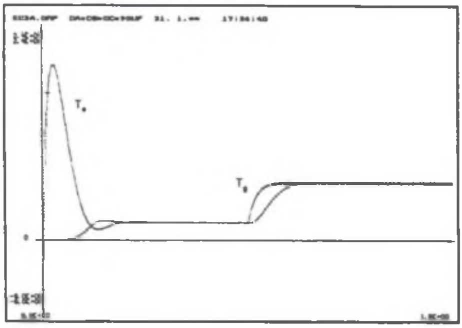

Fig. 14. Full-wave rectifier - torques responses

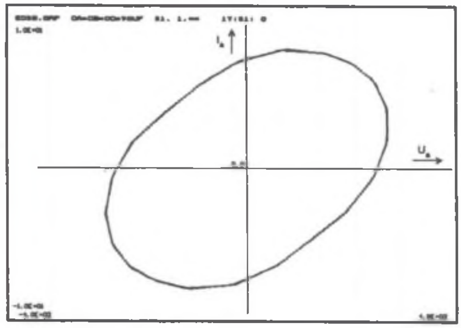

Fig. 15. Full-wave rectifier - current-to-voltage trajectory

3.3. Short-termed single-phase short circuit

One of possible, but not required, operation states of the generating aggregates is a single-phase short circuit between one phase terminal and the neutral terminal of the induction generator. This short circuit may be either short-termed (of the order of units or tens of milliseconds) or long-termed (of the order of hundreds of milliseconds and longer). The aim of the simulation of this case of operation was to analyse the ability of the generator to re-excite itself.

The simulated responses of both torques T_g and T_e are in Fig. 16 for the case, when the duration of the short circuit was 10 ms, only. At the beginning, generator torque T_g increased intensively to a relatively high value and then it decreased to zero followed by oscillations. Engine torque response T_e was done by the dynamics of the engine speed-dependent feedback loop.

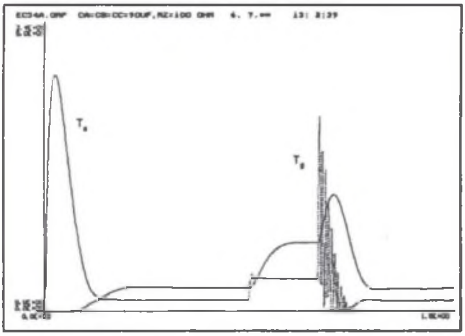

Fig. 16. Short-termed short circuit - torques

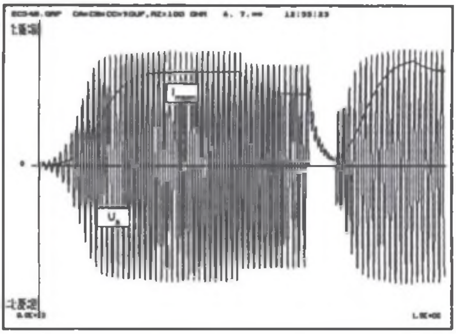

Fig. 17. Short - termed short circuit – shorted - phase voltage

Voltage U_a of the short-circuited phase terminal cut down to zero and magnetizing current I_{magn} decreased to zero in the same time interval (Fig. 17). The rate of that decreasment depends on an equivalent electromagnetic time constant of the stator circuit of the induction generator.

Short-circuit current I_a of the short-circuited phase a intensively increased to the tens multiple of the steady-state value and then it decreased (Fig. 18).

Phase voltages U_b and U_c considerably decreased at the same time interval due to the reduction of magnetizing current I_{magn}.

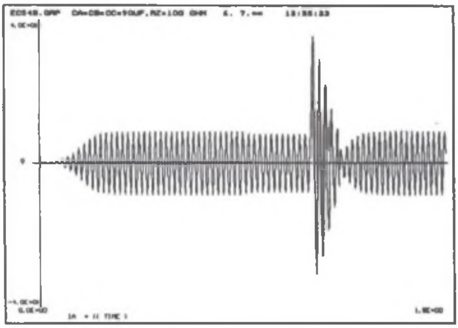

Fig. 18. Short-termed short circuit - shorted-phase current

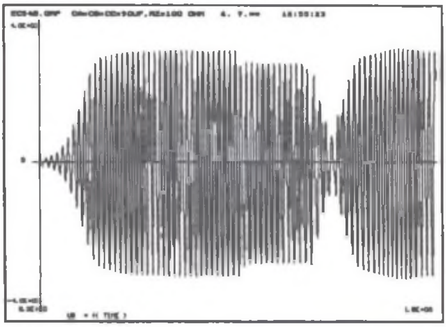

Fig. 19. Shor t-termed short circuit - no-shorted phase voltage

If duration of the single-phase short circuit is too long, magnetizing current I_{magn} would decrease to zero, because all exciting condensers loss seccesively charges and the induction generator would not re-excite itself.

4. CONCLUSIONS

Dynamic simulations of the speed-controlled generating aggregate with the self-excited induction generator in the autonomous mode of operation were performed to understand better generator properties under various kinds of loads. On the basis of those simulations it is possible to draw the following conclusions:

a) When a three-phase symmetrical resistive load is suddenly connected to generator terminals, the generated voltages apparently drop;

b) When identical resistive phase loads are connected to generator phase terminals in time sequence, the magnetizing current and the generator torque oscillate until the last load is not switched on;

c) When the three-phase load is unsymmetrical, the magnetizing current and the generator torque oscillate continuously. In the case of a three-phase half-wave rectifier these oscillations are more intensive in comparison with those in the case of a three-phase full-wave rectifier;

d) When one phase terminal of the generator is short-circuited to the neutral terminal, the corresponding phase voltage cuts down to zero, while amplitudes of the remaining phase voltages return substantial drops due to the de-excitation of the induction generator. If the duration of the short circuit is not too long, the generator can built up the output voltages again (it can re-excite itself).

In conclusion, the realized simulations make it possible to obtain very detailed and valuable knowledge about performance of the generating aggregate in operating conditions close to the real ones.

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