Experimental Investigation of Grid-connected Induction Generator's Behavior during Reconnection Transients

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Abstract – **This paper presents experimental results obtained by recording transient regimes of three-phase grid-connected induction generator. Transients that were considered in these experiments are induction generator's disconnection from the electrical grid and its reconnection. The induction generator, with the rated power of 2.2 kW was investigated by two experiments with the similar procedure, during which it was in two different steady operating points, i.e. generator delivered two different values of active electrical power to the grid. In both experiments Y-connected capacitor bank with the capacitance $C = 30\mu F$ was directly connected in parallel to the generator with the goal to reduce reactive power, taken from the electrical grid. In both situations, generator's disconnection from the grid was followed by its self-excitation, as a consequence of the mentioned capacitor bank's existing. In both experiments this state lasted a few seconds and thereafter the generator was reconnected to the grid. Obtained results showed generator's electrical parameters behavior during described transients.**

Keywords – **Experiments, Induction generator, Transient regimes, Disconnection, Reconnection**

I. Introduction

In the past, during the long history of their usage, induction machines were operating most often as electrical motors. Energy crises and introduction of renewable sources have caused more frequent use of induction machines as generators, especially for utilization of water's and wind's energy potential [1-2]. Generator's mode of induction machine occurs when the rotor is spinning by another driving machine in the direction of the magnetic field's rotation at the speed higher than synchronous [3]. Two types of induction generators are available: "grid-connected" and "self-excited". Grid-connected induction generators are connected to the electrical energy system (EES) producing active electrical energy and delivering it to the EES. At the same time, grid-connected induction generators take from the EES a certain amount of reactive energy that is used for their excitation [4-5]. Self-excited induction generators are usually used at some specific locations with the energy potential, where generator's connection to the EES is not possible. At these locations their autonomous operation is possible under special conditions [6] (cheap solution for voltage and frequency regulation still does not exist and in this manner generated active energy should be used just for thermal consumers).

In this paper grid-connected induction generator was considered. Since it is connected to the electrical energy system, this type of generator operates at the voltage and frequency of the EES [7]. There are a lot of situations when capacitor batteries are connected in parallel to the generator in order to compensate a certain amount of reactive electrical energy taken from the electrical grid. As the demanded, by the generator, reactive power varies continuously and the capacitor batteries may be changed stepwise in order to avoid unwanted higher excitation of the generator, resulting in high voltage [4].

One of the most interesting aspects for science research in the area of induction generators is certainly its behaviour during different types of transient regimes. The main objective of the work presented in this paper is to investigate changes of induction generator's electrical parameters during its disconnection and reconnection transients. Electrical parameters that were analyzed, based on the presented experiments, are voltages, currents and frequency.

II. Theoretical Background

Generally, transient regimes could be very dangerous for both electrical machine's parts – electrical and mechanical. Transients that are the subject of this paper happen during generator's disconnection from the electrical supply and thereafter during its reconnection. Grid-connected induction generator operates at the voltage and frequency of electrical system. It delivers a certain amount of active electrical power to the grid, but it takes reactive power from the electrical system which is used for its excitation. Capacitor bank is connected in parallel with the generator and reactive power consumption is reduced. Generator could operate in different steady state points, depending of its load. In the moment of generator's disconnection from the system, it continues with its operation, but his excitation is now caused by capacitor bank. Really dangerous situation could happen, if the capacitor bank is with the higher capacitance than is recommended. Higher value of capacitance causes higher excitation's current that leads to a really high value of machine stator's voltage. Meanwhile, with the increasing of generator's voltage, frequency is increasing, as well. Rotor's speed is in dependence of the frequency and its value is also higher. Controlling of rotor's speed is here really important,

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because if the rotor's speed continues with increasing, mechanical equipment failures can be caused. Values of stator's currents in the moment of disconnection are lower, but with the higher voltage caused by capacitor's excitation, these values increase again. This mode of generator's operation could last a few second and it could lead to stationary state operation, if the machine could hold voltage and rotor's speed increase. All things considered, the induction generator during this period is operating as "self-excited".

Other group of transients considered in this paper are induction generator's reconnection transients. In the moment of generator's reconnection, voltage and frequency decrease to the electrical grid's values. The induction generator is "grid-connected" again. Problems that can appear in the moment of generator's reconnection can be caused by the higher values of stator's currents. These transient currents could be several times higher than the stator's currents rated values. Higher values of stator's currents are followed by higher values of Joule's heating losses that can cause stator's windings failures.

Generally, it is really important to be very careful about described transients in order to avoid generator's electrical and mechanical damages. One of factors that can have a great impact to the generator's behaviour during described transients is the capacitance of capacitor bank, connected to the electrical grid. This impact has already been explained – high values of the capacitance can cause higher excitation and stator's voltage. Another factor that can also have a great impact is the value of active power that generator delivers to the electrical grid .Experiments described in the next chapter were performed with two different values of active power and results obtained by them explain theirs impact to the generator's behaviour during described transients.

III. Description of Experiments

Experiments whose results are presented in the paper were performed using equipment connected as shown in Fig. 1.

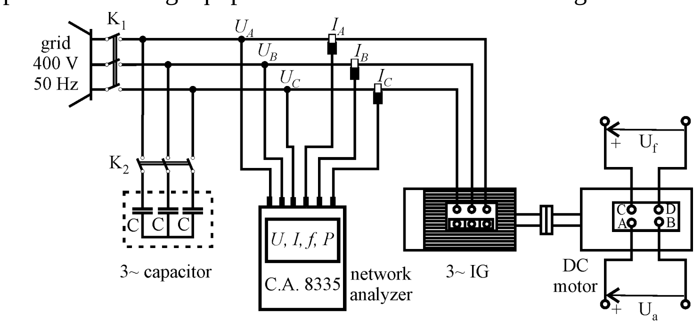

Fig. 1. Connection diagram and equipment used for experiments

An induction machine with cage rotor was used as a grid-connected induction generator. The machine's nameplate data (given for motoring mode of operation) are: $U_n = 380V$, $f_n = 50\,Hz$, $I_n = 4.9\,A$, $P_n = 2.2\,kW$, $\cos\varphi_n = 0.86$, $n_n = 2825\,\text{min}^{-1}$, Y-connected stator.

Generator's rotor was driven by separately excited DC motor, whose excitation current I_f was set to the rated value, while the mechanical power delivered to the generator was controlled by the applied armature voltage U_a.

At the beginning of the first experiment, both contactors K_1 and K_2 were opened, while armature voltage of the used DC motor has been set to the value that resulted with almost synchronous rotation of the system ($n_0 \approx 3000\,\text{min}^{-1}$). After that, contactor K_1 was closed and induction generator was connected to the electric grid, operating at no-load regime and consuming reactive power only. By closing the contactor K_2, symmetrical, Y-connected capacitor bank with capacitance $C = 30\,\mu F$ per phase was directly connected in parallel to the generator, in order to mitigate consumption of reactive power. Note that the contactor K_2 remained closed during the rest part of the experiment. By increasing the value of armature voltage U_a, mechanical power on the generator's shaft was increased, and the generator reached steady operating point characterized by active power $P_{G1} = 1430W$ delivered to the grid. After that, contactor K_1 was opened, and closed again after a short period of time. This action had caused transient behavior whose nature has been the subject of this investigation. Relevant electrical parameters were registered using portable network analyzer C.A. 8335b, with capability of recording complete voltage and current waveforms.

The second experiment had the same procedure, with only difference that before opening and reclosing of contactor K_1, induction generator was in steady operating point characterized by greater value of delivered active power, $P_{G2} = 1720W$.

IV. Results and Discussion

Diagrams of relevant electrical parameters recorded by portable network analyzer during described experiments are presented in following figures.

In Fig 2. and Fig. 3 changes of stator's line voltage U_{AB} are shown for the first and second experiments, respectively. From Fig. 2. it can be noticed that before generator's disconnection, generator's stator voltage U_{AB} was equal to the grid's voltage. From the moment of its disconnect, voltage started to grow and after about 1.7 seconds it achieved the peak value $U_{AB}=720\ V$, which is a direct consequence of generator's self-excitation, caused by parallel connected capacitor bank $C = 30\,\mu F$ .Voltage increase settled approximately this value and a new steady state was reached. Generator continued to operate with this value of U_{AB} for 0.8 seconds more and it was reconnected to the grid. In the moment of generator's reconnection, voltage U_{AB} was again equal to the grid's voltage. Generally, during the first experiment induction generator was delivering $P_{G1}=1430\ W$ to the grid and while it was working as self-excited for about 2.5

seconds, it achieved peak value of stator's line voltage $U_{AB}=720\ V$ and reached new steady state of its operation.

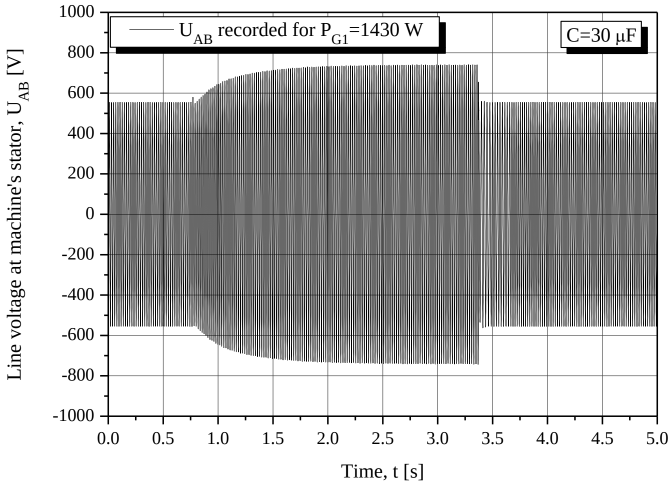

Fig. 2. Diagram of line voltage U_{AB} at generator's stator for $P_{G1}=1430\ W$

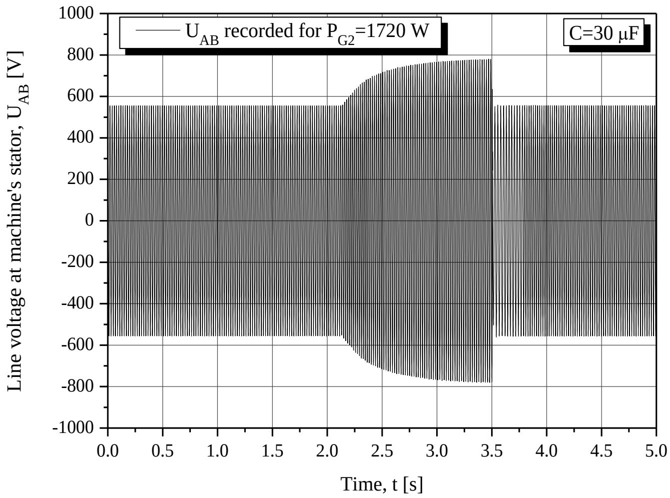

Fig. 3. Diagram of line voltage U_{AB} at generator's stator for $P_{G2}=1720\ W$

In Fig. 3. diagram of stator's line voltage U_{AB} that induction generator had during the second experiment is presented and differences between the U_{AB} during the first experiment can be observed. In the beginning, the situation is the same – line voltage at generator's stator is equal to the grid's voltage. The generator was in steady operation point characterized by almost 30 % greater value of delivered active power than in the first experiment, $P_{G2}=1720W$. In the moment of its disconnection, voltage started to increase and after a while it achieved the peak value $U_{AB}=790\ V$, which is 10 % higher value than in the first experiment. The difference between these two experiments is also in the lasting of generator's operation as self-excited and for the second experiment in this mode generator was working for about 1.4 seconds and then it was reconnected, when stator's line voltage U_{AB} was again equal to the grid's voltage. In the second experiment induction generator didn't reach new steady state as self-excited, because it was dangerous for it to operate longer with this value of voltage taking into the account the fact that the frequency and rotor's speed were also higher.

In Fig 4. comparative diagrams of machine's frequencies are shown for two described experiments. In both situations before the disconnection frequencies at induction generator's stator were equal to the electrical grid frequency ($f=50Hz$). For both experiments in the moment of generator's disconnection frequency started to increase and in the first experiment it achieved the value of $f=64.5Hz$. In the second experiment frequency reached the value $f=67Hz$, with the possibility of continuation of its increasing in the case of longer period of generator's operation as self-excited. Approximately, steady state of generator's operation could be reach for the frequency of $f=68Hz$. Unfortunately, it wasn't safe for generator's equipment to achieve this steady state, because the frequency's rise was following with the rotor's speed increasing and rotor's overspeed could lead to mechanical damage. In general, for less than 30 % higher value of active power delivered to the grid during the disconnection transients, frequency can reach 5 % higher value. In both experiments after generator's reconnection induction generator stator's frequency again reached the value of grid's frequency.

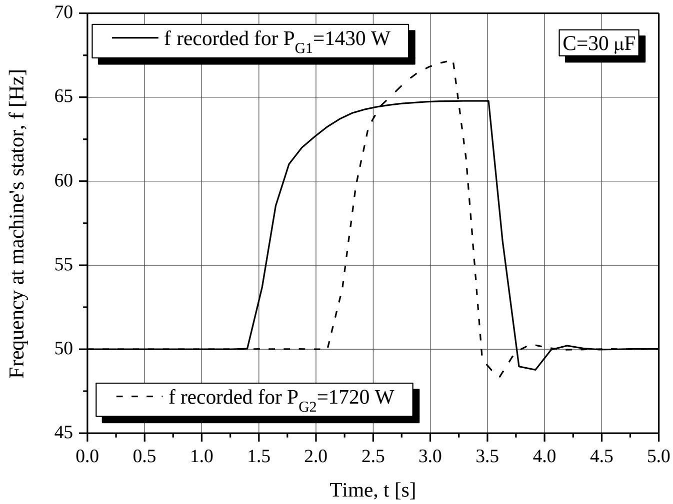

Fig. 4. Comparative diagrams of frequencies at generator's stator for $P_{G1}=1430\ W$ and $P_{G2}=1720\ W$

Finally, in Fig. 5 and Fig. 6. changes of stator's phase current I_C are shown for the first and second experiments, respectively. This phase current is chosen, because it was useful to show what happened with the phase, which wasn't considered by line voltage U_{AB}. For both experiments in the moment of generator's disconnection the value of stator's phase current started to decrease, but after a while with the increase of stator's voltages it stopped with decreasing and started to rise. During the generator's self-excited operation, stator's phase currents didn't reach values that they had before the disconnection.

The situation that is more interesting, when currents are considered, is in the moment of generator's reconnection. In that moment transient currents at generator's stator can be few times higher than their rated values.

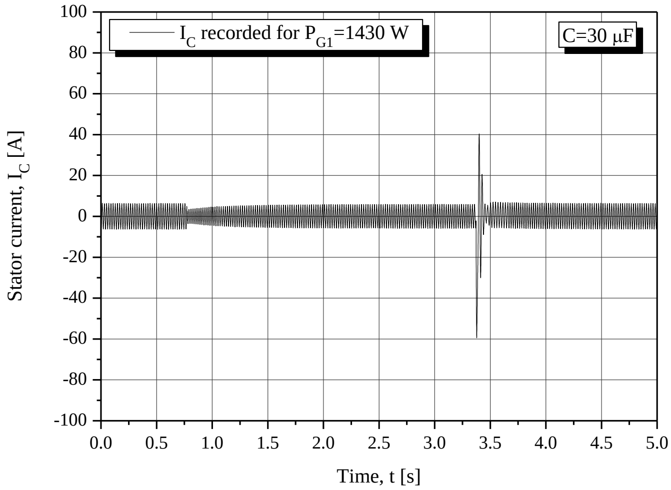

Fig. 5. Diagram of phase current I_C at generator's stator for $P_{G1}=1430W$

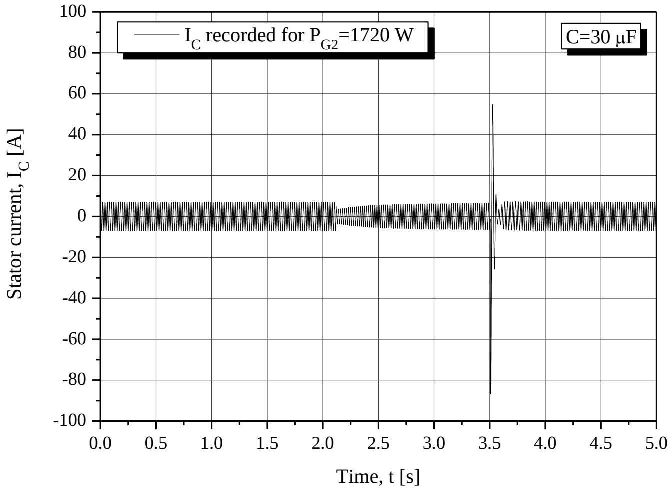

Fig. 6. Diagram of phase current I_C at generator's stator for $P_{G2}=1720W$

In Fig. 5. it can be noticed that the signal of phase current I_C in the moment of generator's reconnection reached *40 A* in positive part of diagram and *-60 A* in its negative part. The current's signal value in negative part is higher because of the existing of aperiodic component of transient current.

In Fig. 6. changes of phase currents I_C during the second experiment are presented. The situation is similar to the first experiment with the different values that current's signal reached in the moment of generator's reconnection: *55 A* in positive and *-85 A* in the negative part of the diagram. Therefore, if the positive part of current's signal is considered (influence of aperiodic component is not taken into the account) it can be seen that the peak current I_C is almost eight times higher than the peak value of generator's rated current. In general, for less than 30 % higher value of delivered active power, peak current during generator's reconnection transient regime can reach almost 40% higher values. Those high currents can be really dangerous, because they can produce high values of Joule's heating losses that can cause generator's windings damage.

V. Conclusion

Grid-connected generator's behaviour during its disconnection and reconnection transients for two different values of active power delivered to the electrical system was presented in this paper. It was shown that increasing of less than 30 % of active power that induction generator delivers to the grid can cause significant differences in diagrams of specified electrical parameters presented in previous chapter. Changes of considered electrical parameters during generator's operation as self-excited were shown and described.

Disconnection and reconnection transients were considered for only two values of electrical power that generator delivers to the grid. Future investigation in this area can include induction generator's behaviour recorded for a larger range of those values. Differences between changes of electrical parameters for that research will also be analyzed.

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