A STUDY OF THE OUT-OF-PHASE CONNECTION OF DISTRIBUTED GENERATORS

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ABSTRACT

Distributed generation (DG) systems are increasingly acquiring relevance due to energy requirements and the use of renewable energy sources. The DG application – operating as an island – is mainly advantageous from the reliability viewpoint. The main disadvantage is the out-of-phase reconnection which could take place when reclosers or circuit breakers are used. The present situation of DG connected to distribution systems changes the concept that the interconnection must be done at a very precise phase matching. The impedance of the elements located between system generators and the DG controls and attenuates the overcurrents, thus the acceptable out-of-phase limits must be updated to the new situation. An exhaustive experimental study has been conducted where the out-of-phase connection for both synchronous as induction generators was analyzed. Experimental results were confirmed by simulation tools. In the case of full out-of-phase connection of synchronous or induction generator, the maximum current values are approximately twice those obtained when the terminals are short-circuited. The current behavior varies according to whether the out-of-phase connection takes place shortly either before or after the phase opposition. It is recommended to adopt an average maximum of reconnection current a value of 160% of the short-circuit current. For the induction generator the limits are met for voltage phase between –30º and +40º, while for the synchronous generator the phase angles were –45º and +60º. For such phase tolerances the specific energy is very low. The phase tolerance clearly shows that the DG synchronization can be carried out with larger phase discrepancies than for the traditional high-power systems. This study needs to be extended to include the allowed voltage magnitude and frequency differences for DG safe synchronization.

INTRODUCTION

Distributed generation (DG) is presently used to increase reliability and reduce (or defer) system investments. Besides, DG systems are increasingly acquiring more relevance than conventional methods due to energy requirements and the use of renewable energy sources. The DG application – operating as an island – offers several advantages from the reliability viewpoint mainly for industrial customers. Also, the islanding operation is convenient from the economical point of view in reducing the production losses in case of blackouts [1]. The main disadvantage of DG is the much feared out-of-phase reconnection which could take place when reclosers or circuit breakers are used upstream the distribution system. The present situation of DG connected to the distribution system changes the concept that the interconnection of distribution system/DG must be done at a very precise phase matching. The impedance of the elements located between system generators and the DG plus their own internal impedances controls and attenuates the overcurrent due to phase differences, thus the acceptable out-of-phase limits must be updated to the new situation [2].

Tolerances for the synchronization of DG are given by several standards [3]. There are several cases of DG application that considerable benefit can be reached if the synchronization is given within a wider tolerance range [4]. Out-of-phase synchronization creates undesirable consequences from both mechanical and electrical viewpoints due to the stresses that can exceed the withstand values of both system and machines and lead to equipment damage. Therefore, it is necessary to determine the relationship between widening synchronization tolerances and stresses increase. The present work is aimed at studying of electrical consequences (electromechanical and thermal stresses) of the out-of-phase synchronization. The stresses under study are caused by over-currents that occur during out-of-phase synchronization and will be compared with the corresponding three-phase terminal short-circuit currents, which is adopted as a reference stress. As the system and generator were designed with the short-circuit stresses in mind, it would be able to withstand the stresses caused by the phenomenon under study, provided that certain limits would not be exceeded.

METHODOLOGY

Experiments have been conducted in a teaching laboratory (machines rated powers between 4 and 15 kW) where the out-of-phase connection for both synchronous (salient-pole rotor) and induction generators (wound rotor) was analyzed. Firstly, the short-circuit currents for both machines were determined. Due to the limitations of induction generator excitation, both machines were not directly interconnected to the laboratory supply but through a three-phase transformer in order to increase the voltage to 3 x 380 V which is the normal laboratory supply. The generator short-circuit currents were determined with the transformer connected in the test circuit [5]. The short-circuit current peak values for synchronous and induction generators – based on rated current – were 12 pu and 1.2 pu, respectively. The experimental setups are shown in Figure 1 and 2. The plots of short-circuit currents for both machines are shown in Figures 3 and 4.

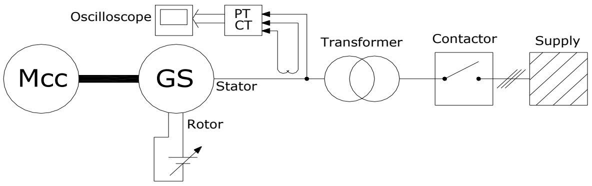

Figure 1. Test circuit for synchronous generator studies.

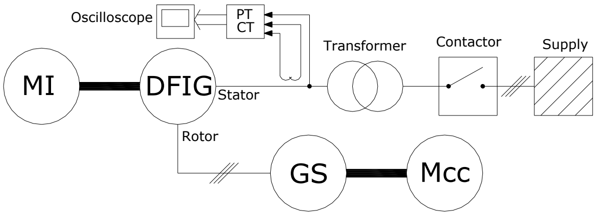

Figure 2. Test circuit for induction generator studies.

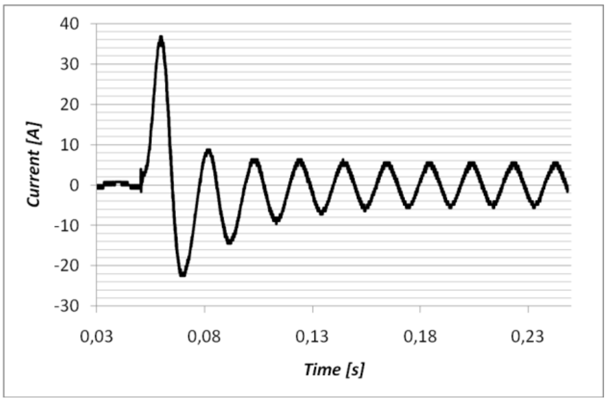

Figure 3. Synchronous generator short-circuit current at transformer terminals.

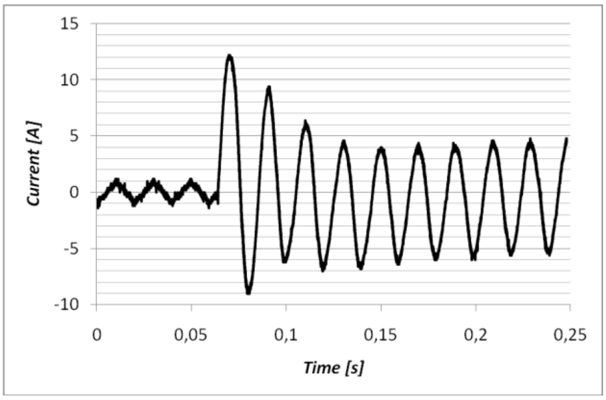

Figure 4. Induction generator short-circuit current at transformer terminals.

An exhaustive experimental study has been carried out on both generators where the synchronizing over-currents were analyzed. Experiments were supplemented by simulation using MATLAB/SIMULINK and the results were in good agreement with the experimental outcomes. More than one hundred tests were conducted and validated by simulations.

RESULTS

Figures 5 and 6 show currents recorded for a synchronous generator when reconnected out-of-phase. In the first case the reconnection take please past the full-phase opposition, and in Figure 4 the reconnection take please before the full-phase opposition.

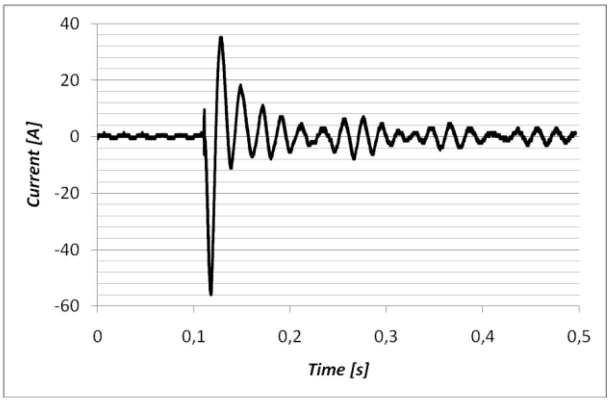

Figure 5. Current during the reconnection process after full-phase opposition.

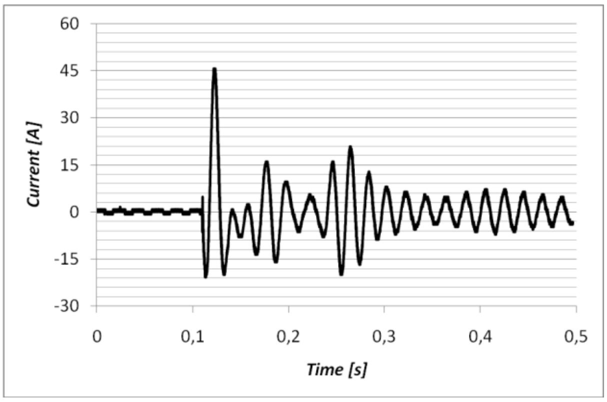

Figure 6. Current during the reconnection process before full-phase opposition.

Similarly, Figures 7 and 8 show the voltage and current recorded for an induction generator when reconnected out-of-phase after reaching the full-phase opposition.

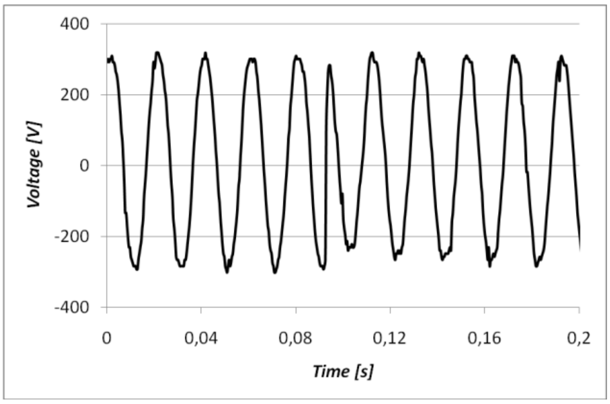

Figure 7. Voltage during the reconnection process.

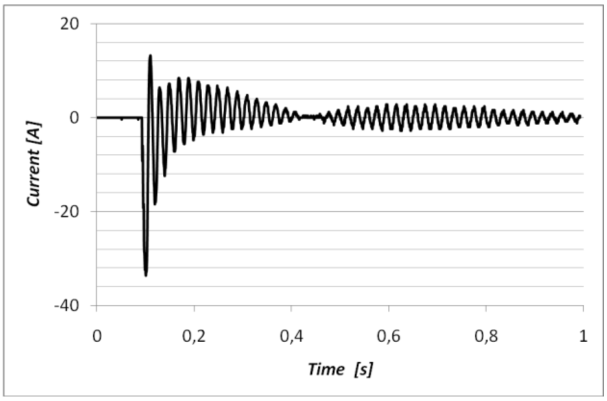

Figure 8. Current during the reconnection process.

As mentioned above, the electromechanical stress – due to out-of-phase synchronization – was evaluated as a function of the stress that corresponds to the terminals short-circuit currents. Figures 9 and 10 show the ratio “synchronizing current to short-circuit current” for synchronous and induction generators and phase angles changing from + 180º to – 180º.

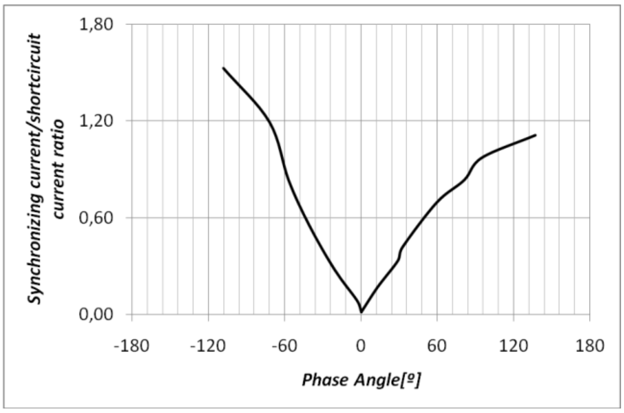

Figure 9. Synchronizing current/short-circuit current ratio for synchronous generator.

Figure 10. Synchronizing current/short-circuit current ratio for induction generators.

From the above two figures it can be seen that the stresses in the case of induction generator are higher than those for synchronous generator, for the same phase angle. The electromechanical stresses, as a function of the squared peak current, are 1.3 and 4.1 times the short-circuit values for synchronous and induction generators, respectively.

In order to study the machine thermal stress, specific energy was adopted as an indication of the windings heating by comparing it with the I^2t of the short-circuit current for two time instants, 20 ms and 100 ms. The time instants were selected based on short-circuit and out-of-phase connection currents wave shapes. Figure 11 shows the results where the curves are smoother than those corresponding to the peak current values due to the integral calculation done for the specific energy evaluation. It can be noticed that the thermal stress due to the induction generator out-of-phase synchronization can reach six times the value corresponding to the short-circuit stress, while for the synchronous generator the thermal stress can reach only twice the short-circuit value.

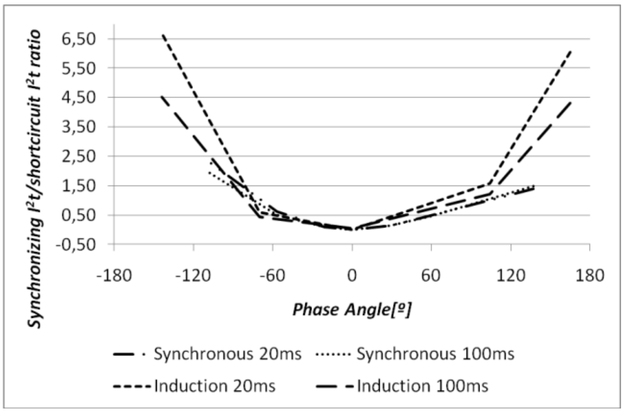

Figure 11. Synchronizing/short-circuit specific energy ratio for 20 ms and 100 ms.

Due to space limitations, only one of the current oscillograms obtained by simulation – corresponding to the parameters of Figure 5 – is included. Figure 12 shows the simulated synchronous generator current at reconnection after full-phase opposition.

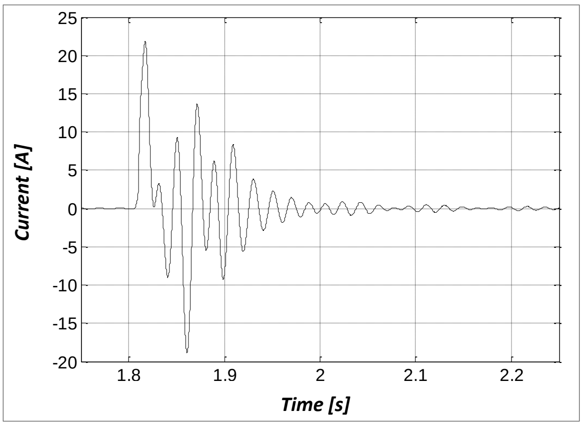

Figure 12. Simulated synchronous generator current at reconnection after full-phase opposition.

CONCLUSIONS

Based on the current magnitudes – measured and simulated – it is preliminarily concluded that free reconnection of DG to distribution systems can seriously affect both the prime mover and generator as well as other equipment connected between them. Therefore, it is recommended to take an average maximum of reconnection current in the order of 60% of the short-circuit value.

For the case of induction generator the reconnection current was given for voltage phase between –30º and +40º without exceeding the mentioned limit. For the synchronous generator the phase angles were included between –45º +60º. For such phase tolerances the specific energy is very low, thus it is only necessary to take the electromechanical stresses into account. This phase tolerance shows that DG synchronization can be carried out with larger phase discrepancies than for the case of traditional high-power systems. The present study requires to be extended for the case when operating near the machine rated values. It is also necessary in the extended study to cover the allowed voltage magnitude and frequency differences for DG safe synchronization.

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