**Analysis of earth faults in a wind farm integrated into the electric power system**

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**Abstract.** The aim of this paper is to investigate the processes of earth faults occurrence in a wind farm network, integrated into the electric power system. The wind power farm is realized with squirrel-cage induction generators (SCIG). Each generator has a 0.69/21kV step-up transformer. The connection of the wind power farm to the electric power system is implemented through a step-up substation with a single 21/115kV transformer. The star center of the transformer 21kV winding is grounded by means of a 40 ohm resistor. A synthesized in MatLab/Simulink computer model investigates the processes of earth faults occurrence in the medium-voltage (MV) network of the wind farm. Results have been obtained, concerning the influence of the earth fault location on the transient voltages and currents at both rated torque of the generators and no-operating generators. When there is an earth fault in one of the lines, the voltages and currents of the MV network are asymmetrical and higher harmonics of the currents and voltages are generated. A harmonic analysis of the current and voltage results has been made and the total harmonic distortion (THD) has been determined for several characteristic points of the wind farm network. The parameters of voltage contamination of the power system with higher harmonics in case of an earth fault occurrence in the wind power substation have been determined. It has been found that the earth faults in the MV network of the wind farm generate voltages and currents contamination of the power system with higher harmonics.

1. **Introduction**

Wind farms are one of the main renewable sources of electricity. The trends in the development of the modern energy systems include an increase in the relative share of electricity produced by wind power farms, as well as increase in their capacity. Wind farms usually work integrated into the region's electricity system. Changes in wind speed and direction over time are largely random, which affects the joint operation of the wind farm and the power system [1]. The wind farms integrated into power systems mainly use squirrel-cage induction generators (SCIG) and doubly-fed induction generators (DFIG). It is known that when taking into account the fluctuation of the parameters of the wind energy these generators have certain advantages if operating in parallel with the electricity system [2]. The reactive power required to excite the magnetic field of the wind farm generators is provided by the synchronous generators in the system or by capacitor banks. The wind farms can consist of a large number of generators (tens, hundreds). There is usually a low-voltage/medium-voltage (LV/MV)
step-up transformer for each generator. Several generators form a group and connect to each other through a main feed cable line. The individual groups are connected by radial lines to a substation that increases the voltage in accordance with the voltage of the electric power system.

The processes in the wind farms are different from those in the traditional power plants with large synchronous generators. The wind farms exert a specific influence on the parameters of the electricity system to which they are connected. This applies both to normal operation and to emergency modes (three-phase and two-phase short circuits, and earth faults). A thorough study of the impact of these processes on the quality of electricity in the electric power systems is of great importance. The wind farms are characterized by a mixed radial-magistral network and presence of elements with nonlinear characteristics (transformers, generators, etc.). Therefore the mathematical models for describing the emergency mode processes in a wind farm integrated into the power system are rather complex [3], [4].

A computer model in MatLab/Simulink, described in [3], examines the normal mode operation processes, as well as the processes in case of a three-phase short-circuit occurrence and in case of a two-phase short-circuit occurrence. In [4], based on a simplified model, presenting the wind farm through an equivalent generator, studies of the effect of both the transformer parameters and the type of generators on the currents at short-circuits and earth faults have been carried out. It is known that the particular method of neutral grounding has a significant influence on the voltages and currents in case of an earth fault in the substation of the MV wind farm. The effect of the different methods of grounding the neutral (on the currents and voltages in case of an earth fault in the MV substation of the wind farm) has been analyzed in [5]. A resistance grounded system is recommended as a compromise option. The studies in [3], [5] show that higher harmonics of voltage and current are generated in the wind farm network in case of earth fault occurrence in it.

The aim of this paper is to study the effect of the earth faults in a wind farm on the voltages and currents of the electric power network. The wind farm under consideration is integrated into the electric power system. The studies have been performed by simulating earth faults by means of an especially designed in MatLab/Simulink computer model.

2. Description of the studied wind farm

The single-line diagram of the wind power farm under study is given in Figure 1. The farm contains eight identical SCIG generators with a step-up LV/MV transformer (0.69/21kV) to each of them. The generators form three groups, which are connected to the input of the medium-voltage/high-voltage (MV/HV) step-up transformer 21/115kV via main feed cable lines. The middle group contains only

![Figure 1. Single-line diagram of the wind power plant.](image-url)
one generator and the other terminals of the main feed are intended for future expansion of the wind farm. The star center of the 21kV winding is grounded by a 40 Ohm resistor. The output of the MV/HV transformer connects the wind farm to the electric power system via the W1 cable line in point 1. The MV network is realized by means of NA2XS(F)2Y cables, while the W1 line uses 2XS(FL)2Y cables. The electrical parameters of the cables, transformers and generators are given in Tables 1÷3.

### Table 1. Electrical parameters of the cables.

| Number and cross-section of the cable | Resistance (ohm/km) | Reactance (ohm/km) | Capacitance (µF/km) |
|--------------------------------------|---------------------|-------------------|---------------------|
| W1, 3x1x800 mm²                     | 0.037               | 0.302             | 0.474               |
| W2, W3, 2x3x1x400 mm²               | 0.078               | 0.312             | 0.341               |
| W4, W5, W11, 3x1x800 mm²            | 0.037               | 0.302             | 0.474               |
| W5, W6, W12, 3x1x630 mm²            | 0.055               | 0.299             | 0.402               |
| W8, W13, W14, 3x1x240 mm²           | 0.125               | 0.334             | 0.300               |
| W9, W10, W15, W16, 3x1x95 mm²       | 0.32                | 0.392             | 0.210               |

### Table 2. Electrical parameters of the transformers.

| Parameters | Units | Transformer LV/MV | Transformer MV/HV |
|------------|-------|-------------------|-------------------|
| Rated power | (MVA) | 2.6               | 63                |
| Primary voltage | (kV) | 0.69              | 21                |
| Secondary voltage | (kV) | 21                | 115               |
| Losses at no-load | (kW) | 3.9               | 24.4              |
| Losses at short circuit | (kW) | 14.4              | 192.9             |
| Relative current at no-load | (%) | 0.37              | 0.74              |
| Relative voltage at short circuit | (%) | 7                 | 12                |
| Connection Scheme | -     | D/yn-11           | Yn/yn-0           |

### Table 3. Electrical parameters of the generators.

| Parameters | Units | Values |
|------------|-------|--------|
| Type       | -     | SCIG   |
| Rated voltage | (V) | 690    |
| Rated frequency | (Hz) | 50     |
| Rated power | (MVA) | 2.6    |
| Rated torque | (N.m) | 14740  |
| Stator resistance | (mOhm) | 1.102  |
| Rotor resistance | (mOhm) | 1.497  |
| Leakage inductance of the stator | (mH) | 0.065  |
| Leakage inductance of the rotor | (mH) | 0.06   |
| Inductance of the magnetizing contour | (mH) | 2.14   |

### 3. Computer model

The computer model was synthesized in MatLab/Simulink based on the connection scheme in Figure 1 and the equivalent electric circuits of the generators, transformers and cables. The parameters of the equivalent circuits were determined in accordance with the electrical characteristics in Tables 1÷3. The impedance of the electric power system in the point where the wind farm connects to it was taken into account. The model makes it possible to simulate an earth fault and to determine the transient...
voltages and currents in predetermined points in the wind farm network. In the model the moment of the earth fault occurrence is set by the moment when the current passes through the zero value of the phase in which the earth fault occurs.

The studies were conducted for the following network characteristic points, as in Figure 1:
1) Point 1 – the point of connection of the wind farm to the grid;
2) Point 2 – the line terminals of the MV winding (21kV) of the MV/HV transformer (21/115kV);
3) Point 3 – the line terminals of the MV winding (21kV) of one LV/MV generator transformer (0.69/21kV), which is at the end of one of the main feed cable lines;
4) Point 4 – star center of the MV winding (21kV) of the MV/HV transformer (21/115kV).

The computer model simulated single-phase earth faults in points 2 and 3 of the network, as in Figure 1. The numerical experiments were performed for the cases when all generators operate at the rated shaft torque, on the one hand, and when the generators do not work and are disconnected from the generator transformers, on the other hand. Results about the transient voltages and currents in the described points were obtained at the moment of occurrence of the earth fault in the interval (0÷10) ms from the moment when the current passes through the zero value. Both the harmonic spectrum and the total harmonic distortion (THD%) of the voltages and currents in the indicated points were determined by post-processing of the results. The THD coefficients for voltage were determined by the following formulae:

\[
THD_U, \% = \frac{\sum_{i=2}^{n} U_i}{U_1} \times 100, \\
THD_I, \% = \frac{\sum_{i=2}^{n} I_i}{I_1} \times 100,
\]

where: \( n \) - total number of harmonics; \( U_1 (I_1) \) - r.m.s. value of the voltage (current) of the main harmonic; \( U_i (I_i) \) - r.m.s. value of the voltage (current) of the respective harmonic.

4. Results

Figure 2 shows the transient voltages for the case of generators, operating at their rated torque and a phase L1 earth fault in point 2. The moment of the earth fault occurrence is when the phase L1 current passes through the zero value.
Figure 2. Transient voltages in case of an earth fault in point 2 for the following points: a) point 1; b) point 2; c) point 3; d) point 4.

Figures 3÷5 give the results related to the harmonic spectrum and the THD coefficient for the voltages in points 1 and 2 at rated torque of the generators and phase L1 earth fault in point 2.

Figure 3. Change in THD, % during the transient process: a) in point 1 for phase L1 (in blue) and for phases L2 and L3 (in green); b) in point 2 for L2 and L3 (in green and red).

Figure 4. Frequency spectrum of the higher harmonics and THD, for one period of the phase L1 in point 1: a) in the beginning of the transient process; b) in a steady-state mode of an earth fault.
Figure 5. Frequency spectrum of the higher harmonics and THD for one period of the phase L2 in the beginning of the transient process in: a) point 1; b) point 2.

Figure 6 illustrates the transient processes of the currents in case of a phase L1 earth fault in point 2. The moment of the earth fault occurrence is when the phase L1 current passes through the zero value.

Figure 6. Transient currents in case of an earth fault in point 2 for: a) point 2 at rated torque of the generators; b) point 2 for no-operating generators; c) point 3 at rated torque of the generators; d) point 4 at rated torque of the generators.
When the generators operate, the current in point 1 is approximately proportional to the current in point 2. For no-operating generators the current in point 2 is zero. The currents in point 4 are the same for operating and turned off generators.

Figure 7 depicts the transient processes of the currents in case of a phase L1 earth fault in point 3. The moment of occurrence of the earth fault is when the phase L1 current passes through the zero value.

![Figure 7](image_url)

**Figure 7.** Transient currents in case of an earth fault in point 3 for: a) point 2 at rated torque of the generators; b) point 2 for turned off generators; c) point 3 at rated torque of the generators; d) point 3 for turned off generators.

5. **Conclusion**

The established r.m.s values of the currents in point 2 of the phases L2 and L3 in case of an earth fault in both point 2 and point 3 at rated torque of the generators are practically unchanged. The observed r.m.s. values of the phase voltages in point 2 of the phases L2 and L3 increase by about 70% for all studied cases of earth faults. This is explained by the method of star center grounding of a MV winding in a 21/115kV transformer through a resistor with an active resistance of 40 Ohm. In the case of no-operating generators, the current in point 2 is 38A (r.m.s.) and it is determined by the idle-run currents of the transformers. In this case, for an earth fault in point 2, the steady-state currents in the phases increase by about 50%.

In case of a single-phase earth fault both in points 2 and 3, network frequency voltage appears over the star center (point 4). Its steady-state value is 1.2kV (r.m.s.) at rated torque of the generators and does not depend on the location and the moment of the earth fault occurrence in the MV network. The current through the grounding resistor in steady state is 30A (r.m.s.). The peak values of voltage and
current through the neutral are obtained at the moment of the earth fault of about 6 ms. Higher harmonics in the star center are practically not generated.

In case of a single-phase earth fault, higher harmonics of the currents and voltages with odd and even numbers are generated in both points 2 and 3. The maximum contamination of the network with higher harmonics occurs in the beginning of the transient process when the moment of the earth fault coincides with the moment when the current passes through the zero value.

The earth faults in the MV network contaminate the voltage of the power system with higher harmonics in the point of the wind farm connection to the system.

In case of an earth fault after the transient process has completed, the contamination coefficients \( \text{THD}_U \) for all cases are up to 2%.

Table 4 gives the results, concerning the maximum coefficients of voltage contamination \( \text{THD}_U \) in points 1 and 2.

| Location of the earth fault and generator mode | Phase L1 in point 1 | Phases L2 and L3 in point 1 | Phases L2 and L3 in point 2 |
|-----------------------------------------------|---------------------|-----------------------------|-----------------------------|
| Point 2 – at rated torque of the generators    | 38                  | 19                          | 45                          |
| Point 2 – at no-operating generators          | 39                  | 20                          | 49                          |
| Point 3 – at rated torque of the generators    | 19                  | 10                          | 38                          |
| Point 3 – at no-operating generators          | 22                  | 11                          | 38                          |

**Acknowledgments**

The authors would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support. The work of I. Hadzhiev is supported by National program "Young scientists and Postdoctoral candidates" of Ministry of Education and Science.

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