POZNAN UNIVERSITY OF TECHNOLOGY ACADEMIC JOURNALS
No 98 Electrical Engineering 2019

DOI 10.21008/j.1897-0737.2019.98.0006

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MODELING TRANSIENTS IN MV RESONANTLY GROUNDED INDUSTRIAL GRID DURING SINGLE LINE TO GROUND FAULTS

Medium voltage distribution power grids mostly operate with ungrounded neutral points of transformer. The philosophy about these power supply systems based on the assumption that the electrical grid is more reliable. However the practice of operation showed that currents of single phase or multiple faults to ground depend mostly on the earth capacitances of cables connected to power grid and configuration and structure in relation to the main substation buses. Moreover, this kind of arcing ground faults on the ungrounded system causes transient overvoltages several times than nominal value. In the consequence, it may be dangerous for the electrical devices connected to the power system. The article focuses on the transient impact the equipment insulation due to faults in the middle voltage industrial grid with adjustable speed drives. The examination results of transient voltages across the system was presented. The Matlab/ Simulink Software was used to modeling system behavior during intermittent faults.

KEYWORDS: electrical grid, grounding methods, transients overvoltage, transient intermittent faults.

1. INTRODUCTION

Industrial plants use many types of grounding methods in medium-voltage (MV) distribution systems which depend on their type (consisting cable, overhead or both lines), operating conditions and structures. These grounding methods can be usually categorized into the following two groups [1, 2]:

A. Large-current grounding:
   - effective (solid) grounding,
   - low-impedance grounding.

B. Small-current grounding:
   - ungrounded or isolated neutral,
   - high-resistance grounded,
   - resonant grounded.

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Nowadays, there are two dominant grounding methods for medium-voltage distribution power grids: the multigrounded method (extensively used in North America) and the resonant-grounded and ungrounded methods (mainly used in Europe). Other grounding methods, such as high-resistance grounding, are more popular in industrial plants where service continuity is a main consideration to prevent costly process shutdowns.

The main objectives of system grounding include: minimizing equipment overvoltage and thermal stress, provide personnel safety, reduce interference to communications systems, assist quick detection and isolation of single-phase-to ground faults and maximize system economic returns. As the operating experience shows, in MV distribution systems single-line to ground faults are predominantly observed. The persistent single-phase-to-ground arcing faults generate high transient overvoltages, cause frequent equipment insulation failures, and propagate to multiphase faults. These are distinguished as bolted (solidly connected to ground) and arcing faults. The arcing faults usually caused by insulation breakdown, creating an arc between a phase and ground. When a distribution overhead grid is simple, it usually runs with isolated neutral to the ground. Because of small its distributed capacitance, the isolated neutral grid has the ability of self-extinction of arcing ground fault due to small fault current. As a grid expands, its distributed capacitance increases and supports ground fault arc burning.

When an ungrounded system contains many miles of cable and lines, the results of system stray capacitance may be so large that arcing ground faults cannot self-extinguish. Using an inductor to ground the neutral point of the system allows compensating the capacitive fault current. Due to the complete compensation condition (when the inductive reactance is equal to one-third of the system zero-sequence capacitive reactance), the grid achieves parallel resonance and the ground fault currents are normally under a few amperes (less than 25 A) [1]. The grounding inductor, which is also called a Petersen coil after its inventor W. Petersen, normally has several taps to tune to different systems. Modern designs of the device allow continuous tuning by positioning the core of the coil. To prevent a large neutral voltage shift, a resonant-grounded system normally operates as overcompensated and the inductive current through the coil is larger than the capacitive current. However, distribution systems are dynamic, and cables and lines are usually switched and one of installed several grounding coils can be out of service for maintenance. Therefore the conclusion is that resonant-grounded system can run at all possible compensation levels, as: overcompensated, undercompensated and 100 percent compensated. The source impedance can therefore change from inductive to capacitive or vice versa.

Medium voltage distribution power grids with resonant grounded can normally operate under a single-ground fault condition and due to such idea the service reliability is high. It has been found that arcing ground faults can cause high transient overvoltages several times than the normal voltage [3, 4], which may be dangerous for the equipment connected to the substation buses. A result is the overall system cost is high because of equipment and devices which have to be line-to-line voltage rated. Moreover, this kind of system grid has to be monitored because of capacitances which continually changes as feeders are switched on and off [5]. Therefore, the variability of the compensating inductor should be high and provide the inductance of slightly larger to avoid a true resonant condition. Otherwise, there can appear conditions to transient overvoltages.

The present paper deals with the modeling and analysis of transient overvoltages in industrial MV cable grid operated with resonant neutral grounding in case of single line to ground faults (SLGF). The comparative transient analysis has been carried out between the results of the examined supply system with several Petersen coil tunings. To analyze this phenomenon the Matlab/ Simulink Software has been chosen because there are known limitations in the field testing with respect to the power grid condition and the number of times that the test can be carried out.

2. DISCRIPTION OF THE INDUSTRIAL GRID

The one-line diagram of MV power grid presented in Figure 1 was examined for the estimation of some transient overvoltages mechanisms associated with the intermittent faults. The power supply system 6 kV is operated by two industrial substations: A - three-section and B - four-section, and is connected to HV 110 kV bus supplying by means of three step-down power transformers TS of 31.5 MVA, having a Yd11 connection group of the windings. All sections of the MV units are connected by intersection reactors of 2000 A rated current having percentage reactance of 10%. The sections supply linear and nonlinear loads via cable lines (CL) in series with line reactors (LR). The substation A of the industrial grid is connected to 6 kV buses of the substation B by three parallel cable lines (CO-L) and line reactor (LR). The rated current of the cable lines is 2500 A and the line reactor inductance is between: (0.14 – 0.20) mH. Four turbogenerators TG of total capacity 37.5 MVA is connected to the MV substation B and supply the industrial loads too.

The analyzed grid is a very extensive industrial system, therefore due to complexity of connection topology of middle and low voltage cable lines, MV/LV transformers, induction and synchronous motors and the relation between A and B substation it can operate in various topologies. Damaging of the cable insulation in this power supply system will cause the intermittent electric arc, that can lead to high amplitude of the transient overvoltage up to 6-8 times of the phase voltage. This high amplitude overvoltage can damage the sensitive equipment, even if the system has the overvoltage protective devices. All cables are represented by their resistances, inductances and capacitances. In the Table 1 and 2 are shown the main parameters and equipment specification of the analyzed industrial grid.

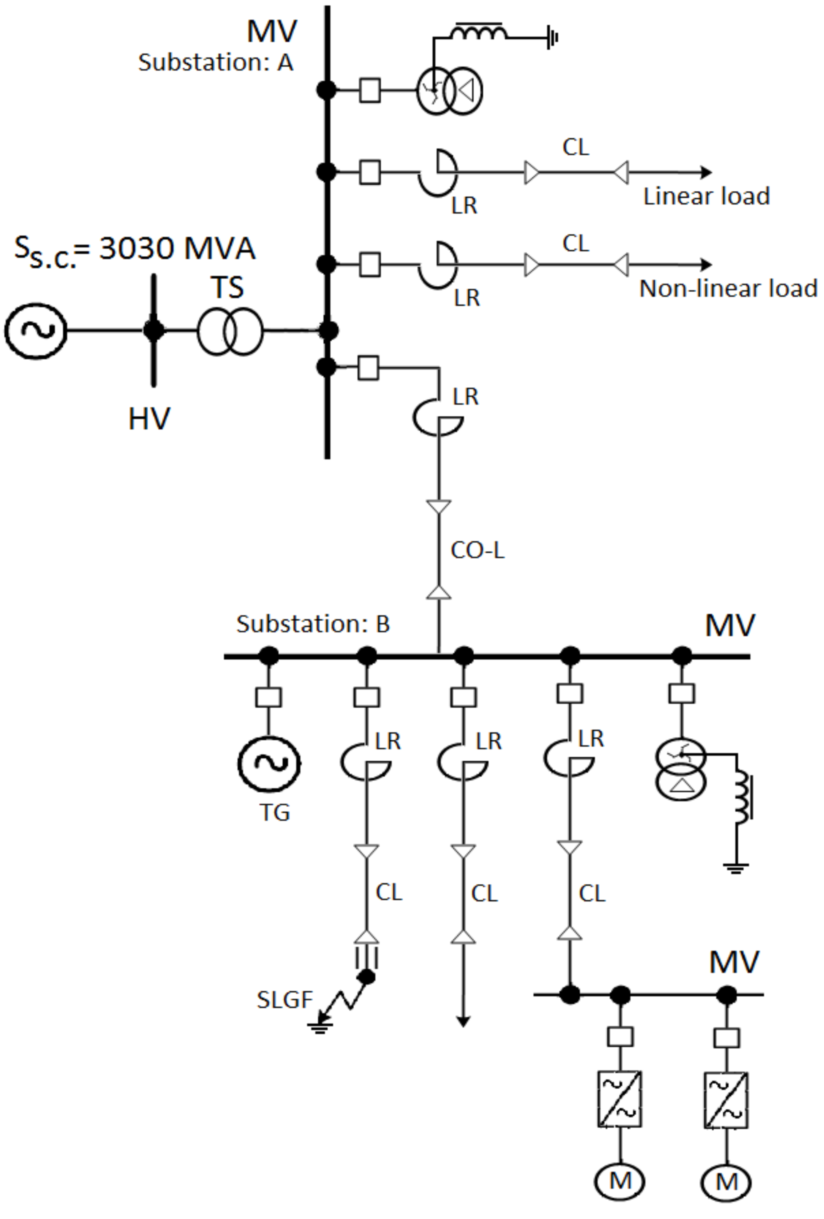

Fig. 1. One line diagram of the power supply industrial grid

Table 1. Equivalent parameters of the industrial grid.

Parameter	Unit	Value
Rated voltage, U_n	kV	6.00
Inductance of system, L_s	mH	0.34
Line-to-ground capacitance, C_o	μF	76.70
Line-to-line capacitance, C_{ll}	μF	28.30

Table 2. Specification of the grid reactors.

Type of reactor	Rated voltage U_n [kV]	Rated current I_n [kA]	Resistance R [Ů]	Inductance L [mH]
Load reactor	6.00	0.60	0.35	0.45
System reactor	6.00	1.00	0.27	1.10

The above MV power grid is operated with neutral point connected to the ground by Petersen coils installed at each neutral point of grounding transformers of the grid substations A and B. The each grounding transformer has the Petersen coil connected to the MV transformer winding neutral and the coil is equipped with 5^{th} manually changed taps. During analysis the grounding coils were set to the 3^{rd} tap of the coils. In Table 3 there are shown the parameters of the resonant grounding system.

Table 3. Specification of the grounding transformer and coil.

Grounding unit	Rated power S_n [kVA]	Rated voltage		Short-circuit voltage ΔU [%]	Inductance L [mH]
		U_1 [kV]	U_2 [kV]		
Transformer	346	6.0	0.4	4.73	15.67
Petersen coil	346	6.0	0.4	15.00	258.22

The two adjustable speed drives (ASD) with total capacity of 500 kW are connected to the 6 kV bus of B industrial substation via MV switchgear. The ASDs are supplied by line reactors (LR) and cable lines (CL) with rated current 1000 A. The ASD circuit diagram for this kind of motor capacity is presented in Figure 2.

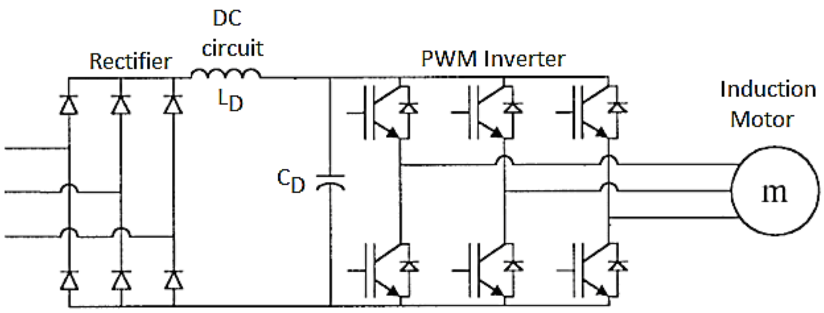

Fig.2. Adjustable speed drive circuit in the examined power supply system

The capacitor of the ASD provides smoothing DC voltage and links the ASD rectifier and inverter. The PWM inverter unit uses the C_D capacitor voltage to create a variable frequency voltage to control the speed of the inductor motor. The reactor L_D of ASD is used to reduce the rate of the current rise due to rectifier is switching-on and provides the reduction of the overvoltage generated on the capacitor.

3. MODELING TRANSIENTS UNDER INTERMITTENT FAULTS

Numeric simulation of the transients caused by faults produced in medium voltage networks is the most efficient method for analyzing that phenomenon. In order to describe the behaviour of the network during single-line to ground fault simulation model was made using the Matlab SimPowerSystem Software. The software provides component libraries and analysis tools for modeling and simulating electrical power systems. The numeric simulator allows to analyze the transient behaviours caused by faults such as the simple grounding type, no mater how the neutral point of the medium voltage network is grounded and whatever are the functioning conditions of the electric network.

This paper considers three phase simulation model included equivalent parameters of the system sources, power transformers, line reactors, cables and ASD circuit. All the components of the model were implemented from the Matlab libraries and have standard equivalent circuits and specifications. The model was created to simulate transients in the industrial power grid having a grounding transformer with Petersen coils to compensating cable capacitive currents at ground faults. In the course of study have been described transients within the substation during single-line to ground fault and the impact of various compensation degrees of the capacitive fault current on the level of occurring overvoltages.

Transient temporary overvoltages during the intermittent arc faults may be dangerous for insulation of the substation equipment and can cause its failure.

Intermittent arcing fault at the cable grids has a stochastic nature and was modeled with subject to the most influencing factors obtained from practical experience [6]. The developed arc model presents a series of successive arc ignitions and breaks in the faulted phase. Figure 3 shows the transient behavior during single line to ground fault under intermittent arc obtained by the analyzed grid model when grounding transformers are off. The line to ground voltages on the buses of the substation B are presented in the Figure 3A, fault current I_{SLGF} is presented in the Figure 3B, and voltages at the ASD rectifier valves are presented in the Figure 3C. The line to ground voltages is marked in the Figure 3 by solid (phase A), dotted (phase B) and dashed (phase C) lines.

The arc ignitions and breaks occur at the 1 and 2 time points respectively, as they are shown in the Figure 3B. Successive recharges of the grid phase capacitance after each arc break cause the rise of the commercial frequency voltage on the faulted phase with adding to it the grid natural frequency transient voltage component. The grid natural frequency f during intermittent arcing SLGF can be estimated for a grid through using values of three phase short circuit current $I^{(3)}$ and the steady SLGF current $I^{(1)}$ at the fault point [7]:

$$f = f_0\sqrt{\frac{I^{(3)}}{I^{(1)}}} \tag{1}$$

where the f_0 is the power system frequency.

The grid natural frequency allows estimating the equivalent resistor frequency dependence in the equivalent circuit to proper accounting the damping rate in the transient simulations. For the examined grid the value of the estimated natural frequency is 850 Hz. Using the value of the frequency, the model equivalent resistances were calculated by the next formula:

$$r_f = r_0\sqrt{\frac{f}{f_0}} \tag{2}$$

where the r_0 is the resistance at power system frequency of 50 Hz, and r_f is the resistance at the grid natural frequency.

4. RESULTS OF SIMULATIONS

In the course of computer simulation of the analyzed network, the influence of network parameters, which vary depending on different production requirements, and the degree of compensation of the steady SLGF current of the industrial grid on transient overvoltages on the ASD rectifier valves was studied.

As it has been shown in the previous section of the paper, the intermittent arcing SLGF causes oscillating overvoltages on the ASD rectifier valves when grounding transformers with compensating coils are disconnected from the grid busses. From the Figure 3C it can be observed, that the overvoltage peak on the faulted phase reaches 1.74 relative to the magnitude of the valve steady voltage. Such level of the overvoltage can trigger the rectifier valve protection and tripping the ASD from the buses.

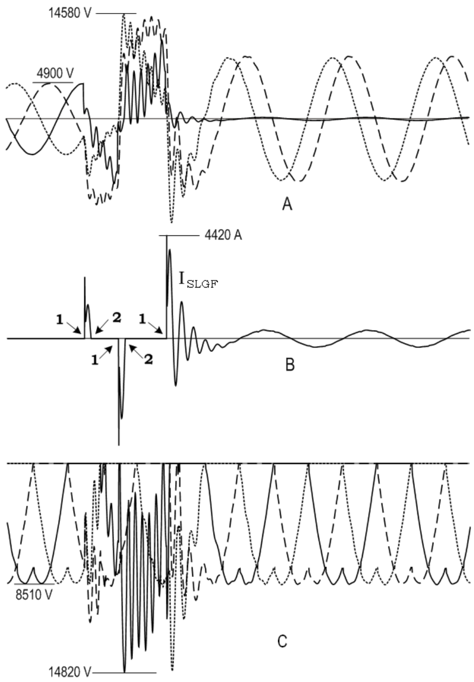

Fig.3. Transients in the grid when grounding transformers are off

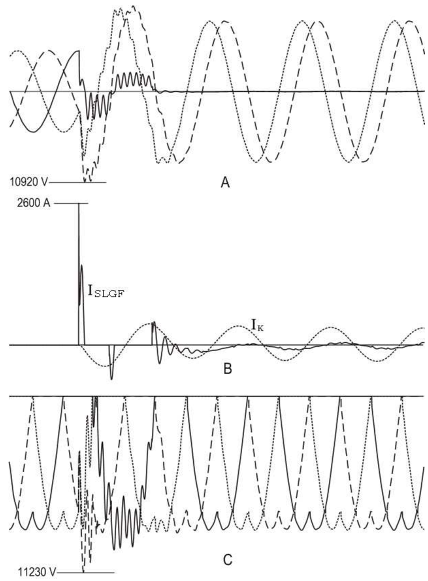

Fig.4. Transients in the grid at complete compensation of the SLGF steady current

Figure 4 shows the grid transients, when grounding transformers with compensating coils are connected to the substations buses and setting up of the compensating coils provides almost complete compensation of the SLGF steady current. Current I_K in the Figure 4B is the equivalent compensating coils current. In this operating state, the compensating coils increase the rate of discharge of the grid capacity after each arc pulse, and therefore the transient voltage does not rise to levels as in the previous case without compensation. As one can see from the Figure 4B the magnitudes of the intermittent arc current pulses in the grid with installed compensating coils are significantly less comparing to the uncompensated grid. The peak of the line to ground transient voltage in these conditions does not exceed 2.23 of the steady voltage magnitude. As a result, the maximum rectifier valve overvoltage ratio in this case does not exceed 1.32 of the valve steady voltage magnitude.

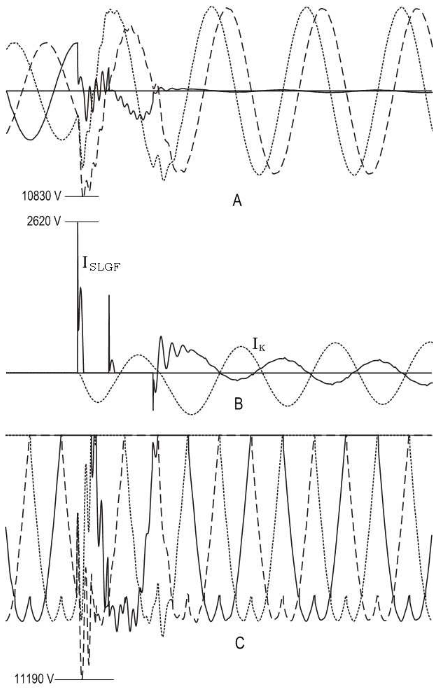

Fig.5. Transients in the grid at undercompensation of the SLGF steady current

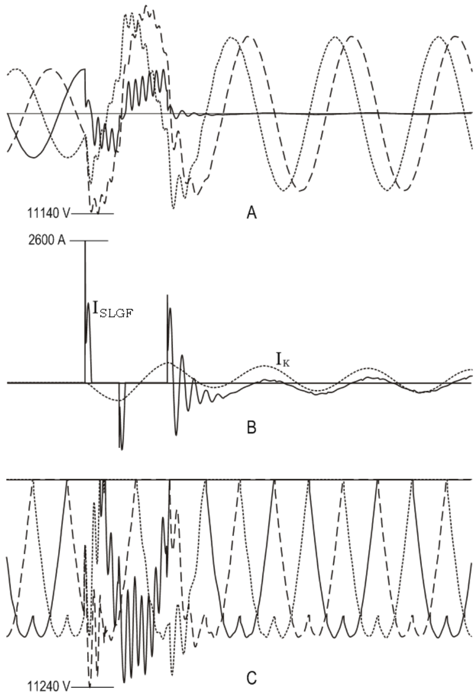

Fig.6. Transients in the grid at overcompensation of the SLGF steady current

Figure 5 and 6 present the grid transients, when the setting up of the Petersen coils in the industrial grid provides undercompensation of the SLGF steady current by 30% and overcompensation of the current by 30% respectively. Such conditions may occur as a result of operational change of the grid configuration.

Undercompensation of the grid capacitive single-line to ground fault current leads to some residual value of the fault capacitive current. As can be seen from Figure 5B, the nature of the arc pulses changes in this case due to the change in conditions for ignitions and breaks of the arc. In spite of this, the magnitudes of the intermittent arc current pulses in the grid are significantly less comparing to the uncompensated grid. The values of the line to ground overvoltages and rectifier valve overvoltages in this case are close to the previous case (see Figure 5A and Figure 5C). The transient voltage of the damaged phase A on the substation buses in this case is significantly damped comparing to the uncompensated grid.

Transient within the overcompensated grid under single-line to ground fault determines changes in the currents and voltages behavior as can be seen in Figure 6. The inductive nature of the total ground fault current in this case causes more intensive transient voltages on the buses and as a result at the rectifier valves compared to the previous cases of the compensations.

Despite of some difference in the transient behaviors on the analyzed grid under different compensation degrees, it can be observed the similar impact of the Petersen coils on the transient voltage: they decrease the transient overvoltage magnitudes on the grid buses and rectifier valves, regardless of the compensation degree of the grid SLGF capacitive current.

5. CONCLUSIONS

Transient overvoltage magnitudes across the substation equipment in the middle voltage ungrounded industrial power supply grid containing adjustable speed drives during single phase to ground faults were investigated by simulation. A comparison of the transient behaviours in the grid with compensation by a Petersen coil of the capacitive ground fault current was carried out.

The results of simulating transients in the industrial grid have shown that compensating Petersen coils reduce the transient overvoltages under arcing SLGF compared to an uncompensated grid with isolated neutral. Varying network parameters, which depend on operational changes on the grid configuration, can change the degree of compensation of the industrial grid SLGF capacitive current. Studying transient overvoltages in the grid with different degree of compensating SLGF fault capacitive current has shown a minor impact of the Petersen coil tuning at the overvoltage levels. In the examined power supply system, comprising ASD, one can see the similar reduction of the transient overvoltages at different Petersen coil inductances.

Podziękowania. Badania były finansowane z subwencji badawczej nr 16.16.210.476.

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(Received: 27.01.2019, revised: 07.03.2019)