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Improving the power supply reliability in resonant earthed systems by fault current path control established through Faulted Phase earthing Switch

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ABSTRACT

This paper shows that appropriate manipulation of the Faulted Phase earthing Switch within the system using resonant earthed neutral, can be used to establish a controlled path for the fault current. In this way the arc extinguishes and the fault can be safely located without interruptions to the energy supply. The proposed current path control method is confirmed with simulations and extensive field-testing.

Introduction

Main task of the distribution power system is a continuous delivery of the electrical energy within specified limits. Unfortunately, interruptions are very common in distribution systems, mostly due to insulation break down or other phenomena caused by weather conditions. The highest share of interruptions can be assigned to earth faults within medium voltage networks. According to statistical data for Slovenian networks, more than sixty percent of all faults are earth faults. Handling earth faults mostly depends on how the neutral point of the energy supply transformer is treated [1–4]. In Slovenian distribution companies, the majority of neutral points are earthed through low ohmic 80 Ω resistors, that are used to limit the fault current to 150 A. A combination of low ohmic resistors and Faulted Phase earthing Switch-es (FPS-es) is also used for neutral point treatment [5] but only for a few percentages cases. In order to suppress the capacitive component of the fault current and improve the reliability of energy supply, resonant earthing has been introduced at some neutral points.

The operation principle of resonant earthing is well-known nowadays and also widely treated through several papers [6–11]. Majority of earth faults in resonant earthed systems are self-extinguishing and therefore switching actions on supply feeder are unnecessary. Permanent faults are also present within earth fault compensated networks. The so-called arcing faults are particularly unfavourable where the fault path contains unstable fault impedance, and where self-extinguishing of the arc is impossible. The resistances of existing earthing systems in medium voltage transformers' substations are below 2.5 Ω, which is indispensable because of low ohmic earthing usage. The low value of the earthing system's resistance and the almost complete compensation of the capacitive current with adequately tuned coil, enable operations under sustained earth faults, as in [12,13]. Although the residual current over the fault path is very low, it still contains resistive and harmonic components for which compensation with a coil is ineffective. The question arises as to what happens if a system operates under an arcing fault that burns and destroys the material at the fault's location. According operating experiences in distribution systems, such arcing faults cause damage to the equipment and the danger of fire spreading, and must, therefore be switched-off. On the contrary to this practice, this paper shows that a proper combination of resonant earthing and FPS operation can be used to control the fault-current path. When applied in the cases of persistent non-self-extinguishing arc faults, it leads to safe network

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Nomenclature

C_0	phase to earth capacitance
C_{0kx}	line to earth capacitance
C_{kmx}	capacitive couplings between individual lines k
$\boldsymbol{I}_{BUS}$	node current injection vector (phasor)
$\underline{I}_{c0}$	current through the phase to earth capacitances C_0 (phasor)
$\underline{I}_f$	fault current (phasor)
i_f	fault current (instantaneous value)
$\underline{I}_{fps}$	Faulted Phase earthing Switch current (phasor)
i_L	Petersen coil current (instantaneous value)
$\underline{I}_p$	Petersen coil current (phasor)
$\underline{I}_{pw}$	current through the resistor R_p (phasor)
$\underline{I}_{px}$	current through the inductance L_p (phasor)
$\underline{I}_{r0}$	current through the phase to earth resistances R_0 (phasor)
L_p	adjustable inductance of Petersen coil
R_0	phase to earth resistance
R_{0kx}	line to earth resistance
R_e	earthing system resistance in the transformer substation
R_f	resistance at the fault location
R_p	resistance representing losses in Petersen coil
u_A, u_B, u_C	line-to-neutral voltages (instantaneous values)
$\underline{U}_{AN}$, $\underline{U}_{BN}$, $\underline{U}_{CN}$	sources line voltage (phasors)
$\underline{U}_f$	voltage at the fault location (phasor)
u_{ne}	residual voltage (instantaneous value)
$\boldsymbol{V}_{BUS}$	node potential vector
$\underline{V}_i$	potentials of the nodes i (phasor)
X_c	capacitive reactance of the entire network
X_p	Petersen coil reactance
$\boldsymbol{Y}_{BUS}$	admittance matrix
$\underline{Y}_{ij}$	admittance between nodes i and j
$\underline{Z}_{0k}$	line to earth impedance
$\underline{Z}_{as}$, $\underline{Z}_{bs}$, $\underline{Z}_{cs}$	system impedances of the source
$\underline{Z}_{kx}$	longitudinal impedance of lines $k = a, b, c$ and feeders $x = 1, 2$
$\underline{Z}_{th}$	Thevenin's impedance

operation without power supply interruptions, until the fault is located and condition are established for its elimination. When operating, the FPS establishes a new current path and, therefore, the fault current through the fault location stops flowing. In this way it is possible to control the fault current path and divert the fault current through low earthing resistance within the transformer substation, without to increase the potential in the transformer substation or outside it over an acceptable level.

The basic principle of operation of the proposed fault current path control method is as follows:

1. The protection system switches off the faulted feeder when fault current exceeds the level which causes dangerous touch voltage.
2. If fault current is below the threshold, the Petersen coil can react in two ways:
   a. Petersen coil successfully suppress the arc and fault disappears without interruptions to the energy supply.
   b. Petersen coil cannot suppress the arc, therefore, FPS is switched on and the fault can be safely located and eliminated without interruptions to the energy supply.

The proposed method relies on faulted phase detection in the existing protection system, whilst the new faulted phase detection methods [14–17] are not discussed in this paper.

This paper shows that by using the proposed fault current path control, the non-compensated part of a capacitive current and resistive currents due to losses in the system, as well as all those higher harmonic order current components, close through the path established by the FPS operation. The potential on the faulted line is reduced to the value near to ground level. In this way all those conditions that cause a sustained arching fault at the faulted location are effectively eliminated. Under such conditions the system can operate safely without supply interruptions even under a permanent (potentially arcing) fault. Of course such an operation is limited to a reasonable short time interval of several hours, which is normally sufficient for effectively locating and eliminating the fault.

The proposed fault current path control method has been extensively tested.

The analysis was performed in four stages:

1. On the basis of simplified equivalent circuit, considering only dominant phenomena, simplified equations were obtained.
2. Neglecting inductive couplings between individual line conductors, nodal electric potential analysis was performed considering only fundamental harmonic components.
3. Considering all inductive and capacitive couplings and unbalanced electrical line parameters dynamic model simulations in MATLAB/Simulink were performed.
4. Field-testing within an operating distribution network was performed.

In this way, all unbalanced line parameters as well as unbalanced operating conditions were considered without introducing symmetrical components, all with the goal to demonstrate the performances of the proposed method.

Theoretical background

When arcing fault occurs, the main problem at the fault location is deterioration and damage to the insulation. Therefore, the arc represents a limiting factor for extending the operation under earth fault. Let us discover what happens if FPS is switched-on while the arc is still present in a system with resonant earthing. In order to do this, a simple distribution system is applied as shown in Fig. 1, which has been widely used for theoretical considerations.

In order to obtain a clearer insight into the physical phenomena, it is sufficient to take only two feeders into consideration. The focus of the interest is the fault current. Therefore, according to established practice, all the healthy feeders are represented by one healthy Feeder 2, whilst the earth fault (EF) appears in Feeder 1. The medium voltage (MV) busbar is fed by line voltage sources $\underline{U}_{AN}$, $\underline{U}_{BN}$, and $\underline{U}_{CN}$. These voltage sources are connected in a series with the supply system impedances $\underline{Z}_{as}$, $\underline{Z}_{bs}$ and $\underline{Z}_{cs}$. The network's neutral point (N) is earthed through Petersen coil (resonant earthing) with the adjustable inductance L_p and the resistance R_p. The last one represents the losses. One pole of the FPS is connected to the MV busbar whilst the other pole of the FPS is connected to the earthing system in the substation, as represented by the