Analysis on Faulty Phase Grounding in Medium-Voltage Networks with Isolated Neutral

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Abstract

Medium voltage (MV) networks in Estonia are operating at 6, 10, 15, 20 and 35 kV levels, often with isolated neutral mode. These isolated neutral networks have different fault scenarios with single-phase earth faults compared to networks with grounded neutral. In view of this, approach towards the single-phase ground faults is different and different protection methods are used. An old single-phase ground fault protection method is observed in this paper. Revisiting this method brings answers to the questions of its capabilities and problems, also to questions why it is no longer in use.

Keywords

Medium-voltage networks, single-phase earth fault, isolated neutral.

Introduction

Medium-voltage (MV) networks are part of power distribution networks and can carry power of several megawatts (MW) to distances over 10 or 20 km. In order to achieve this, MV networks have quite high voltage – in Estonia starting from 6 and reaching up to 35 kV levels. This way, current of 100 A could be used for example to transmit 1.7 MVA. Consumers usually have low-voltage (LV) equipment, therefore MV substations are used to convert the voltage down to 400 V. In order to decrease losses, the MV substation can be placed in the vicinity of the consumer’s LV device.

In Estonia, MV networks operate in either isolated network or resonant grounded mode. Older MV networks tend to have isolated neutral, which suits well with an YNd transformer scheme, common in high voltage (HV) substations for converting voltage to MV network levels. This way, the network does not have a direct path to ground, which means that the single-phase fault currents are relatively low. However, even these levels are dangerous and are not allowed for a longer duration in operation. New HV substations have Petersen coils installed, which makes the MV networks resonant grounded. The latter method is used very widely in the world and provides quite good protection against the single-phase ground faults [3].

In this paper, focus is on an old, yet not widely used solution. In the essence, this solution is very simple – it only uses a switch to ground the wire with a ground fault. Idea is to decrease the voltage difference at the fault location to as minimum as possible. In an optimum, when the wire voltage to ground at fault location is zero, also the current passing from wire to ground would be zero.

Single-phase earth faults

If a network has isolated neutral, it means that this network is not tied to ground using a galvanic connection. With grounded neutral, every fault to earth brings significant fault currents of several hundreds of amperes. Isolated neutral has still capacitors, formed by wire itself and ground. Capacitance of such a capacitor is small, however lines are long also and can sum quite high capacitance values.

In a MV network with isolated neutral, single-phase earth fault can be estimated using a simple formula [1]

\[ I_{\text{fault}} = \frac{V_{\text{line}} l_{\text{network}}}{300} \]

Figure 1. Single-phase ground fault in MV network with isolated neutral

Ground fault current of a isolated neutral network can be estimated using a simple formula [1]

where \( V_{\text{line}} \) is line voltage of the network (in) kV and \( l_{\text{network}} \) is the total span of isolated neutral networks connected together (in km).
Graph in Figure 2 presents the relation between fault resistance and earth fault current for a network with span of 100 km.

![Figure 2. Ground fault current and voltage depending on fault resistance](image)

When an earth fault occurs, its current causes quite high voltages in soil around the fault location. Imminent danger of step-voltage to people and animals is caused by this. Problem with single-phase earth faults in networks with isolated neutral is caused by the fact that earth fault can be undetected for days or even longer periods. Even today, it is quite difficult to detect high-resistance earth faults in such networks; however, high fault resistance still means high voltage in the earth fault site (see Figure 2).

**Protection against the single-phase earth fault**

One of the virtues of single-phase earth faults in networks with isolated neutral is the possibility of clearing the faults without switching off the network or power line. This is guaranteed by using appropriate devices to protect the network. Here two approaches are introduced.

![Figure 3. Example of resonant grounding in MV networks](image)

A well-known fact is that capacitor current can be balanced with current from inductive components, such as coils. The compensating coil, also known as Petersen coil, should be connected to the network neutral point. The coil needed to compensate the earth fault current should have reactance of

\[
x_{le} = 3x_{CP,E}
\]

where \(x_{le}\) is compensating coil reactance at 50 Hz and \(3x_{CP,E}\) is the networks total capacitive reactance at 50 Hz (three phase wires capacitive reactance).

Petersen coil performance is rather good and can reduce the number of outages by significant amount [3]. On the downside of Petersen coil application, MV networks are not static and due to their occasional configuration changes, coil needs to be tuned often to maintain resonance with the network’s earth fault current. Second problem is created by the harmonic currents in the network which are not compensated. Also, Petersen coils are highly expensive and thus a search for alternative possibilities and improvements to the system is continuing.

An old method is to use a switch that would ground the faulty phase (see Figure 4). This way voltage to earth of this phase is decreased instantly to a minimum. While large portion of single-phase earth faults are self-clearing, decreasing voltage would help to extinct electric arc and make restriking more difficult. Method would introduce a second and better conducting current path to ground and this way minimize current passing in the fault location. Latter is guaranteed as in real situations earth fault resistance is typically in tens of ohms. Path to ground in a substation with excellent grounding would only have resistance in range of 2…5 Ω. Current decrease in the fault location is more effective when protective switch ground path resistance would be even smaller.

Some countries have given up on the possibility to clear the faults without switching off the network. In such cases, network is switched off once earth fault is detected.

**Safety requirements of power lines**

In Estonia, safety voltage limit of faulty electric outdoor AC equipment is 50 V [2]. In Europe, this limit could be up to 75 V [4]. This voltage is considered relatively harmless and in general not life-threatening. All equipment operating have to guarantee, that any of the parts touchable does not exceed this limit. Even in fault conditions, when such limit cannot be guaranteed, the equipment has to be shut down immediately.

A single-phase earth fault protection system has to ensure also, that this limit is met, when faults are cleared without switching off the network.

**Faulty phase grounding and network load**

When a faulty phase is grounded in the substation, a second point of grounding is introduced to the faulty phase wire (Figure 4).
This way also a current path is created for the load current that passes through a wire. While current is not large compared to load current running through the wire, it may increase fault current drastically instead of decreasing it in the fault location.

**Figure 4. Grounding the faulty phase in substation and load current paths after grounding**

Load current passing through fault is dependent on fault distance, as the wire resistance increases with fault distance from the substation. Earth can be seen as a constant zero resistance substrate, having no resistance effect due to distance.

The load of the network branch exiting from a substation is usually in range of hundreds of kVA up to some MVA. For example, a branch with household load could have load of 100 – 200 kVA while a small industrial company could have load of 2 – 3 MVA. Load in the rural areas can be up to 10 – 20 km away from a substation. A small lumber mill uses usually 2 MVA just for wood drying and is placed in quite distant areas from larger centres with substations.

**Analysis on faulty phase grounding performance with load**

Analysis on effects of load on application of faulty phase grounding takes into account a variety of loads, fault distance from substation and variety of earth fault resistance values. Goal of the analysis is to determine range of safe operation for the faulty phase grounding.

Analysis has been carried out using simulation on a distribution network computer model. Simulations have been carried out on PSCAD-EMTC software, which allows detailed analysis on transient and steady state operation of distribution networks. Schematic of the substation used for simulations has been presented in Figure 5.

The substation provides power to 7 MV power lines operating at 10 kV. All lines are supplied from common 110/10 kV transformer YNd transformer, which guarantees MV network isolated neutral. Total span of the MV power lines is 100 km. As high-frequency transients are not monitored, the network model has no sub-branches of the power lines. Wires of the faulty MV line are A50 type aluminium wires [5] with 215 A rated current and 0,57 Ω/km DC resistance, corresponding to common type used in rural MV distribution networks.

Single-phase earth faults are created in distances 1, 3, 5 and 10 km from the substation. Line with earth fault is little over 10 km long. Each fault distance is simulated with variable load from around 100 kVA up to 2 MVA in the end of the line. With each load, different fault resistances are observed, ranging in from 35 Ω to 3000 Ω (total 7 resistance values). This way, a clear relation of load power to fault current can be established.

**Figure 5. Simulated substation model with exiting MV lines and parameters (o/h – overhead; c – cable). Fault is simulated on Seliküla line**

Load itself is a LC-type load with power factor of 0,97, which corresponds to real networks and load is located in the end of faulty line. Thus all load current through the faulty line flows by the fault location. Faulty phase grounding resistance is set to 2,5 Ω in the substation.

During the simulation, faulty line current and voltage, fault current and voltage at fault location are measured. All data has been recorded in RMS values for the steady state operation.

**Results**

Simulation results from a fault distance of 1 km from the substation show that every load condition and every fault resistance produces quite different fault current (see Figure 6).

**Figure 6. Fault current dependence on load power and fault resistance, fault being 1 km away from substation**
As it is quite difficult to tell if the operation is within safety margins based on current value only, the current value is multiplied with fault resistance to produce voltage in the fault location. Voltages calculated based on the fault currents are presented in Figure 7.

The graph of fault voltages in Figure 7 presents clearly, that despite the fault current and fault resistance are different, voltage at fault location and line load are in quite good relation.

Using this as a reference, voltages at fault locations can also be found for faults with distance of 3, 5 and 10 km.

It would be quite obvious to state that the further the fault location is from substation, the higher the fault current and thus also voltage at fault location. Figure 8 confirms this.

In addition, Figure 8 also shows a fault location safe voltage level of 50 V. The fault voltage is over this limit by a large margin for most of the line load values, pointing at problems near the fault location.

**Conclusions**

Results show that if the faulty phase switching to ground is used to protect the MV network, the voltage at fault location could exceed the safety limits even several tens of times. The voltage in the fault location is higher depending on fault distance from substation and line load.

The results also present the safe operating range for the faulty phase grounding. Taking into account the network load, guaranteed safe operating area will be less than 1 km from the fault location. This means that there should be multiple faulty phase grounding points in the network to ensure safety. Only one switching location in the network substation is clearly insufficient.

**References**