TUNING OF RESONANCE GROUNDED NETWORKS AND ITS EFFECTS ON EARTH FAULT DETECTION

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ABSTRACT

In resonance earthed MV networks, the tuning of the Petersen coil is a critical issue for system performance. This paper is based on test results from a downsized distribution network laboratory. In a laboratory it is possible to evaluate two different criteria for optimal coil tuning. Either it is possible to use the traditional criterion that minimizes the fault current, or alternatively to maximize the neutral point voltage at resistive earth faults. In the paper it is showed that often, but not necessary always; these two criteria are optimized simultaneously.

INTRODUCTION

Each country has unique characteristics, such as varying distances, population density and grounding conditions. This results in country specific electric safety regulation for resonance earthed MV network. For example, in Sweden, earth faults (< 3 kohm) must be disconnected within 5 seconds, whereas other countries might allow operation.

To explain the newborn Swedish interest in coil tuning, we have to go back to 2005. That year a monstrous hurricane severely damaged the Swedish distribution network. Around 600 000 customers lost their electricity, of which 10% where disconnected for more than a week and 2% where without electricity for as long as tree weeks [1]. As a consequence the government enforced stricter regulations for the grid owners. Customers get compensation after 12 hours and the maximum allowed interruption time is 24 hours [2]. To comply with the stricter rules, E.ON Sweden launched a project to increase supply reliability. The goal was to weather proof 17000 km's of power lines, where most of it would be achieved by replacing overhead lines with underground cables in the MV network. The increased use of MV-cables will be accompanied with more automatically tuned Petersen coils, hence the newborn interest.

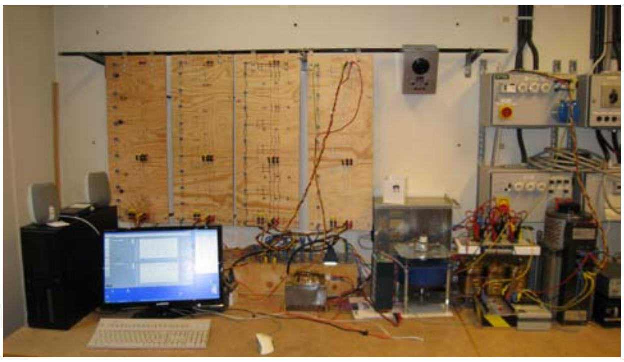
Automatic tuning of Petersen coil

For resonance grounded networks it is necessary to continuous match the coil with the network capacitance to earth. Typically, after switching of longer cables the Petersen coil needs to be re-tuned. The paper by Griffel [3] presents advantages and disadvantages with different neutral grounding techniques, and motivates EDF's decision to change their MV networks to resonant earthed (Petersen coil). Also Italian ENEL has a large project to introduce Petersen coils [4]. Reference [5] describes a patent for coil tuning based on current injection, also reference [6] use current injection, but adds the feature of varying the signal frequency. In a paper by Zamora [7], different coil tuning methods are evaluated by their ability to minimize the current at the fault location. The patent [8], and also paper [9], use current injection at non-fundamental frequency to improve coil tuning. Auer [10] presents an excellent historical review of state-of-the-art and points out the main future challenges.

Cheng Lu [11] and Jin Wangyi [12] suggest the use of power electronic to control the coil value. The advantage is faster control dynamics - nearly instantaneous - compared to a conventional tunable coil. Due to the fast dynamic response, the coil tuning can be done at fault occurrence, thus avoiding the problem of coil tuning at only small un-symmetries.

DLAB

A downsized laboratory for distribution networks was initiated in 2008. The aim was, and still is, to provide a good platform for teaching and research on resonance earthed MV networks. DLAB is a research group within Lund University and is sponsored by E.ON Elnät Sverige. The name DLAB is an abbreviation of Distribution LABoratory,



Picture 1. Overview of downsized distribution laboratory (DLAB).

Within DLAB a low voltage model (110 V) of a MV distribution network has been created. The model includes underground cables, overhead lines, protection units, neutral point resistance, a Petersen coil with automatic tuning based on either network un-symmetry, or current injection. There is a possibility to apply permanent earth fault with different fault resistance, but also short duration intermittent earth faults. The model properties have been compared against both field tests and simulation results, and agrees reasonable well [13].

OPTIMAL TUNING OF RESONANT GROUNDED GRIDS

In resonance grounded networks, the neutral coil is used to compensate the capacitive currents at the fault location. The key objective is to kill the fault arc. At perfect tuning, the only remaining current at the fault location is the active component. The level of resistive current is often a compromise between two conflicting demands. Too high resistive current might cause dangerous voltage of exposed parts at earth faults. On the other hand, too low resistive current makes it harder for the relay protection to determine the faulted feeder. One major advantage of resonance grounding is that arcing earth faults, such as insulator flash-over at overhead lines, often are self-extinguishing. Hence, the synonymous name arc-supression coil (ASC). Low current in the fault point also minimize damages to equipment and dangers for third-parties.

Maximum neutral point voltage

In the experimental setup it was verified that the neutral point voltage increased with better tuning [14]. This criterion was used to tune the Petersen coil to resonance with the network capacitance. The figure below illustrates a resonance curve produced by sweeping the Petersen coils interval of compensation. This sweep is done without any fault connected; however the same result is applicable in the faulty case but results in a higher p.u. voltage.

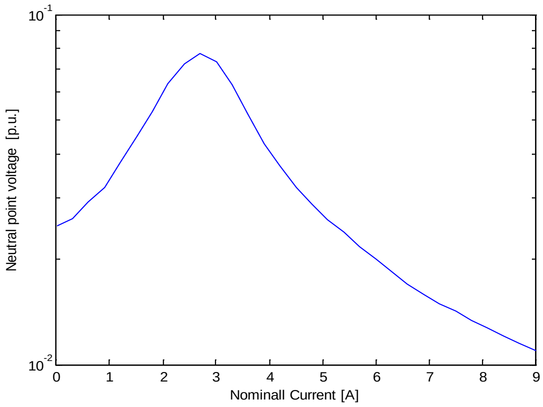


Figure 1. Resonance curve. X-axis is current for Petersen coil at nominal voltage.

Many earth fault protection schemes use non-zero neutral voltage as a starting criterion. Pickup values to detect high resistive faults, might be as low as 3-5%. To get best sensitivity, it is equally important, that the MV network is tuned to resonance. Hence there are two good reasons for correct coil tuning:

1) Minimize fault current for arc suppression.
2) Maximize neutral point voltage for high sensitivity to detect earth faults.

Minimal fault current

An optimal tuning of the system should results in a minimal fault current. The current at fault point, I_F consists of three parts:

- The active current I_R which is determined by losses in feeder and neutral point resistance, as well as fault resistance.
- The capacitive charging current I_C of the resonant grounded system.
- Compensation current I_L from the Petersen coil, which is inductive.

The total fault current could be described by:

$$I_F = I_C + I_L + I_R \tag{1}$$

When correctly tuned, I_L will fully compensate I_C and:

$$I_F = I_R \tag{2}$$

Engineering Trade off's

Simplified theory used in textbook, says that these two criteria are optimized simultaneously for the same coil tuning. For low resistive earth faults, laboratory measurements in DLAB have indicated that simultaneous optimization of both criteria is not always possible.

CALCULATION OF TUNING POINT

In a laboratory, it is possible to use either maximum neutral point voltage, or minimum fault current to tune the Petersen coil. In real MV networks, coil tuning is restricted to use neutral point voltage. Implicitly, it is assumed that maximizing neutral point voltage always results in minimal fault current.

For analysis of coil tuning it is common to only consider the zero sequence network and ignore the effect of the positive and negative sequence networks. This section includes the positive and negative sequence Thevenin impedance in the analysis. If coil tuning is done when the network has a low resistive earth fault, then the criterion to maximize neutral point voltage, does not produce minimal fault current. Standard textbook theory for symmetrical components is used to analyze single-phase-to-earth fault, see for example [15]. Consider the equivalent circuit in Figure 2.

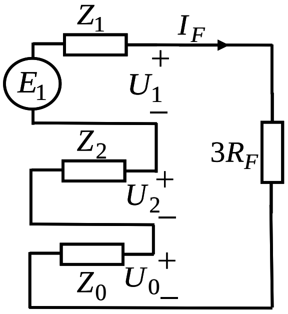


Figure 2. Equivalent circuit for an earth fault

Some of the components in Figure 2 can be merged, giving the more compact circuit in Figure 3.

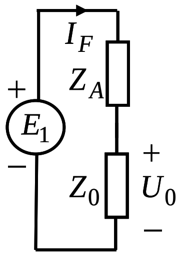


Figure 3. Equivalent circuit for coil tuning with an earth fault.

In the circuit, the zero sequence impedance Z_0 consist of the network capacitance in parallel with neutral point coil and resistor, that is

$$Z_0 = \frac{1}{Y_0} \tag{3}$$

with

$$Y_0 = \frac{1}{3R_N} + j\left(\frac{1}{X_C} - \frac{1}{3X_N}\right) = G_0 + jB_0 \tag{4}$$

where

X_N , is reactance of the Petersen coil

R_N , is resistance of neutral point resistor

X_C , is reactance for network zero sequence capacitance.

The impedance Z_A is a lumped component, consisting of positive, negative and fault resistance as,

$$Z_A = R_A + jX_A = Z_1 + Z_2 + 3R_F \approx 3R_F + j2X_1 \tag{5}$$

The question to consider is: how to select the coil value X_N , to optimize the chosen criterion? Assume that the coil has a control range from 0 up to twice the networks capacitive current. Then it is possible to change B_0 , within the interval

$$-\frac{1}{X_C} < B_0 < \frac{1}{X_C} \tag{6}$$

Maximization of neutral point voltage

From Figure 3, the neutral point voltage is

$$U_0 = \frac{Z_0}{Z_A + Z_0} E_1 = \frac{E_1}{1 + Z_A Y_0} \tag{7}$$

Substitute $Y_0 = G_0 + jB_0$ gives

$$U_0 = \frac{E_1}{(1 + R_A G_0 - X_A B_0) + j(R_A B_0 + X_A G_0)} \tag{8}$$

To maximize $|U_0|$ it is equivalent to minimize

$$h(B_0) = (1 + R_A G_0 - X_A B_0)^2 + (R_A B_0 + X_A G_0)^2 \tag{9}$$

Calculating the derivative and setting $\frac{\partial h}{\partial B_0} = 0$ gives

$$\tilde{B}_0 = \frac{X_A}{(X_A^2 + R_A^2)} \tag{10}$$

where the notation $\tilde{B}_0$ is used for the resulting mismatch susceptance. Introduce a separate notation for the zero sequence admittance that gives maximum neutral point voltage,

$$\tilde{Y}_0 = G_0 + j\tilde{B}_0 \tag{11}$$

The maximal neutral point voltage becomes

$$|U_0|^{\max} = \frac{E_1}{|1 + Z_A \tilde{Y}_0|} \tag{12}$$

The corresponding mismatch current ΔI becomes

$$\Delta I = \tilde{B}_0 \cdot |U_0|^{\max} \tag{13}$$

For fault with high fault resistance, $R_F >> X_1$, which results in $\tilde{B}_0 \to 0$ and $\Delta I \to 0$ which mean zero mismatch. Hence, if automatic coil tuning is done during high resistive faults, the coil will be tuned to closely match the network capacitance. In other words, for high resistive faults, maximal neutral point voltage can be used as criterion for coil tuning.

What happens if automatic coil tuning is done during earth faults with low fault resistance, such as discussed in [11], [12]. Can the criterion maximal neutral point voltage be used for coil tuning which simultaneously minimize the fault current?

Example: Coil tuning at fault with low resistance

Some typical values are taken for a 20 kV network. The rated neutral point voltage

$$E_1 = \frac{1}{\sqrt{3}} 20 \cdot 10^3 \text{ V}.$$

The positive sequence reactance used is

$X_1 = 4 \text{ ohm}$.

Consider a low resistance earth fault, $R_F = 15 \text{ ohm}$, then

$Z_A = 3R_F + 2X_1 = 45 + j8 \text{ ohm}$

Assume the neutral point resistance is $R_N = 577 \text{ ohm}$, so

$$G_0 = \frac{1}{R_N} \approx 1.7 \cdot 10^{-3} \text{ ohm}^{-1}$$

The impedance Z_A is used to calculate the susceptance mismatch at the peak value of the neutral point voltage

$$\tilde{B}_0 = \frac{X_A}{|Z_A|^2} = \frac{8}{8^2 + 45^2} \approx 3.8 \cdot 10^{-3} \text{ ohm}^{-1},$$

The corresponding admittance is

$$\tilde{Y}_0 = G_0 + j\tilde{B}_0 = 1.7 \cdot 10^{-3} + j \cdot 3.8 \cdot 10^{-3} \text{ ohm}^{-1}$$

From this, the maximum neutral point voltage is calculated

$$|U_0|^{\max} = \frac{E_1}{|1 + Z_A \tilde{Y}_0|} \approx 10.9 \text{ kV}$$

In comparison, tuning for minimal fault current at $B_0 = 0$, gives $|U_0|^{\min(I_F)} \approx 10.7\,\mathrm{kV}$, which is obviously slightly less than the maximum neutral point voltage. Finally the mismatch current between the two tuning strategies becomes

$$\Delta I = \tilde{B}_0 \cdot |U_0|^{\max} \approx 3.8 \cdot 10.9 \approx 41\,\mathrm{A}$$

The compensation current from the coil will not match the capacitive current. The mismatch, in this example 41 A, will be added to the resistive fault current giving sub-optimal fault current amplitude.

CONCLUSIONS

In conclusion, coil tuning based on maximum neutral point voltage will not work satisfactory at low resistive earth faults. This theory correlates well with the phenomena observed in DLAB. For existing coil tuning devices, which does not operate during low resistive earth faults, the observation seems to be of minor practical importance. However, it might be of some relevance for future tuning devices based on power electronics that can operate during low resistance earth faults.

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