

## NEW TECHNIQUES FOR COMPENSATED NETWORKS: TUNING THE PETERSEN COIL, DETERMINING THE NETWORK PARAMETERS AND PERFORMING EARTH FAULT CURRENT PREDICTION AND RECONSTRUCTION

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### ABSTRACT

*This paper presents the advantages of a new technique of pulse injection into the zero sequence system of compensated networks. With this technique all important network parameters of the zero sequence system can be estimated and the Petersen coil can be tuned. Furthermore, the maximum of the expected current of a future single phase earth fault can be predicted and the current of an already occurred fault can be reconstructed as a function of time.*

### INTRODUCTION

The first control systems for automatic Petersen coil tuning changed the inductivity of the Petersen coil towards the maximum amplitude of the zero sequence voltage and declared this maximum as the resonance point. Generally, for the proper functioning of this method a relatively high and stable zero sequence voltage signal is needed, especially with regards to the amplitude. Because of the increase of cable networks and the symmetric nature of the cable parameters the zero sequence voltage in compensated networks decreased and so the conditions for a proper functionality are not given any longer.

These circumstances led to the development of two further methods. The former one is based on the fact that the locus curve of the zero sequence voltage as a function of the detuning describes a circle which intersects the coordinate origin. For the application of the latter method a network frequency signal is injected into the zero sequence system of the network by the auxiliary winding of the Petersen coil. By measuring the zero sequence voltage and current differences with and without injection the zero sequence admittance (respectively the impedance) of the whole network can be calculated.

The common disadvantage of these methods mentioned above is the fact that the part with network frequency of the zero sequence admittance spectrum is relatively low when the zero sequence system is detuned and therefore the zero sequence voltage signal itself and also the resulting signal difference caused by the injection is very low. The conclusion of the described facts is that these methods will work properly in the case of a tuned network. In all other cases the conditions will be more difficult because the small amplitude of the zero sequence voltage signal results in a bad signal to noise ratio which influences the numerical conditioning of the applied methods and can affect the reliability of the system.

To overcome the mentioned limitations, ARS developed a new injection method based on pulses. The method, applied

in a real device, demonstrated the capability for:

- Estimating the detuning of a network
- Prediction of the earth fault current (worst case)
- Reconstruction of the earth fault current.

The capability has been tested and proved in a simulated network and recently in a real network operated by an important Italian distribution company.

The success of tests opens a new approach to monitor and control the MV networks in a more strict and effective way. In particular, the possibility to reconstruct the fault current at the fault location, joined with a new localisation algorithm makes it possible to build up a database of network fault points which even takes auto extinguishing faults in consideration. This poses the basis for a maintenance focused in crucial points of the network.

Even faults in customer networks could be monitored and giving the operator an additional tool to interact with its clients.

### THE PULSE INJECTION METHOD

The basic idea of the new technique described in this paper is based on the injection of pulses into the zero sequence system of the network. It can be shown that the equivalent circuit diagram of the zero sequence system of compensated networks consists of a parallel-resonant circuit formed by the sum of the phase-earth capacities of the whole network in parallel with the inductivity of the Petersen coil, driven by a current source which represents the injection pulse current (Fig. 1).

The Laplace transform of the impedance function of this parallel-resonant circuit has a damped pole at resonance frequency. If the injected current signal is similar to a Dirac pulse in time domain, the Fourier transform delivers constant spectral values over a wide range of frequencies in the frequency domain.

This fact induces in consequence a strong excitation of the zero sequence network pole, even with small injection signal amplitudes and *independent of the detuning of the system*. This means that a pulse injection into the zero sequence system overlays a damped, high amplitude sine wave signal to the stationary zero sequence voltage signal. The frequency of this overlaid signal is defined by the pole.

Additionally, with the injection of suited pulse patterns into the zero sequence system of the network the zero sequence admittance spectrum in the range from approx. 5 Hz up to 300 Hz can be estimated with high numerical stability.

This spectral information together with the knowledge of the network topology allows the spectral calculation of the

worst case fault current conditions occurring in the case of very low-ohmic earth faults. The knowledge of the maximum spectral fault current components is important for the network operator to predict worst case earth fault currents in advance and guarantees compliance to regulations regarding maximum values of allowed earth fault currents.

Furthermore, the knowledge of the spectral components of the zero sequence admittance is needed for the reconstruction of the earth fault current which occurred at the fault location as a function of time (post mortem analysis).

### CALCULATION OF THE ZERO SEQUENCE PARAMETERS

A necessary precondition for the model of the zero sequence system of the whole network is the definition of a mathematical algorithm for the description of specific line elements. This model has to describe the behaviour of the specific line elements in a predefined frequency range sufficiently and accurately.

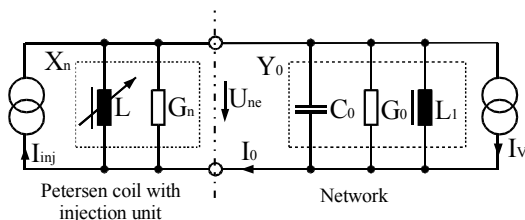
#### Low Frequency Range

If the considered frequency range is limited to frequencies lower than 80 Hz, the equivalent circuit describing the electrical relation between zero sequence current and zero sequence voltage of a line section can be approximated with a parallel circuit consisting of the sum of the zero sequence capacities and the sum of zero sequence conductances of all line elements over this section. The Laplace transform of the admittance of this parallel circuit is denoted as earth admittance  $Y_0(s)$ . The term of the so called “displacement current”  $I_v(s)$  is taken into consideration by superimposition of effects. It is easy to show that the spectral components of the displacement current  $I_v(s)$  consist of the sum of a part with network frequency and the odd harmonic parts. The reason for such displacement currents are differences both in the phase-earth parameters and also of the phase voltages. Eq.(1) describes the relation between the Laplace transforms of the zero sequence voltage and the zero sequence current of a specific line element under consideration of an uncorrected fault current term  $I_{f0}(s)$  in the case of an earth fault.

$$I_0(s) = U_{NE}(s) \cdot Y_0(s) + I_v(s) + I_{f0}(s) \quad (1)$$

Fig. (1) shows the equivalent circuit diagram that describes the behaviour of a whole network  $Y_0(s)$  in parallel with the Petersen coil and the injection current source.

For low frequencies the zero sequence parameters of the network can be described by the sum of all phase-earth capacitances  $C_0$  and the sum of all phase-earth conductances  $G_0$  and a possibly present additional coil  $L_1$  within



**Figure 1: Equivalent Circuit Diagram for the Injection into the Zero Sequence System**

the compensation area.

The pulse-formed injection signal  $I_{inj}(t)$  causes both a displacement in the zero sequence voltage signal  $U_{NE}(t)$  and the zero sequence current signal  $I_0(t)$  from the stationary (steady) state. The stationary states of the zero sequence voltage and zero sequence current are caused by signals with network frequency and its odd harmonics. If these stationary signals are extrapolated continuously for the time after the pulse injection ( $t=0$ ) and are subtracted from the currently measured signals of  $U_{NE}(t)$  and  $I_0(t)$  after the start of the pulse injection ( $t=0$ ), the resulting differences describes the effect of the injection pulse signal  $I_{inj}(t)$  into the zero sequence system. Therefore these two signal differences are denoted as zero sequence voltage response  $\Delta U_{NE}(t)$  and zero sequence current response  $\Delta I_0(t)$ . It is import to highlight that the usage of these zero sequence voltage and current differences ( $\Delta U_{NE}(t)$  and  $\Delta I_0(t)$ ) eliminates the influence of the displacement current  $I_v(t)$  on these signals and therefore the displacement current can be removed from the equivalent circuit.

The functional relation between  $\Delta U_{NE}(s)$  and  $\Delta I_0(s)$  in the frequency domain is described by Eq.(2). The parameters  $G_0$ ,  $C_0$ , and  $L_1$  of the zero sequence system of the network can be calculated by usage of a best-approximation method either in time or frequency domain. Parseval’s equality shows the equivalence of the error functions from the different approximation methods in time or frequency domain. Therefore whether using frequency or time domain we can expect equivalent results for the quality of the approximation methods. It is simple to show that the result of the transformation of Eq.(2) back to the time domain results in a linear differential equation of 2<sup>nd</sup> order.

$$\Delta I_0(s) = [\Delta U_{NE}(s)] \cdot G_0 + [\Delta U_{NE}(s) \cdot s] \cdot C_0 + [\Delta U_{NE}(s) / s] \cdot (1 / L_1) \quad (2)$$

The Petersen coil parameters  $L$  and  $G_n$  can be calculated in an analogous way using also a best-approximation method. Because of Fig.(1) the calculation of the Fourier transform of the parallel circuit of the parameters  $L$ ,  $G_n$ ,  $C_0$ ,  $G_0$  and  $L_1$  describes the admittance of the zero sequence system of the whole network. Because the real part of the zero sequence network admittance is independent of the frequency, the minimum of the absolute value of this admittance is given at that frequency where its imaginary part is zero. This frequency is a good approximation for the resonant frequency induced by the described pole of the zero sequence system. Eq. (3) describes the well known parallel circuit resonance condition.

$$\omega_{res}^2 \approx (L + L_1) / (L \cdot L_1 \cdot C_0) \quad (3)$$

The resonant frequency  $\omega_{res}$  can be determined also in a simpler manner.

Using Eq.(2) at points of time after the injection pulse is finished for more than several milliseconds, the injection current  $I_{inj}(t)$  can be set to zero.

Therefore the zero sequence current response  $\Delta I_0(s)$  can be replaced by the coil current flowing trough  $L$  and  $G_n$ . After several transformations and neglecting of the start condition we get as result Eq.(4).

$$[-\Delta U_{NE}(s) \cdot s] = [\Delta U_{NE}(s)] \cdot \{(G_n + G_0) / C_0\} + [\Delta U_{NE}(s) / s] \cdot \{(L + L_1) / (L \cdot L_1 \cdot C_0)\} \quad (4)$$

We see that the resonant frequency  $\omega_{res}$  from Eq.(3) is contained in Eq. (4) as an unknown constant. Both constants of Eq.(4) marked by curly brackets  $\{ \}$  can be calculated also by a best-approximation method in either the frequency and/or the time domain as mentioned above.

Furthermore, this method has the advantage that the algorithm uses only the signal of the zero sequence voltage for the estimation of the resonance frequency.

Additionally it should be noted that Eq.(4) describes the behaviour of an exponential damped sine wave. Therefore the requirements in accuracy for the zero voltage measuring equipment are very low because just the resonance frequency is to be calculated and so phase- and amplitude errors of the measuring equipment do not influence the correctness of the result.

### Medium Frequency Range

The mathematical description of the behaviour of the zero sequence admittance in the frequency domain from a line segment or a given line topology for the frequency range up to approximately 300Hz needs a more complex and higher order model.

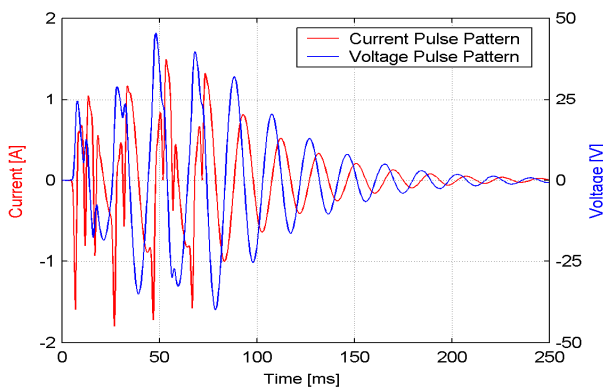
The upper limit of the frequency spectrum used and the necessary accuracy of the mathematical zero sequence admittance model define the order of the polynomials of the resulting fractional transfer function.

Basically it can be shown that also for high order line models Eq.(1) can be used structurally. In this case the earth admittance  $Y_0(s)$  of Eq.(1) is represented by a fractional-polynomial transfer function of high order, whereas the properties of the displacement current  $I_v(s)$ , especially the harmonic content and the periodicity regarding the network frequency, remains unchanged. The uncorrected fault current term  $I_{f0}(s)$  can be used in an analogous way too.

It is easy to show that the fault current signal  $I_{f0}(s)$  of Eq.(1) corresponds to the real earth fault current signal in the case of faults which occurred close to the bus bar.

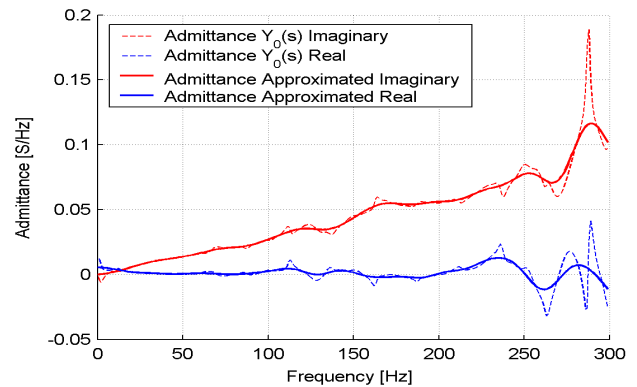
Taking into consideration the fault location and the network topology of the faulty branch, the exact fault current signal can be reconstructed with a specifically designed correction filter.

For the fault current reconstruction the knowledge of the Fourier transform of the network earth admittance  $Y_0(j\omega)$  is



**Figure 2:**  $\Delta U_{NE}(t)$  and  $\Delta I_0(t)$  during and after Injection

necessary. As already presented in several ARS publications and patents, the spectrum of the earth admittance can be determined in a simple way by pulse injection into the



**Figure 3:** Earth Admittance Spectrum  $Y_0(s)$

zero sequence system of the network. Of course it is possible to produce a certain pattern of single pulses to excite specific parts of the spectrum. Analogously to the parameter estimation method for the low frequency range, just the signal differences  $\Delta U_{NE}(t)$  and  $\Delta I_0(t)$  induced by the described injection pulse pattern are used for the algorithm. Figure 2 shows the zero sequence response signals  $\Delta U_{NE}(t)$  and  $\Delta I_0(t)$  during and after the pulse injection in time domain.

These two response signals have some interesting characteristics. In the time before the injection they are zero per definition. Furthermore, the amplitudes of these continuous response signals are limited and reach zero again after a certain time. These signal properties guarantee the existence of the Fourier Integrals and therefore there are no formal difficulties to use the Fourier transformation algorithm. The Fourier transformation of the earth admittance  $Y_0(j\omega)$  can be defined as quotient of the spectral parts of the Fourier transforms from current and voltage response signals in the following manner:

$$Y_0(j\omega) = [\Delta I_0(j\omega) / \Delta U_{NE}(j\omega)]; \forall \omega \in [\omega_{min}; \omega_{max}] \quad (5)$$

One of the conclusions of the line theory is the fact that in the case of a homogenous line the expected admittance spectrum has an equidistant pole-zero distribution.

Because of the mix of overhead lines and cables as well as mixed and meshed topologies in practical applications the spectrum of the earth admittance of a whole network  $Y_0(j\omega)$  will consist of a sum of (overlay of) different non-linear spectral admittance functions with a very complex pole-zero configuration. Especially the poles of the earth admittance spectrum will cause significant numerical problems in practice, because at the related frequencies (points) the spectral part of the voltage response  $\Delta U_{NE}(j\omega)$  tends towards zero and therefore the quotient of the spectral parts of the zero sequence current response and zero sequence voltage response will tend towards infinite with a resultant numerically bad condition.

To overcome this numerical problem a mathematical method was developed which approximates the spectrum of the earth admittance function. Fig.(3) shows the earth admittance spectrum of a typical network. The calculated spectrum in accordance with Eq.(5) is represented by the dotted and the result of the approximation algorithm by the solid lines.

It should be highlighted that a linear interpolation method for the numerically bad conditioned pole regions of the admittance function produces bad errors and therefore it is not applicable because of the strong curvature of the admittance function, especially in proximity of the poles.

## PREDICTION OF THE EARTH FAULT CURRENT SPECTRUM

Taking into account that during an earth fault the injection current signal  $I_{inj}(t)$  is zero and considering that the admittance spectrum of the Petersen coil  $Y_L(j\omega)$  and the earth admittance spectrum of the whole network  $Y_0(j\omega)$  is known, the spectrum of the uncorrected earth fault current  $I_{f0}(j\omega)$  can be calculated as a conclusion of Eq.(1) in the following manner:

$$I_{f0}(j\omega) = [-U_{NE}(j\omega)] \cdot [Y_0(j\omega) + Y_L(j\omega)] + I_v(j\omega) \quad (6)$$

The elimination of the disturbing displacement current spectrum  $I_v(j\omega)$  is carried out analogously by the usage of voltage differences. This voltage response  $\Delta U_{NE}(t)$  represents the difference of the actual voltage signal during a fault condition and the periodically extrapolated steady state voltage signals before the fault occurred.

Applying the superimposition principle in the mentioned manner, the disturbing displacement current term  $I_v(j\omega)$  from Eq.(6) is eliminated by difference operation and facilitates the calculation of the uncorrected earth fault current:

$$I_{f0}(j\omega) = [-\Delta U_{NE}(j\omega)] \cdot [Y_0(j\omega) + Y_L(j\omega)] \quad (7)$$

In the case of low-ohmic earth faults (worst case conditions) the sum of the neutral-earth voltage and the voltage of the faulted phase is approximately zero. So the spectral parts of the voltage response signal  $\Delta U_{NE}(j\omega)$  can be replaced directly by the spectral parts of the voltage signal from the faulted phase.

Measuring of all three phase voltages, calculation of their Fourier spectral components and substitution of  $\Delta U_{NE}(j\omega)$  by the Fourier spectrum of the measured phase voltages in Eq.(7) induces the possibility to calculate a prediction for the spectral components of the fault current in the case of a low-ohmic earth fault near the bus bar (worst case scenario). To increase the operational safety the results of the predicted earth fault current spectrum can be monitored continuously.

## FAULT CURRENT RECONSTRUCTION

According to Eq.(1), the zero sequence current of a line segment of a branch or of the whole network can be calculated as the sum of the zero sequence currents caused by the earth admittances  $[U_{NE}(s) \cdot Y_0(s)]$ , the displacement current  $I_v(s)$  and in case of an earth fault the uncorrected earth fault current  $I_{f0}(s)$ .

Using the method of signal differences to eliminate the influence of the displacement current in Eq.(1) in an analogous way as mentioned above we define the two resulting signal responses as  $\Delta U_{NE}(t)$  and  $\Delta I_0(t)$  in time domain and  $\Delta U_{NE}(s)$  and  $\Delta I_0(s)$  in frequency domain respectively. After elementary transformations of Eq.(1) we get the equation

for the uncorrected earth fault current  $I_{f0}(s)$ :

$$I_{f0}(s) = \Delta I_0(s) - [\Delta U_{NE}(s) \cdot Y_0(s)] \quad (8)$$

As already mentioned, the Laplace transform of the real (corrected) earth fault current  $I_f(s)$  at the fault location can be calculated by the application of a special correction filter  $K(s)$  according to Eq.(9), which is determined by a complex algorithm taking into account the fault location, the network topology and many other line parameters.

$$I_f(s) = K(s) \cdot I_{f0}(s) \quad (9)$$

It should be noted that the influence of this correction filter on the accuracy of the reconstruction algorithm is significant for fault current spectral components with frequencies  $> 100$  Hz and/or fault distances more than several kilometers from the bus bar.

Eq.(8) and (9) describe a method to calculate the fault current at the fault location by measuring  $U_{NE}(t)$  and  $I_0(t)$  in the substation as well as by the determination of the earth admittance  $Y_0(s)$  of a faulty line segment, branch or network and by the application of a special correction filter  $K(s)$ .

Fig. (4) shows the reconstructed and the measured earth fault current at the fault location of an earth fault in a real network.

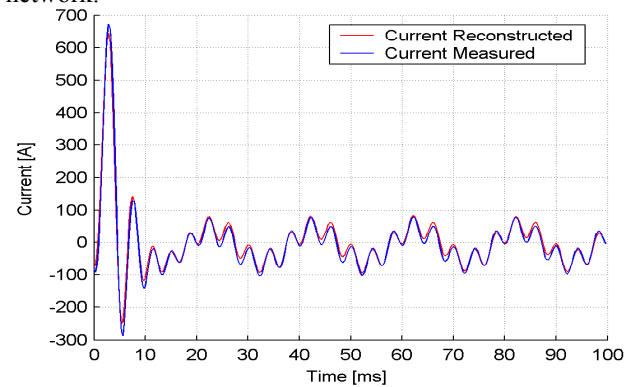


Figure 4: Earth Fault Current Reconstruction

## SUMMARY

This paper describes the new pulse injection method for compensated networks with the following advantages:

- Determination of the resonance point in compensated networks.
- The application of three different methods increases the security of the resonant point tuning process significantly (diversitive redundancy).
- Estimation of all relevant parameters of the zero sequence system.
- Determination of the earth admittance spectrum for the frequency range from 5 to 300 Hz.
- Prediction of the spectrum and the root mean square value of the maximum values of expected earth fault current (worst case scenario).
- Reconstruction (post mortem analysis) of the earth fault current which occurred at the fault location using the measured zero sequence current and the zero sequence voltage signal by consideration of the fault distance and the topology of the faulted branch.