# NEW METHOD FOR THE STATE EVALUATION OF THE ZERO-SEQUENCE SYSTEM

**Gernot DRUML**
A. Eberle GmbH
Germany
g.druml@ieee.org

**Olaf SEIFERT**
Dresden University of Technology
Germany
seifert@ieeh.et.tu-dresden.de

**Abstract – In this paper we present a new method for the evaluation of the zero-sequence network parameters by injecting two frequencies in the zero-sequence system. These parameters can be used for the decision to move a Petersen-Coil and also for the high ohmic earth fault detection in resonant grounded networks.**

**The major problems for the correct calculation of the line-to-ground capacity ,respectively of the resonant-point are the missing or very low zero-sequence voltage and the non negligible crosstalk of the varying load currents to the zero-sequence-voltage. As a consequence, the number of tuning operations and non correct tuning operations increases in today's networks.**

**The new method uses the injection of two currents with frequencies unequal to 50 Hz into the zero-sequence system for the calculation of the network parameters. Therefore it is possible to supervise complete symmetrical networks and to suppress the 50 Hz crosstalk of the load current. In consequence, the number of coil movements and also the number of wrong tuning positions are drastically reduced. This new method can be extended for the estimation of the parameters of each feeder, to detect also high ohmic earth faults.**

***Keywords: resonant grounded system, earth fault, high ohmic earthfault detection, current injection, Petersen-Coil***

## 1 INTRODUCTION

The tuning of the Petersen-Coil is a preventive operation already done in the healthy network. With the existing methods it is not possible to determine the network parameters during a solid earthfault. The fault location and the resistance at the fault location are unknown and are not accessible for a measurement. In case of a solid earthfault, the zero-sequence voltage is impressed and the measurement of the zero-sequence current at the fault location is impossible. The zero-sequence current can only be measured at the substation or in some cases at some dedicated switching-stations.

In the past, different control algorithms were developed. Most of these algorithms are based on the necessity to move the Petersen-Coil. The development of today's distribution networks is characterized on one side by an increase of symmetrical cables, which results in smaller usable zero-sequence-voltages and, on the other side, in an increase of the crosstalk of the positive sequence of the load current to the zero-sequence system. With the decreasing zero-sequence voltage the controller must be set much more sensitive. Due to the crosstalk of the load current to the zero-sequence voltage, each change of the load current can release a tuning operation, which is, in most of the actual algorithms, combined with a physical movement of the Petersen-Coil. Due to the disturbances the state and parameter estimation of the network is much more difficult and results in a necessary movement of the Petersen-Coil over a longer distance. Nevertheless, sometimes a correct tuning is impossible.

One problem arises because the motor-drive of the Petersen-Coil is only designed for few tuning operations per day. The other problem arises because of the longer detuning time. This is caused by the increase of tuning cycles, respectively by wrong tuning positions.

Therefore it is necessary to find methods, which are able to find the correct tuning position, even if the natural zero-sequence voltage is zero, respectively if the disturbances in the zero-sequence voltage are not negligible. Additionally, the number of necessary moving operations should be reduced.

## 2 DISTURBANCES OF THE CONTROL OPERATION

Using the standard simplified equivalent circuit for a resonant grounded system [3],[1] as it is shown in *Fig. 1* it seems to be very easy to find the resonance point of the sound network, even for very small neutral-to-earth voltages.

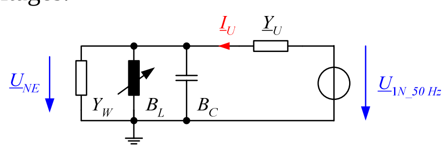


*Fig. 1: Standard equivalent circuit for a resonant grounded system*

The problem becomes more difficult because several disturbances generate an additional non-zero neutral-to-earth voltage $\underline{U}_{NE}$. Thus, it is very difficult for the control algorithm to distinguish between "real" resonance points and "fictitious" resonance points, caused by the disturbances.

### 2.1 Description of the network

The network under consideration consists of a transformer, the Petersen-Coil, a transmission line and a load as depicted in *Fig. 2*.

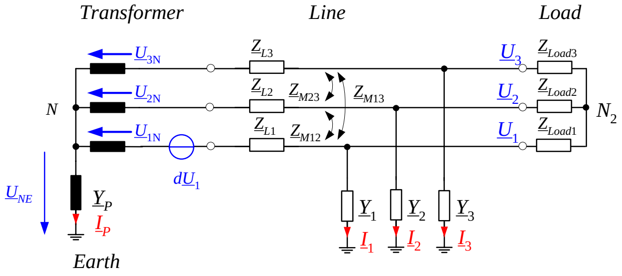


*Fig. 2: Equivalent circuit for the investigation of disturbances on $\underline{U}_{NE}$*

For the sake of clarity, we further assume, without restriction of generality, that unbalances of the transmission line only occur in phase 1. Furthermore, the mutual coupling of the transmission lines is neglected, because if the network is symmetrical this only has minor influence on the results. The case of asymmetrical mutual coupling can be treated in a similar way as an unbalance in the series reactance of one phase. It is worth mentioning that the equations for a complete description of the different coupling effects of networks with asymmetrical components are very complex, and cannot be simplified by using the classical symmetrical component concept.

The disturbances can be summarized to the following three main coupling effects [3] based on *Fig. 2*:

1. Unbalance of the voltage
2. Unbalance of the line-to-earth capacitances
3. Coupling of the load current over the normally negligible series line resistances and reactances

The second item results in a natural unsymmetry, which depends more or less on the natural capacitive unbalance of the network. Due to the voltage drop along the line, the unbalance can change in a small range with the change of the load current (see *Fig. 3*). Also changes of the load current in other feeders, not shown in *Fig. 2* influence the residual voltage $\underline{U}_{NE}$..

The tap-change of the transformer also influences the zero-sequence voltage, mainly by changing the size of $\underline{U}_{1N}$ , but also by an additional unsymmetry.

The most important result describes item 3. Due to this behaviour, an additional phasor is added to the natural $\underline{U}_{NE}$ and the size of this phasor depends on the size of the load current (see *Fig. 4*). This phasor is added in the complex plane to the natural unbalance and can increase or decrease the residual voltage $\underline{U}_{NE}$. Especially in symmetrical networks the resulting relative changes of the residual voltage, due to the crosstalk, become very large and are not more negligible.

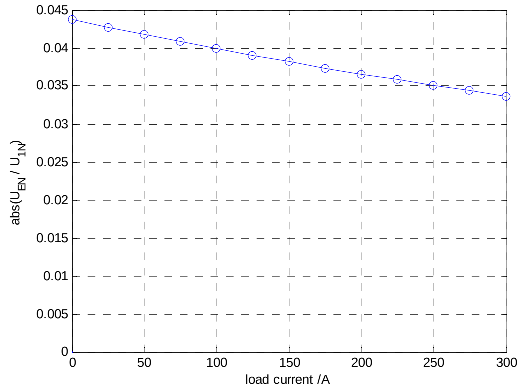


*Fig. 3: Neutral-to-earth voltage due to the voltage drop along the line*

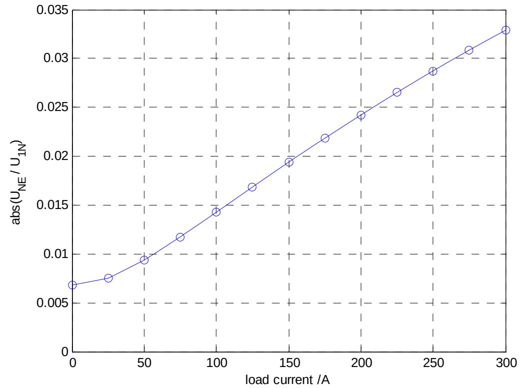


*Fig. 4: Neutral-to-earth voltage due to an unbalance of the serial impedances in the line*

The asymmetry of a line may be caused for example by the kind of cable laying, as shown in *Fig. 5*a (for further details the reader is referred to [5], [6], [7], [9]). If the cables are laid in a triangle like in *Fig. 5*b the mutual coupling of the three phases is obviously the same. A similar situation can be found for overhead lines where an improvement can be made by transposing the phases.

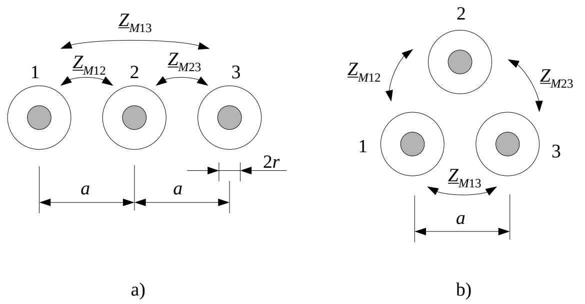


*Fig. 5: a) Single conductor cables in parallel.*
*b) Single conductor cables in triangle*

## 3 CONTROL ALGORITHMS

### *3.1 Existing Algorithms*

Up to now, mainly the following algorithms are used to determine the network parameters respectively to tune the Petersen-Coil. The relative change of the zero-sequence voltage is normally used as the criterion for the detection of a switching operation in the network.

1. **Artificial Earthfault**

By measuring the current over the artificial earthfault location and searching for the minimum of the current by tuning the Petersen-Coil, the tuning point and the parameters of the equivalent network can be determined. This method is actually only used to check the quality of a control algorithm.

2. **Search of max | $\underline{U}_{NE}$ |**

This algorithm searches the maximum of the residual voltage. Improved versions of this algorithm determine additionally the network parameters by using the $\sqrt{2}$ method [3]. Alternative algorithms are using least-square techniques to estimate the network parameters already from a part of the resonance curve.

3. **Least square based on | 1/$\underline{U}_{NE}$ |**

A lower sensitivity against disturbances can be reached by using an algorithm based on the inverse of the resonance curve [1][3].

4. **Locus Diagram of $\underline{U}_0$**

This method is based on the fact that a circle can be constructed with only three points. This method assumes that the third point of the circle is the origin of the complex plane. A short detuning can be achieved for example by switching a capacity in parallel to the Petersen-Coil. This switching results in a second point of the locus diagram of $\underline{U}_{NE}$. Measuring the voltage with amplitude and angle it is possible to construct the locus diagram.

5. **50 Hz Current Injection**

This algorithm is based on the idea to inject an artificial current into the neutral point of the system if there is no unsymmetrical current from the natural unsymmetry. The influence of the natural unbalance can be partly compensated by using a differential measurement from two time points. Eq. (1) in combination with the coil position enables to determine the network parameters.

$$\underline{Y}_{CI} = \frac{d\underline{I}_{CI}}{d\underline{U}_{NE}} \approx Y_W + j(B_C - B_L) \qquad (1)$$

### *3.2 New Algorithm*

**Principle**

All the existing algorithms are based on the fact, that the residual voltage is generated either by the natural unbalance of the network or by an artificial 50 Hz current injection. These methods are assuming, that there is no change in the network respectively no change of the crosstalk of the load current during the calculation period. Please pay attention that the calculation period can last from several seconds up to several minutes.

In reality there are a lot of situations where these assumptions are not valid, for example in the sphere of heavy industry with symmetrical networks but heavy changes of load.

The new CIF-algorithm (Control by Injecting Frequencies) suppresses the 50 Hz crosstalk from the load current by using frequencies unequal to 50 Hz for the measuring and for the parameter estimation.

The simplified equivalent circuit with a current injection according to *Fig. 6*

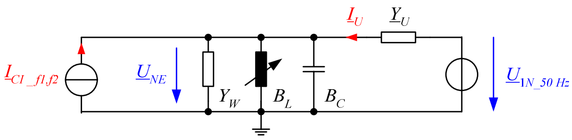


*Fig. 6: Simple equivalent circuit with current injection*

results for the frequencies unequal to 50 Hz to *Fig. 7*

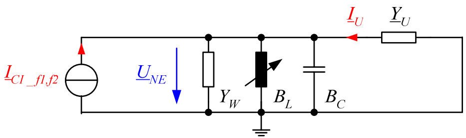


*Fig. 7: Simple equivalent circuit with current injection unequal to 50 Hz*

For the frequency *fn* the admittance, seen from the current injection, can be described as:

$$\underline{Y}_{CI\_fn} = \frac{\underline{I}_{CI\_fn}}{\underline{U}_{NE\_fn}} = \underline{Y}_U + Y_W + j(\omega_n C - \frac{1}{\omega_n L}) \qquad (2)$$

For symmetrical networks with a small $\underline{Y}_U$ this results in

$$\underline{Y}_{CI\_fn} = \frac{\underline{I}_{CI\_fn}}{\underline{U}_{NE\_fn}} \approx Y_W + j(\omega_n C - \frac{1}{\omega_n L}) \qquad (3)$$

Using two different frequencies $f_1$ and $f_2$ one gets two complex equations with three variables, which leads to the following solution:

$$Y_W = real\left\{\frac{\underline{I}_{f1}}{\underline{U}_{NE\_f1}}\right\} \quad (4)$$

$$C = \frac{imag(\underline{Y}_{CI\_f1})\,\omega_1 - imag(\underline{Y}_{CI\_f2})\,\omega_2}{\omega_1^2 - \omega_2^2} \quad (5)$$

$$L = \frac{1}{\omega_1(-imag(\underline{Y}_{CI\_f1}) + \omega_1 C)} \quad (6)$$

Assuming a linear system enables the current injection of two frequencies and evaluation of the corresponding $\underline{Y}_{CI\_fn}$ at the same time. This results in very fast measurement possibilities and depends more or less on the used frequencies and filter algorithms [8]. The duration of the measurement is usually in the range of 240 ms.

The following items list the main advantages of this new CIF-algorithm:

- Very fast measurement
- Suitable also for symmetrical networks
- Determination of the sum of all Petersen-Coils including distributed fixed-coils in the compensated area
- Insensitive to the 50 Hz open-delta VT error
- Suppression of 50 Hz crosstalk

### Additional requirements

Depending on the resonance curve and the normal operation philosophy of the network, there arise some additional requirements for the current injection.

1) The injected current should be variable in the amplitude to enable adaptation to the losses of different switching states of the network.

One of the most used criteria for the earthfault detection is the zero-sequence voltage. In small networks the losses in the network are smaller, so that only a reduced current should be injected, not to exceed the threshold level of the earthfault detection system, especially in the resonance point.

On the other side, in case of situations with a large detuning a small injected current will not deliver a reliable measurement of the residual voltage $\underline{U}_{NE\_fn}$. In this case a higher injected current is recommended.

2) The injected frequencies should not include 50 Hz components.

3) Using a current injection with variable frequencies, it is possible to select the injected frequencies in such a way, that these frequencies are near to the resonance of the network. In this case small injected currents result in large values of the residual voltage. The accuracy of the parameter estimation is increased, especially for systems with a large standard detuning.

### Operation philosophy

Depending on the operation philosophy the current injection can be activated only for a short time after the detection of an essential relative change of the zero-sequence voltage, to check if a new tuning of the Petersen-Coil is necessary. In symmetrical networks the current injection can be switched on continuously, to detect any switching operation in the network immediately. Combinations of these two philosophies are possible, for example to check every 10 min the actual network parameters in symmetrical networks.

### More Precise Models

In *Fig. 8* a connection of the Petersen-Coil to the neutral point of the transformer is shown. For a more accurate calculation of the network including a Petersen coil, as shown in *Fig. 8* , it is necessary to use a more precise equivalent circuit as depicted in *Fig. 9*.

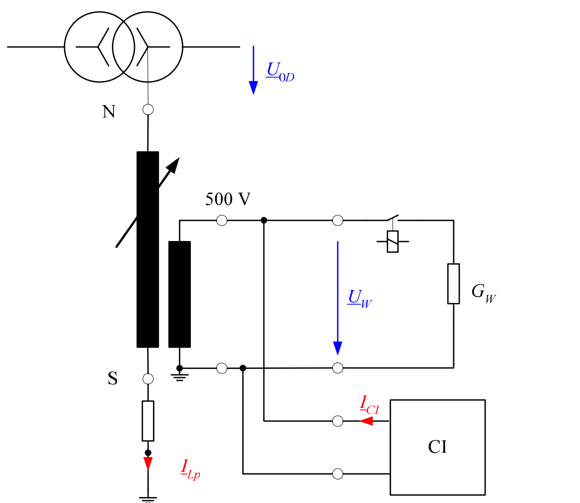


*Fig. 8: Petersen-Coil with current injection (CI) and wattmetric increase $G_W$*

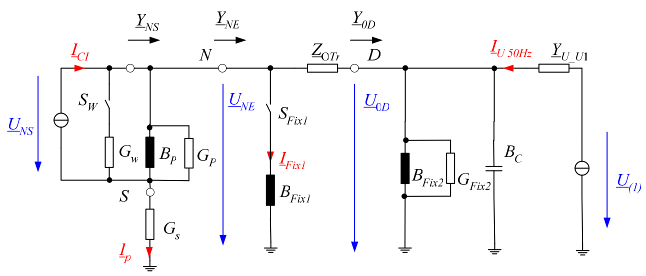


*Fig. 9: Simple equivalent circuit with current injection (CI) and wattmetric increase $G_W$*

Using frequencies unequal to 50 Hz enables now an accurate measurement of the following components during normal operation of the network

- Zero-sequence capacity of the network
- External Petersen Coils existing in the network (distributed Petersen-Coils)
- Zero-Sequence Impedance of the Transformer
- Values of the fixed-coils in the substation
- Detuning
- Value of additional damping resistors
- Calculation of the unsymmetry of the network

### *3.3 High Ohmic Earthfault Detection with the DIF-algorithm (Detection by Injecting Frequencies )*

The parameter estimation of the network can be extended for each feeder by measuring the injected currents in each feeder of interest either with the Holmgreen-Circuit (summation CT) or with the core-balance transformer.

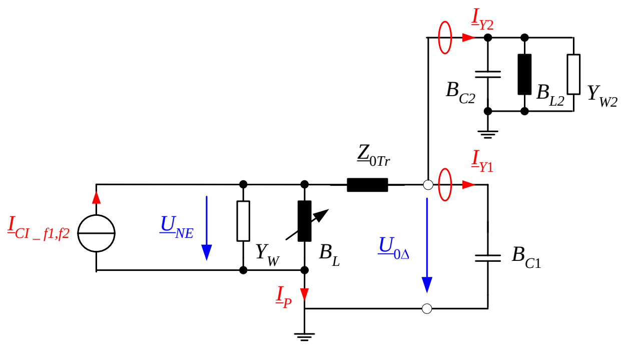


*Fig. 10: Parameter estimation for each feeder*

As the crosstalk from 50 Hz is suppressed, the measurement of $\underline{U}_{0D}$ can be used for the calculation of the essential parameters for each line.

It is possible to calculate the capacitive part $B_{Cx}$, the losses $Y_{Wx}$ and the size of distributed coils $B_{Lx}$ seen on feeder x, with the same method as explained above. By using additionally the 50 Hz components at the same time, the actual unbalance of the network can be determined and supervised.

The advantage of this algorithm is, that all measurements are made at the same time. The usual problem to check for a switching operation is removed. The determination of the network parameter is included in the algorithm directly.

### *3.4 Types of multi-frequency Current Injections (CI)*

The most simple way is to use a standard frequency converter (FC) in the mode of a current source as shown in *Fig. 11*. To reduce the disturbances on the 400 V side, a frequency converter with a power factor correction module (PFC) is recommended [4]. The coil L1 respectively the parallel circuit L1//L2 is used to convert the pulsed voltage to an impressed current. The size of L1//L2 defines the maximum available injected current. The auxiliary winding of the Petersen-Coil is usually designed for 500 V, which makes necessary, in these cases, an additional transformer for the adaptation. With this type of current injection two currents with individual amplitude, frequency and phase can be injected very easy. On the other side the physical realisation is not the cheapest one.

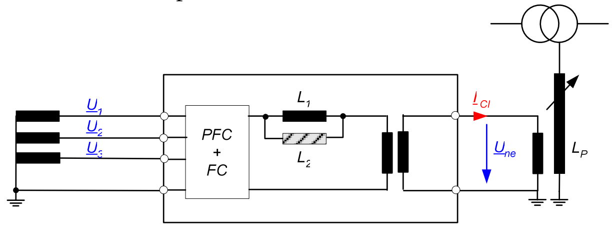


*Fig. 11: Current injection using a Frequency-Converter(FC) with Power-Factor-Correction (PFC)*

If the requirement for variable frequencies is cancelled, a much cheaper version to generate a current with more frequencies is available, as shown in *Fig. 12*.

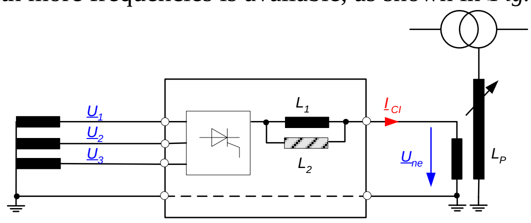


*Fig. 12: Current injection with AC-switch for three frequencies (AC-1)*

The following figure shows one possible pattern of pulses for the current injection.

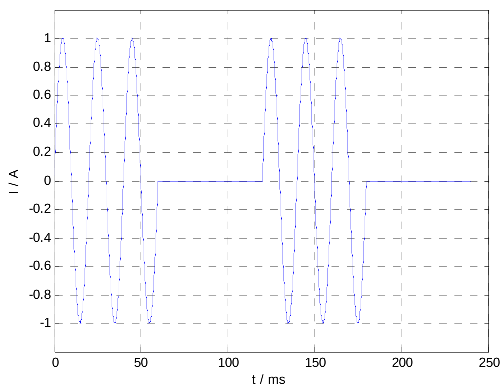


*Fig. 13: Sample pulse pattern for AC-1*

The corresponding frequency spectrum is shown in *Fig. 14*.

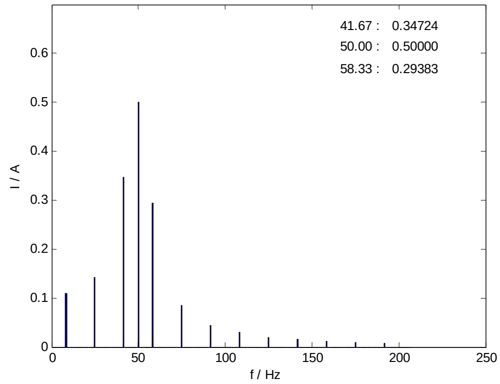


*Fig. 14: Frequency spectrum for AC-1*

The major disadvantage of this type of current injection is that the main spectrum of the injected current is 50 Hz. This can be avoided by the following type of thyristor-switch, where it is possible to invert the direction of the current during the previous pause time.

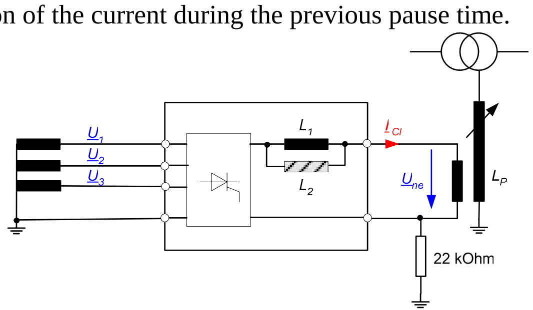


*Fig. 15: Current injection with AC-switch for two frequencies (AC-2)*

The resulting pulse pattern is shown in *Fig. **16***

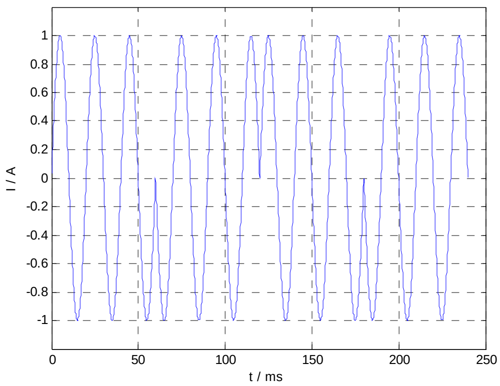


*Fig. 16: Sample pulse pattern with AC-2*

with the corresponding frequency spectrum shown in *Fig. **17***

Depending on the pulse pattern and the number of periods different frequencies are available. The previous figures show a 100 % phase-firing. The amplitude can be reduced by a reduced phase-firing, as for example depicted in *Fig. **18***. This AC-switch (AC-2) can also be used to generate the pattern for three frequencies like shown in *Fig. **13***.

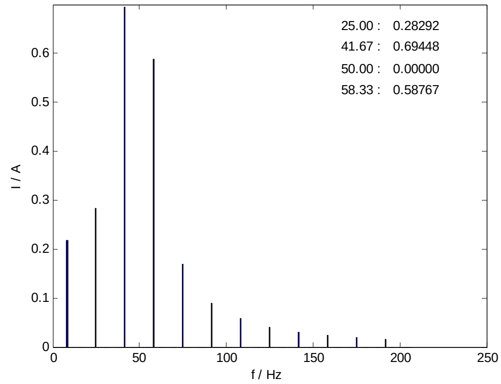


*Fig. 17: Frequency spectrum for AC-2*

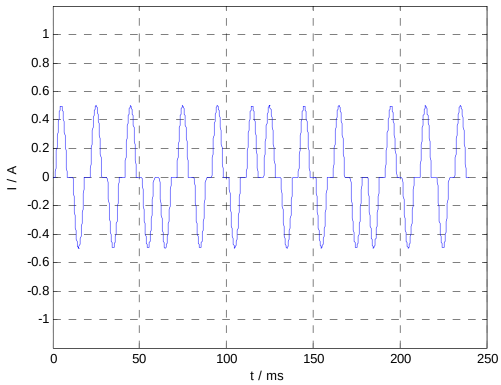


*Fig. 18: Sample pulse pattern with AC-2 with phase-firing*

## 4 RESULTS OF FIELD TESTS

In the meantime, the new algorithms have been implemented in real hardware and they have shown their advantages in real network configurations.

The following picture shows for example a 19” rack with two controllers using the CIF-Algorithm for two Petersen-Coils and one earthfault monitoring and detection system for up to 40 feeders using the DIF-Algorithm.


*Fig. 19: EDCSys (Earthfault Detection and Control System)*

The Current Injection, type AC-Switch, has been included directly in the enclosure of the motor-drive of the Petersen-Coil.

*Fig. 20: 375A – Petersen Coil with AC-Switch Current Injection and Resistor for Wattmetric-Increase.*

This combination has been used for tests in a real network with different artificial high ohmic earthfaults of 20kOhms in different phases. The estimation of the 20 kOhm unbalance was detected with an accuracy of 1%. The calculation of the resonant-point under the worse condition of 250 A overcompensation had an accuracy of about 2%.

This system was tested and approved by ENEL.

## 5 CONCLUSION

In this contribution we have discussed the effects of the crosstalk of the positive sequence load current to the zero-sequence system and the consequences to existing control algorithms. With the new **Control by Injecting Frequencies** (CIF) algorithm the crosstalk can be suppressed. With the CIF a faster and more accurate state estimation of the zero-sequence system can be achieved. This results in a tuning of the Petersen-Coil with an essential reduced number of coil movements. Additional functions, like the measurement of the zero-sequence impedance of the transformer under normal operation and the use of it for the correction of the measured capacitive earth-current, can be achieved with the new CIF algorithm. With this algorithm it is possible for the first time to measure also the value of distributed Petersen-Coils.

With the new **Detection by Injecting Frequencies** (DIF) algorithm, which is based on the same measurement principles as the CIF algorithm, now a fast and high sensitive earthfault detection system is available.

The field tests and the first practical experiences have shown the effectiveness of this new concept for the control of Petersen-Coils and detection of high ohmic earthfaults.

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