NEW METHOD OF ARC SUPPRESSION COIL TUNING USING TRULY MULTIFREQUENCY CURRENT SIGNAL

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ABSTRACT

Due to significant influences of rapidly changing load crosstalk on characteristics of zero sequence voltage in resonant earthed networks there is an increasing demand for reliable method of proper and sensitive Petersen-Coil (Arc Suppression Coil, ASC) tuning. Also increasing cabling of the distribution networks causes ever higher demands on ASC tuning systems.

This paper will present new method of ASC tuning based on the injection of the multifrequency current signal into zero sequence system through network's neutral point. Measuring of voltage response in zero sequence system (Neutral Voltage Displacement, NVD) enables then to evaluate the tuning status of the ASC very precisely.

INTRODUCTION

Resonant grounding is the most commonly used method of neutral point treatment in European middle voltage distribution networks and it is increasingly being applied in other parts of the world due to its very advantageous features:

- The residual earth fault current is reduced to 2-4% of the earth capacitive current of the network.
- Most single phase earth-faults in overhead lines are cleared without any protection system reaction needed.
- Power quality and reliability for customers is higher due to lower number and shorter duration of supply interruptions.
- Risk of exceeding the permissible touch voltage is greatly reduced.

The main condition for assuring the above-mentioned positive properties of resonant grounding is a correct tuning of the Arc Suppression Coil. Standard methods require changing of the coil impedance (moving of its core) each time the coil tuning is to be verified. Another weakness of the standard tuning method is the tuning in cable networks with very low voltage unbalance (low resonant curve of Neutral Voltage Displacement).

That is why it is increasingly necessary to use the current injection method for the Arc Suppression Coil tuning. Auxiliary current signal is injected into zero sequence system, mostly through the power auxiliary winding of the arc suppression coil. Measuring of the voltage response in Neutral Voltage Displacement enables then to evaluate the tuning status of the ASC. Results of this measuring are often negatively influenced by rapidly changing load crosstalk in case of fundamental frequency current injection. That is why more developed tuning devices use current injection of different frequency than the network's fundamental.

INJECTED CURRENT

The current signal of frequency not equal to the fundamental frequency of the network is usually produced by alternating switching of both polarities of fundamental frequency voltage source over some limiting impedance. Frequency analysis is then possible based on detection of several side frequency components at a suitably selected time window. Two of these frequencies are then used for the network characteristics evaluation, i.e. calculation of actual ASC detuning and network damping.

Fig. 1 shows typical frequency spectrum (amplitudes of frequency components) of such a current signal produced by alternating switching of current of 5 A RMS value. In this case, the polarity was changed every 6 fundamental periods.

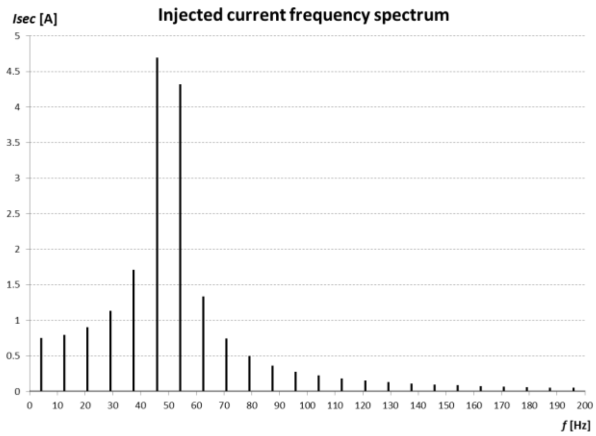

Fig. 1 Typical frequency spectrum of a current signal produced by alternating switching of fundamental frequency source.

There are some disadvantages of the above mentioned method:

- The true current source is not used, injected current value depends on the magnitude and phase shift of the actual NVD.

- As evaluated frequency components are close to the fundamental frequency, the magnitude of the voltage response to the injected current decreases rapidly with ASC detuning.
- The magnitude of generated side frequency components decreases sharply with the increasing difference of their frequency from the fundamental frequency.

With increasing ASC detuning the resonance frequency of zero sequence system of the network moves away from the fundamental frequency. In this situations it would be better to use some of the frequency components farther away from the fundamental, but in the injected current the magnitude of such components is very small (see *Fig. 1*).

Described weaknesses of signals created by the fundamental frequency switching led to the idea of using a semiconductor frequency inverter to produce a truly multifrequency current signal that would not have the above-mentioned disadvantageous properties. The main features of the method are:

- The use of a true current source to suppress the influence of the natural NVD and its changes on the generated signal.
- Injected current signal comprises only several frequency components without wasting power on producing of side frequency components not used for evaluation
- Primarily the frequency components with sufficiently high voltage response can be used to calculate the network parameters.

Suitable frequency spectrum

In practise if ASC tuneable in the range of 10-100 % of its rated current is used, resonant frequencies of zero sequence system can be expected in the range of approximately 15-160 Hz.

Fig. 2 shows the frequency spectrum of one of possible current multifrequency signals covering expectable range of resonant frequencies of zero sequence system of a distribution network. Such signal consists of 8 frequency components of equal amplitude of 2.5 A, resulting RMS value of this current is still 5 A only.

If all the frequency components of the signal have equal amplitude I_{max}, it can be inferred that the resulting RMS value of the composite signal is given by

$$I_{RMS} = \sqrt{\frac{n}{2}} I_{max}$$

where n is the number of individual frequency components.

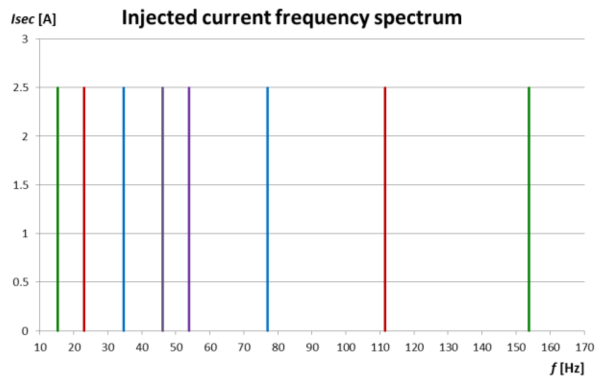

Fig. 2 Frequency spectrum of a truly multifrequency current signal.

Next diagrams show "worst case" examples of voltage response covering the expectable resonant frequency range if the multifrequency current signal is injected into network. As an example, a typical 20kV distribution network with an usual value of damping was chosen, the used ASC is tuned in interval of 60-600 A.

In the diagrams (*Fig. 3* and *Fig. 4*), the values of voltage response in NVD are displayed for all the frequency components used in the signal.

If the network has earth capacitive current I_C=60 A only, the coil can be over-tuned up to ten times (+900 % of I_C), the resulting voltage response over the whole coil tuning interval is shown in *Fig. 3*.

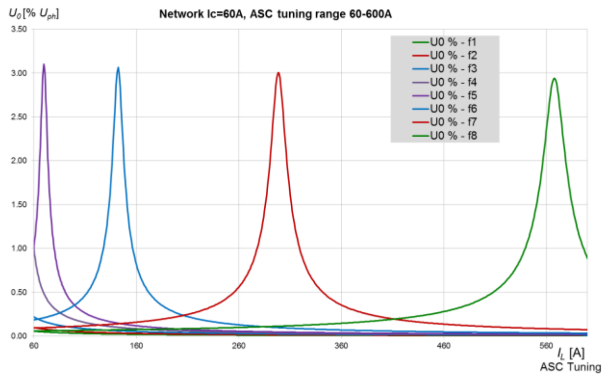

Fig. 3 Voltage response for all the frequency components in zero sequence system in case of over-tuned ASC

If the network has the earth capacitive current 600 A, the coil can be up to ten times under-tuned (-90 % of I_C), the resulting voltage response over the coil tuning interval is shown in *Fig. 4*.

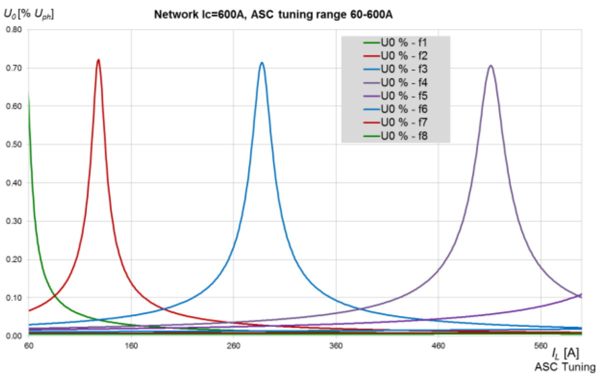

Fig. 4 Voltage response for all the frequency components in zero sequence system in case of under-tuned ASC

It is obvious that at least one frequency component is available at each point of the coil tuning range with voltage response value sufficient for evaluation of the coil tuning status.

Complementary pairs of frequency components

If the frequency components in the current signal have the same value, interesting feature can be used for a very simple method of ASC tuning. For each frequency component it is possible to find a complementary frequency whose voltage response has the same value just at the point, where the arc suppression coil is properly tuned to the resonant point for the fundamental frequency of the network. For one of these two complementary frequencies the ASC is over-tuned at this point, for the other one under-tuned. The principle of this phenomenon is shown in *Fig. 5*.

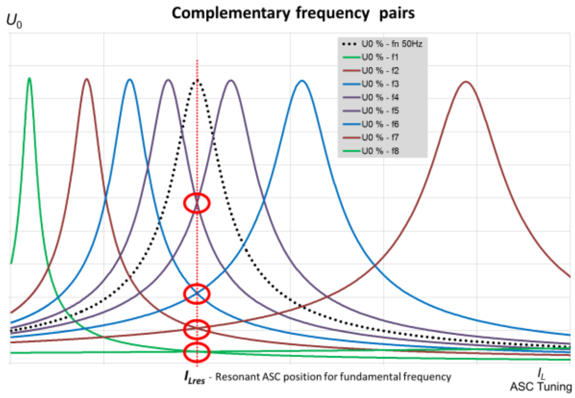

Fig. 5 The principle of complementary frequency pairs.

These complementary frequency pairs are defined by the following equation:

$$f_i \cdot f_{ii} = f_s^2$$

where f_i and f_{ii} are the frequencies of the complementary pair and f_s is the fundamental frequency of the network.

For this reason it could be advantageous to compose the signal frequency spectrum nonlinear around the fundamental frequency over the whole frequency range as it is obvious from the example in *Fig. 2*.

The basic task for the ASC tuning device is the network characteristics evaluation, i.e. calculation of actual values of earth capacitive current of the network, inductive compensation current of all the connected ASCs and network damping. When the complementary frequency pair is used, this calculation is simpler compared to using non-complementary frequencies.

Current signal composition

Fig. 6 shows the current multifrequency signal created by a simple way as a sum of 8 frequency components of equal amplitude 2.5 A, frequency spectrum of this signal is in *Fig. 1*. Resulting RMS value of this current is 5 A only, but maximal amplitude 20 A can be achieved if the phase shifts between the frequency components are not optimised.

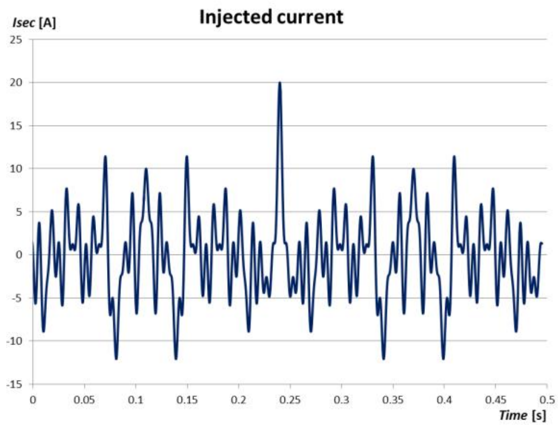

Fig. 6 Multifrequency current signal if phase shift optimization is not used.

Some advanced optimization method can be used for current signal composition leading to resulting signal with the amplitude lower than 10 A. Identification of optimized combination of phase shifts between the frequency components enables to reduce the demands on current dimensioning of used device (frequency inverter). *Fig. 7* shows an example of optimized current multifrequency signal created by 8 frequency components of equal amplitude 2.5 A.

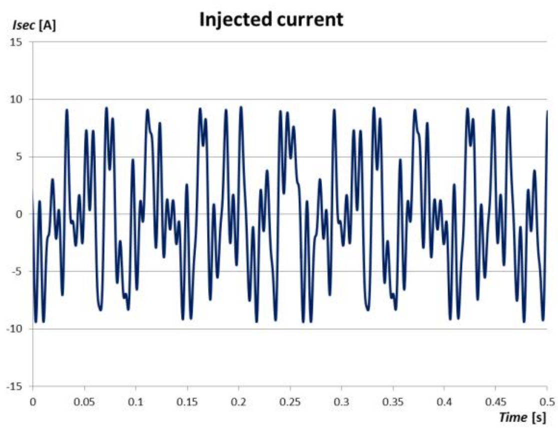

Fig. 7 Optimized multifrequency current signal.

ASC TUNING METHOD

The most important condition for proper function of ASC tuning device is the correct evaluation (measuring) of voltage response in NVD of the network for the frequency components used in injected signal.

Indirect voltage measurement

For the voltage response measuring it is possible to use external source – voltage from open delta of one-phase VTs or from a separate VT placed in the network star point. This is an increase in the installation requirements. Another possibility is to use measuring winding of ASC, but its accuracy is not high enough for correct measuring of relatively low voltage value and phase shift. Moreover, there is a problem of direct influence due to mutual inductance between the power auxiliary winding and measuring winding of ASC without "binding" over the main power winding.

To reduce device installation requirements and due to the mentioned disadvantages of using ASC measuring winding, indirect voltage measurement can be used. Voltage response in MV network is evaluated from the voltage on the power auxiliary winding where the current signal is injected. Recalculation of the measured value over the ASC model is necessary for all used frequencies. The recalculation is possible because the current is given by the injected signal and the coil parameters can be determined during commissioning.

About 20 different types of ASC were used for testing of developed mathematical model. Until now, possibility of such an indirect measurement in a real device was tested on coils with rated power between 150 kVAr and 8 MVAr with rated voltage from 3.6 kV to 38 kV.
The principle of indirect measurement and connection of multifrequency current injector (MCI) are shown in *Fig. 8*. The mathematical model of ASC is used for each frequency component "*i*" to recalculate the measured secondary voltage U_{seci} to corresponding primary side voltage component U_{0i}. This voltage component is a network response to injected primary current I_{primi}.

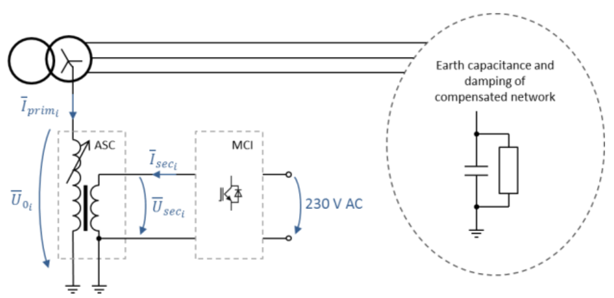

Fig. 8 Principle of indirect NVD measuring

Network parameters evaluation

When the above mentioned multifrequency current signal is injected into the power auxiliary winding of ASC and the voltage response in NVD of MV network is measured, the actual basic parameters of zero sequence system can be calculated. The zero sequence admittance of the MV network has to be determined as a complex value Y_i for every frequency component:

$$\bar{Y}_i = \frac{\bar{I}_i}{\bar{U}_i} = G_i + j \cdot B_i$$

The real part G_i corresponds to the damping and determines the active part of the earth fault residual current.

The imaginary parts B_i, B_{ii} of every pair of measured admittances enable to calculate resulting network parameters. For example, when complementary frequency pair is used, the detuning of the system for fundamental network frequency can be calculated as imaginary part of admittance:

$$\Delta B_s = \frac{f_s}{f_i + f_{ii}} \cdot (B_i + B_{ii})$$

When multiplied by network rated phase voltage U_{ph}, the system detuning can be determined in form of reactive part of the earth fault residual current:

$$\Delta I_s = \Delta B_s \cdot U_{ph}$$

Also the earth capacitive current or total capacitance between the network and the earth C_{NET} can be calculated:

$$C_{NET} = \frac{(f_s B_{ii} - f_i \Delta B_s)}{2\pi f_s \cdot (f_{ii} - f_i)}$$

or actual inductivity of all connected ASCs L_{NET} can be calculated by similar way:

$$L_{NET} = \frac{f_{ii} - f_i}{2\pi f_s \cdot (f_s B_{ii} - f_{ii} \Delta B_s)}$$

ASC TUNING DEVICE

The ASC tuning device using above mentioned innovative method should be based on a semiconductor frequency inverter which enables to produce a true current signal consisting of at least two frequency components. The possibility of generating more frequency components at the same moment covering wider frequency range and ensuring the same magnitude for all produced frequency components will be advantageous.
The control part of the device must be able to control the current signal generation and to measure the voltage

response on the primary side of ASC for all the evaluated frequency components. Calculated network characteristics can be used directly for ASC control or communicated to superior ASC controller which enables necessary HMI connection to the substation control systems etc.
Such a device will have a lot of advantages for reliable and precise ASC tuning:

- reliable tuning in very large or very damped networks
- precise evaluation of network characteristics even in case of very detuned ASC
- very low influence of rapidly changing NVD due to the load crosstalk or other reasons
- continuous evaluation of network parameters during ASC tuning
- reliable tuning and detection of network characteristics in case of more parallel operating coils without communication between their controllers
- no need of use of external VT or use of open delta VT measuring from the substation
- very low demand on power supply, the external power supply covers the losses only
- compact dimensions of the device, possibility of its simple installation separately or in the ASC control box.

HW of the injector was built; it is dimensioned according to the parameters of ASCs normally used in middle voltage distribution networks. Algorithms for direct control of the injected current have been implemented and tested in this new device; the real current is shown in *Fig. 9*.

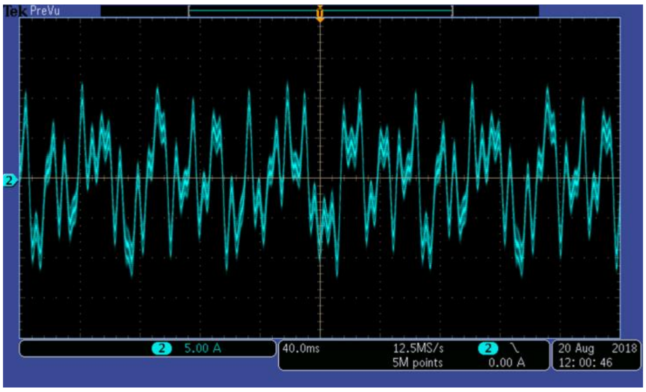

Fig. 9 Real measured current signal of prototype device

Measuring algorithms for indirect evaluation of current and voltage on the primary side of ASC over its mathematical model have also been implemented and tested in the prototype device enabling to fulfil the basic task - evaluation of network parameters.
In cooperation with the leading manufacturer of ASC controllers, the developed device is being prepared for practical use with ASC controllers enabling its control and parametrisation. The prototype of the mentioned device is shown in Fig. 10.

Fig. 10 The prototype of Multifrequency Current Injector

SUMMARY

The correct setting of a tuneable ASC secures the compensation of the capacitive part of the earth-fault current which occurs as a result of earth-faults in the power distribution network.
The introduced innovative method of ASC tuning in resonant earthed distribution networks is based on creation of truly multifrequency current signal and indirect measuring of voltage response in NVD of the network for the frequency components used in the injected signal.
Compared to today's methods, for similar current signal value the evaluated voltage is significantly higher even in case of very high value of detuning of arc suppression coil due to the broad frequency spectrum used.
The introduced innovative tuning method has been tested in real distribution networks. A new device is being developed using this new method in cooperation with the leading manufacturer of ASC controllers.
The use of such a device with a reliable controller as an ASC accessory will enable a stable operation of ASC even when installed in large and dynamically changing distribution networks.

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