CALCULATION OF NETWORK EQUIVALENTS USING TRANSIENT RECORDINGS

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This paper presents a method for the calculation of network equivalents as a basic parameter of power quality rating. The calculation is done by the evaluation of transient recordings of network disturbances or other transient reactions of the net.
The presented method demonstrates how the transient data can be obtained with little expenditures and how the equivalent can be evaluated with high accuracy.

INTRODUCTION

Nowadays a quantity of measured values and transient recordings are available in the control centre of electrical networks. This is a consequence of the increased application of state of the art numerical protection devices and substation control systems. Based on the multitude and the digital storage method of these data, together with the higher accuracy of modern measuring equipment, new evaluation methods may be used for further utilisation.
Thus general conclusions of the current workload of the net and the service reliability of the network and some of its devices are possible. In particular the determination of specific parameters is possible by the evaluation of transient recordings. Transient reactions of the network are caused by network disturbances like short-circuits, or by state changes. State of the art protection relays possess a built-in transient recorder for fault logging. Stand alone transient recorders, which are usually placed at selected locations in the electrical network, add extra records. The essential extractable parameters are shown in table 1.

Table 1: Parameters achievable from transient recordings of network disturbances

Network parameter Network impedance $\underline{Z}_N$ Network time constant τ Network equivalent $\underline{Z}_i$ Network unbalance factor	Short-circuit parameter Short-circuit impedance $\underline{Z}_K$ Short-circuit current $\underline{I}_K$
Line parameter Line impedance $\underline{Z}_L$ Earthfactor $\underline{k}_E$	Load parameter Loadimpedance $\underline{Z}_{Load}$ power factor $\cos\varphi$

THE NETWORK EQUIVALENT

The knowledge of the short-circuit power respectively of the short-circuit current at a certain location in the network is essential for a undisturbed and reliable operation.

These parameters can be assessed with the help of the network impedance $\underline{Z}_N$. This is generally done by a short-circuit calculation program on the basis of known equipment parameters, like line and cable, generator and transformer data. However, these parameters are generally inaccurate or worse, even incomplete. Moreover, the calculation procedure disregards all resistance, all static loads and all prefault current [1]. The short-circuit current calculated like this will differ from the actual one. The network equivalent however is the actual short circuit impedance at the regarded network location. Therefore the actual short-circuit current and -power can be accomplished.

THEORY

The Helmholtz theorem implies that a network regarded between two nodes can be transformed into an ideal voltage source ($\underline{U}_q$) and an equivalent impedance, the network equivalent ($\underline{Z}_i$) (Fig. 1).

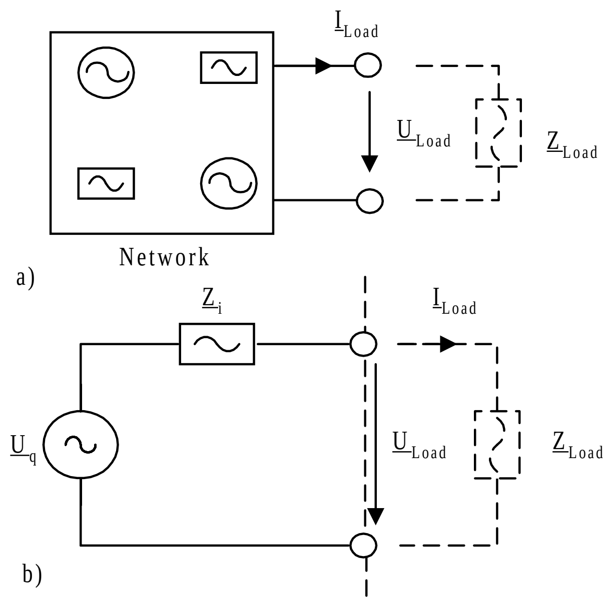

Figure 1: Electrical network (a) and its corresponding Thevenin equivalent (b)

Any two terminal network can be characterised by its current-voltage characteristic according to equation (1). Two points of the characteristic line are needed for the determination, e. g. the open-circuit voltage and the short-circuit current, but any other two points will do it as well.

For any load applied to the terminals of the network, equation (1) is valid.

$$\underline{U}_{Load} = \underline{U}_q - \underline{Z}_i \cdot \underline{I}_{Load} \qquad (1)$$

Therefore two different voltage and current measurements with different load conditions (*Load1 and Load2)* are necessary to evaluate the equivalent $\underline{Z}_i$. Equation (2) specifies the calculation.

$$\underline{Z}_i = \frac{\underline{U}_{Load1} - \underline{U}_{Load2}}{-(\underline{I}_{Load1} - \underline{I}_{Load2})} = \frac{\Delta\underline{U}}{-\Delta\underline{I}} \qquad (2)$$

In case of a 3-phase network, the impedance matrix of the natural system (equation (3)) has to be applied.

$$\begin{pmatrix} \Delta\underline{U}_a \\ \Delta\underline{U}_b \\ \Delta\underline{U}_c \end{pmatrix} = \begin{pmatrix} \underline{Z}_{aa} & \underline{Z}_{ab} & \underline{Z}_{ac} \\ \underline{Z}_{ba} & \underline{Z}_{bb} & \underline{Z}_{bc} \\ \underline{Z}_{ca} & \underline{Z}_{cb} & \underline{Z}_{cc} \end{pmatrix} \cdot \begin{pmatrix} -\Delta\underline{I}_a \\ -\Delta\underline{I}_b \\ -\Delta\underline{I}_c \end{pmatrix} \qquad (3)$$

Transformation of equation (3) into symmetrical components yields equation (4).

$$\begin{pmatrix} \Delta\underline{U}_0 \\ \Delta\underline{U}_1 \\ \Delta\underline{U}_2 \end{pmatrix} = \begin{pmatrix} \underline{Z}_{00} & \underline{Z}_{01} & \underline{Z}_{02} \\ \underline{Z}_{10} & \underline{Z}_{11} & \underline{Z}_{12} \\ \underline{Z}_{20} & \underline{Z}_{21} & \underline{Z}_{22} \end{pmatrix} \cdot \begin{pmatrix} -\Delta\underline{I}_0 \\ -\Delta\underline{I}_1 \\ -\Delta\underline{I}_2 \end{pmatrix} \qquad (4)$$

Usually electrical networks are built as a balanced system, so the matrix elements $\underline{Z}_{ij}$ with $i \neq j$ can be assessed to zero. The positive sequence impedance, as well as the negative and zero system impedance can be obtained from equation (4). The change in load can be caused by a network disturbance. An alternative is to switch on an additional consumer, or an idle transformer, or a capacitor bank, if available.

CALCULATION OF THE EQUIVALENT

This chapter explains the evaluation principle by means of an example.

An idle transformer was switched-in to generate a load step. The voltages were recorded at the busbar and the currents directly in the outgoing feeder unit (see also fig. 7). Pre- and posttrigger times can be set up to several seconds. The unbalanced and non-linear load during the switching on causes unsymmetries and harmonics. Figure 2 shows the recorded line-to-ground voltages and the line currents. The different magnitudes of the inrush-currents are causing different voltage dips in the 3 phases.

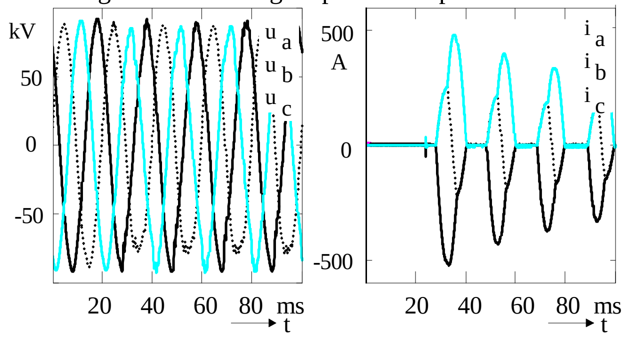

Figure 2: Voltage and current measurement

A harmonic analysis of the measured values is then carried out. The complex Fourier analysis with equation (5) is done within a window with the size of $1/f_n$ (f_n, nominal frequency). The values of the first harmonic ($\nu = 1$) are stored and the window is shifted by one sample step for the next analysis.

$$\underline{A}_\nu = \frac{\sqrt{2}}{n} \cdot \sum_{k=0}^{n-1} a_k \cdot e^{2\pi j \left(\frac{\nu}{n}\right) k} \qquad (5)$$

where: ν harmonic's number

$\underline{A}_\nu$ complex value of harmonic no. ν

k value no. k in the interval

n total number of sampled values in the time interval (e.g. n=400)

a_k sampled value no. k of measured value a (e.g. U, I)

The result of each calculation is a complex vector. The so originated time characteristic of the absolute values of the first harmonic component are shown in Figure 3.

Dependent on their magnitude higher harmonics ($\nu > 1$) may also be evaluated.

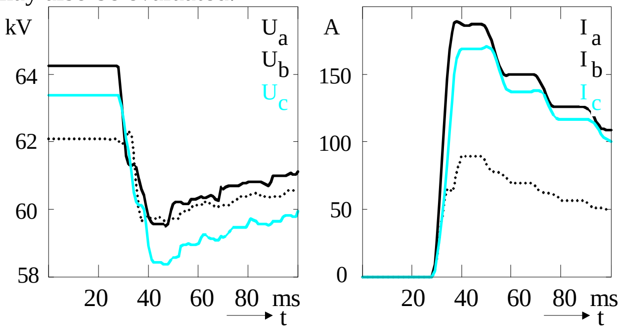

Figure 3: Absolute values of the voltage and current vectors for $\nu = 1$ in a-b-c system

Next step is the transformation into the symmetrical components (figure 4).

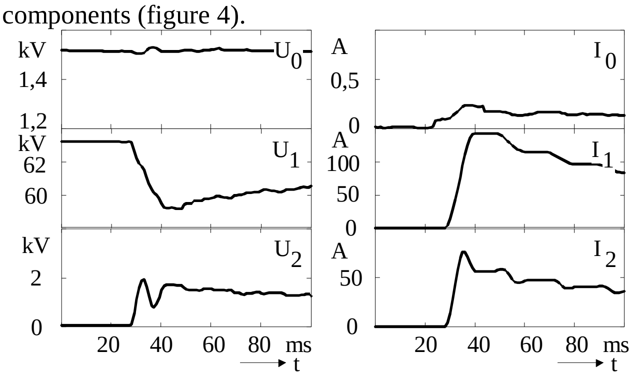

Figure 4: Absolute values of the voltage and current vectors for $\nu = 1$ in symmetrical components

The positive sequence values will be used further on.

The Fourier analysis was done with a gradually shifted window. Therefore the calculated phase angle will be out of phase by $2\pi/n$ (n quantity of sampled values per f_n period) per sampled window. To compensate this it has to be related to an f_n-normvector. Equation (6) shows the appropriate specification.

$$\underline{A}^{\#}_m = \underline{A}_m \cdot e^{-j \cdot 2\pi \cdot \frac{m}{n}} \qquad (6)$$

The absolute values are not affected by this operation.
Figure 5 shows the result of the operation. Remarkable is that the phase angles show still a deviation over the time. This indicates that the actual frequency of the network did not exactly coincide with the supposed one. The frequency deviation can be calculated from the inclination of the characteristic. The deviation itself is linear, if the network frequency is constant during the measuring period.

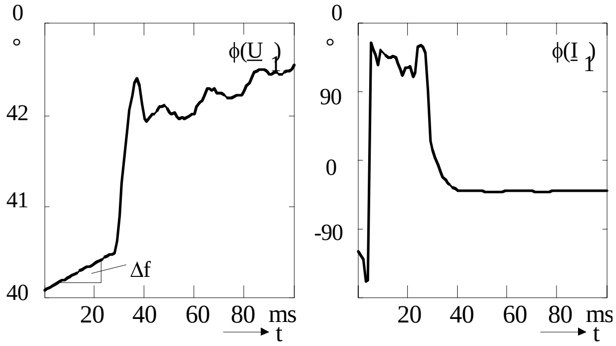

Figure 5: Reference to f_n-norm-vector of the positive sequence values

Finally the size of the voltage and current alteration has to be determined. For that purpose the absolute values of the time characteristics are approximated through lines for both load cases L1 and L2 (fig 6) by the least square method.

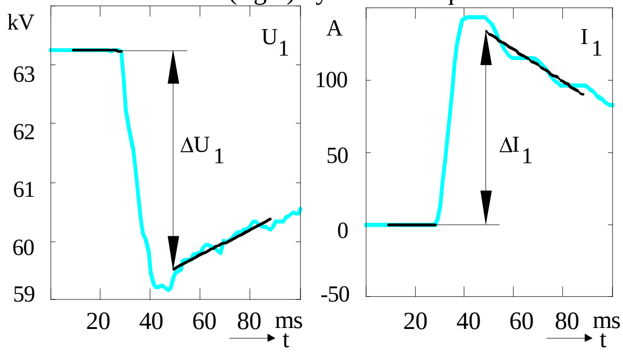

Figure 6: Line approximation and determination of the positive sequence leaps.

The values of the approximation lines at the switching instant are used for the difference determination. The quotient of the two differences (equation (7)) results in the positive sequence impedance, the network equivalent.

$$\underline{Z}_1 = \frac{\Delta \underline{U}_1}{-\Delta \underline{I}_1} \qquad (7)$$

The same procedure was also applied on each phase separately without the transformation into the symmetrical components (fig. 7).

Parallel measurements at different nodes reveal additional statements regarding the impedance of net-elements, like cables, over head lines, transformers, etc., between the net nodes.

FIELD TESTS

Field tests were carried out in order to rate the efficiency of the procedure. Extensive measurements took place simultaneously at two network nodes under specific network configurations. An idle transformer (Tr 101) was connected to the network. All measurement devices were independent and not synchronised.
A total number of 48 switching operations were carried out with 6 different network configurations (fig. 6).

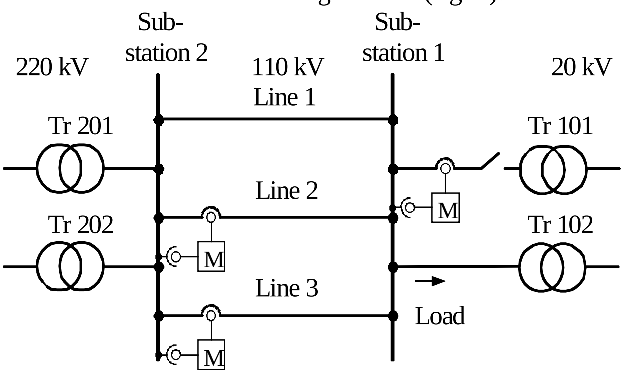

Figure 6: Network with measurement

The inrush current of the transformer Tr 101 and the busbar voltage in substation 1 were recorded. Transformer Tr 102 was in charge of the load supply for customers. The measurement system in substation 2 recorded the busbar voltage and the current of the supplying lines (net-configuration 3,4 and 6).

The different impedances for the different configurations are clearly recognizable (fig. 7). The network configurations 3 and 4 show differences in the phase impedance, both with the same tendency. This indicates line 3 as unbalanced.

Table 2. Network configuration

Config.	Line 1	Line 2	Line 3	Tr 201
1	on	on	on	on
2	on	off	on	on
3	off	off	on	on
4	off	off	on	off
5	off	on	on	on
6	off	on	off	on

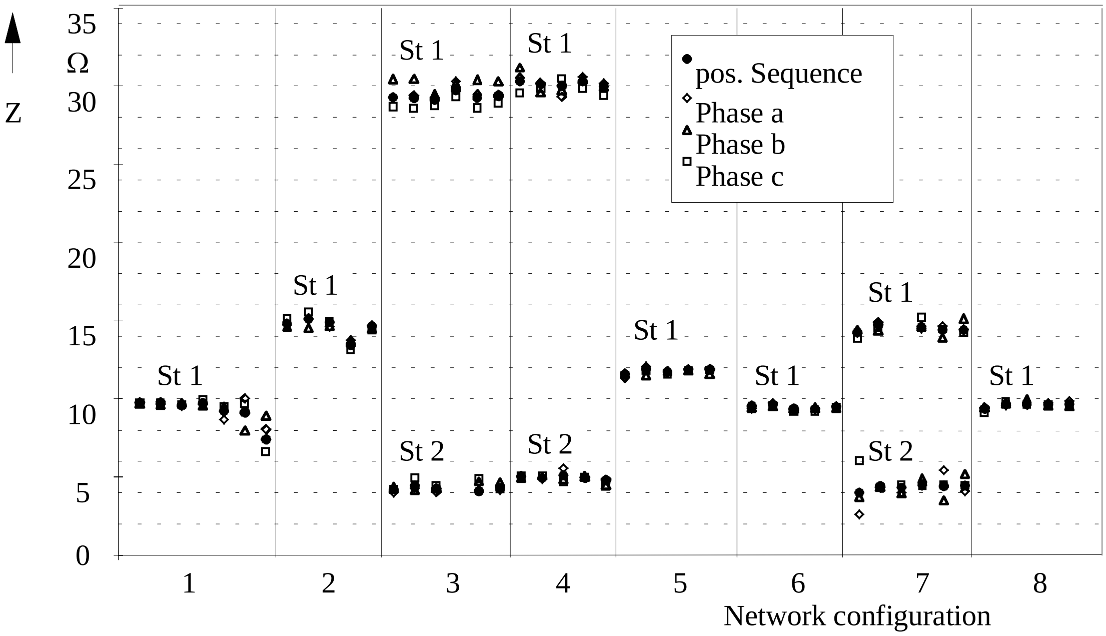

Figure 7: Impedance results at Station 1 (St. 1) and Station 2 (St. 2). Absolute values of positive sequence and for each phase

The difference of the impedance between the two substations is the line impedance and can so be determined.
In substation 1 only the inrush current of transformer Tr 101 was measured and the load at transformer Tr 102 was ignored. Therefore the calculated impedance is inaccurate. With the knowledge of the load current and the transformer data the order of the deviation can be assessed.

ERROR CONTEMPLATION

The accuracy of the evaluated equivalent depends on two major subjects. The first one is the accuracy of the available measured data, the other one is defined by the evaluation procedure.
The main influence on the data accuracy is done by the measuring equipment. The measuring current and voltage transformer for the primary values, the secondary sided measurement transducers and the analog-digital converter (ADC) of the recording device effect the measurement uncertainty.
The transformer accuracy depends on various conditions, such as design, overcurrent factor or form factor. Present evaluations imply that the commonly used protective voltage- and current transformer is no explicit source of error [3]. Further should any systematic error be mitigated by the two measurements and the subsequently substraction of the values.
The discretization error caused by the ADC can be neglected, if a 12 or 16 bit device is used. The harmonic analysis of a 64 kV sine voltage, sampled at 20 kHz and converted with 12 bit, show a worst case error of 5 V (0.008%) and a phase displacement less than 0.0003°.
The evaluation procedure is affected by the fourier analysis, the transformation into symmetrical components and the determination of the line approximation.

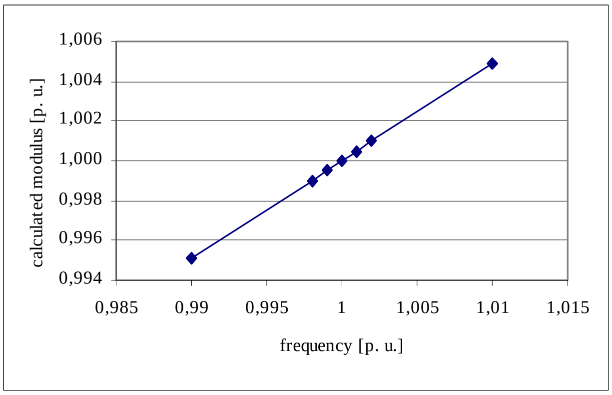

Figure 8: Absolute value of the deviation caused by differing frequency

The main error of the fourier analysis is caused by a deviation of the actual frequency and the proposed fourier frequency (f_n). Figure 8 shows the error of a fourier analysed sine signal with a frequency differing from the nominal frequency.
This relatively small error source may be enlarged by the algorithm for the equivalent evaluation. The size of the deviation however is especially affected by the size of the voltage and current alteration. The higher the difference (see figure 6), the smaller is the calculated error. Figures 9a and 9b display the deviation caused by a differing frequency, without any compensating methods, for two different load steps (case 1 and case 2). Case 1 (R_1 res. X_1) displays a high voltage and current alteration, whereas case 2 (R_2 res. X_2) represents a smaller one.
The frequency deviation enlarges this error.

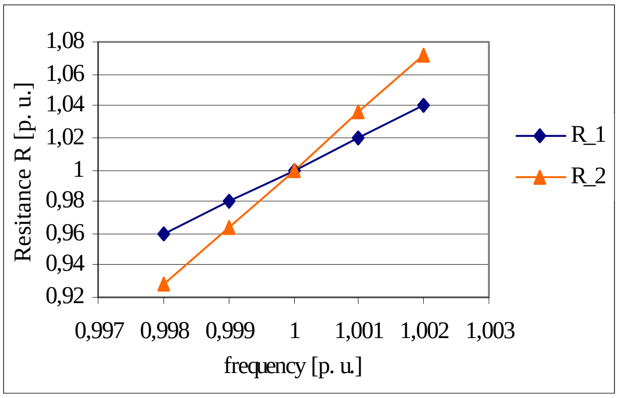

Figure 9a: Deviation of the calculated resistance caused by frequency deviation and different load steps

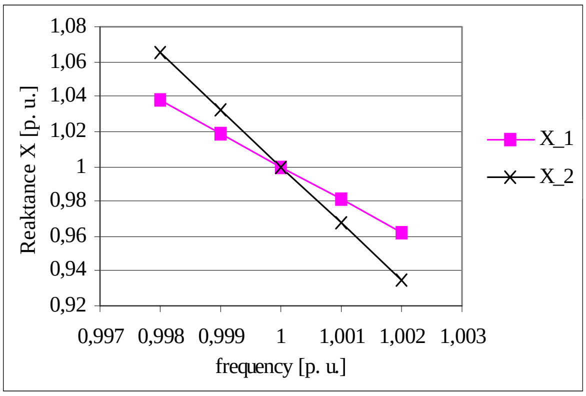

Figure 9b: Deviation of the calculated reactance caused by frequency deviation and different load steps

With the knowledge of this deviation (see figure 5), the phase shift can be compensated and the error tends towards zero (figure 10).

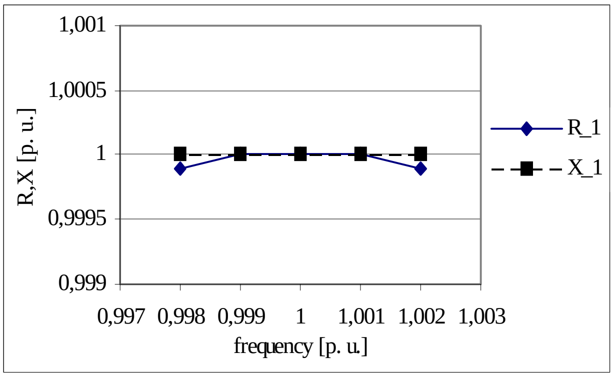

Figure 10: Deviation after phase shift compensation for case 1

The displayed impedance values are from load case 1.

CONCLUSIONS

The paper presented a method to gather transient data by the switching-on of an idle transformer, and a method to evaluate the data in order to calculate the network-equivalent. It was also demonstrated how additional data pre-processing leads to an improved accuracy.
The results were rated and they showed a very good correspondence with the expected values. The applicability was confirmed.
The evaluation of transient data of ordinary fault recordings in order to calculate the network- equivalent is in realisation.

Literature

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