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Single - Point Methods for Location of Electromagnetic Disturbances in Power System

Streszczenie. *Często w przypadku wystąpienia znaczącego poziomu zaburzenia elektromagnetycznego na zaciskach odbiorcy powstaje potrzeba lokalizacji jego źródła, przykładowo harmonicznych, wahań napięcia, zapadów napięcia, niekiedy także asymetrii. Dostawcy i odbiorcy energii w coraz większym stopniu są zainteresowani jednoznaczną oceną odpowiedzialności za złą jakość dostawy energii. Nabiera to szczególnego znaczenia w okresie formułowania kontraktów na dostawę energii i egzekwowania, poprzez taryfy, opłat za pogarszanie jej jakości.*
W artykule przedstawiono, jako przykład, aplikację jednej metody (ze zbioru wielu istniejących) stosowanej do lokalizacji źródeł zaburzeń elektromagnetycznych (harmonicznych, zapadów, wahań i asymetrii napięcia) opartej na badaniu kierunku przepływu mocy w punkcie wspólnego przyłączenia (PWP). ***Jednopunktowe metody lokalizacji zaburzeń elektromagnetycznych w systemie zasilającym***

Abstract. *Often, in the case of a significant level of electromagnetic disturbance in electrical power system, at the customer's supply terminals, there is a need for locating the source of this disturbance, e.g. harmonics, voltage fluctuations, voltage dips, occasionally also asymmetry. Utilities and power consumers have become increasingly interested in quantifying the responsibilities for power quality problems. This issue gains particular meaning when formulating contracts for electric power supply and enforcing, by means of tariff rates, extra charges for worsening the power quality.*
This paper concerns as an example an application of one method (from the collection of many existing) used to locate sources of electromagnetic disturbances (harmonics, dips, voltage fluctuations and asymmetry), based on the study of the power flow at the point of common coupling (PCC).

Słowa kluczowe: jakość dostawy energii elektrycznej, harmoniczna, wahania napięcia, zapad napięcia, niesymetria, źródło zaburzenia
Keywords: power quality, harmonic, voltage fluctuation, voltage dip, unbalance, source of disturbance

Introduction

Often, in the case of a significant level of a disturbance in electrical power system, at the customer's supply terminals, there is a need for locating the source of harmonics (e.g. [9-11][16][39][45][51]-53-58]), voltage fluctuations (e.g. [11-14][46-49]), voltage dips (e.g. [26][28][32][35][36][39][40][50][52]), occasionally also asymmetry ([18][19][54]). With the deregulation of power industry, utilities have become increasingly interested in quantifying the responsibilities for power quality problems. This issue gains particular meaning when formulating contracts for electric power supply and enforcing, by means of tariff rates, extra charges for worsening the power quality.

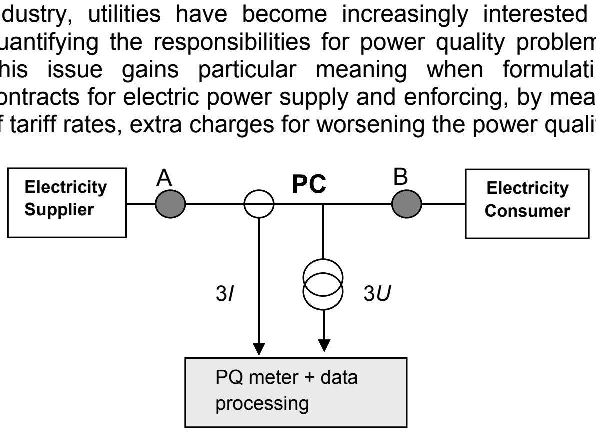


Fig. 1. Problem of locating the voltage disturbance sources

There are two, sometimes separate problems which can be stated as follows (Fig. 1). First details concerning the location of disturbance source. A power quality monitor captures disturbance-containing voltage and current waveforms at PCC. It is required to determine if the disturbance comes from the upstream or the downstream.

The second problem is to assess the emission level of the particular considered load (power consumer) or supplier in order to quantitative evaluation of the both parts contribution to the total disturbance level measured at the point of power delivery. The goal is to check the fulfilment of standard or contract requirements.

Solution for both problems posed above is not a trivial task. Works focused on this subject have been carried out for many years. Numerous methods have been proposed and published, only a part of them having practical significance. They differ in the probability of inference correctness (e.g. locating a disturbance source), the value of error made (e.g. determining an individual customer's share in the total disturbance level), the time required to carry out measurements, the number and complexity of equipment needed, etc.

This paper deals with the first of the two problems specified above - location of the disturbance source based on measurements made at a single point of a network (PCC). As an example only one commonly used location method is presented for high harmonics, voltage fluctuations, voltage dips and unbalance. The considered method is based on the investigation of the power flow at the point of common coupling (PCC).

Harmonics

The distorted voltage (Fig. 2) and current waveforms became a usual operating condition in today's power system.

The most commonly practical method for locating harmonic sources is based on determining the direction of active power flow for given harmonics, though many authors indicate its limitations e.g. [8][44][57][58]. Many other techniques are based on investigation of the "critical impedance" [31], the so-called voltage index value [42-44][55][56], interharmonic injection [57], determining voltage and current relative values [51], etc. Some methods determine the dominant harmonics source together with its quantitative contribution.

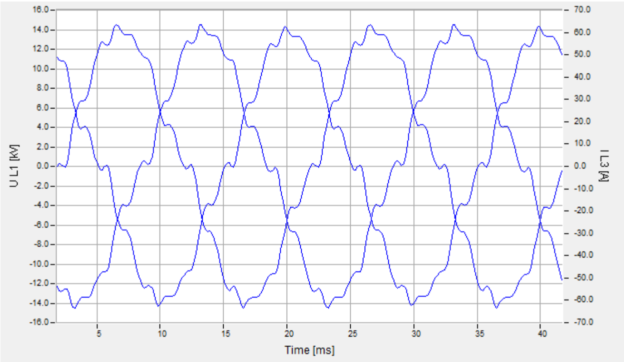


Fig. 2. Waveforms of distorted voltages measured at PCC

In most cases these methods, aside from their technical complexity, require precise information on values of equivalent parameters of the analysed system, which are difficultly accessible, or can only be obtained in result of costly measurements.

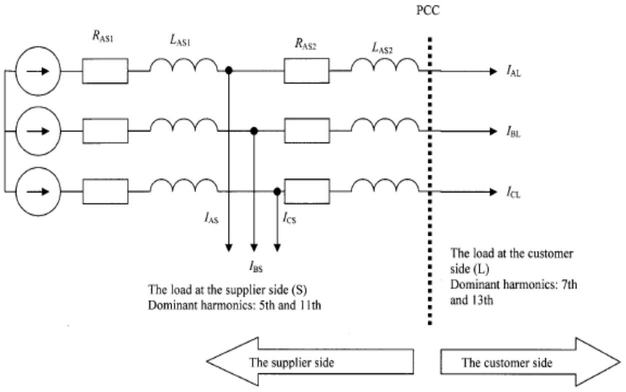


Fig. 3. Model of the electric power network chosen for simulations illustrating the active power flow method

Example 1. The dominant source of the considered harmonic (h-th order) can be located analysing the harmonic active power (P_h) flow at PCC. Analysing the sign of this power at the measurement point we can conclude that:

- the positive sign of active power at PCC (P_h>0) means the dominant source of the considered harmonic is the supplier,
- the negative sign of active power at PCC (P_h<0) means the dominant source of the considered harmonic is the consumer.

A non-zero value of active power is the result of mutual interaction of the same frequency voltage and current, and is determined by the formula:

$$P_h = U_h I_h \cos\left(\Phi_{U_h} - \Phi_{I_h}\right) = U_h I_h \cos\varphi_h \quad (1)$$

U_h (I_h) - rms voltage (current) value of the h-th harmonic, Φ_{U_h} (Φ_{I_h}) - the h-th harmonic current and voltage phase angles. The method is equivalent to examining of the phase shift angle φ_h between the considered harmonic voltage and current. If this angle is contained within the interval $-\pi/2 \langle \varphi \langle \pi/2$ then, according to this criterion, the dominant disturbance source is located at the supplier side. If the condition $\pi/2 \langle \varphi \langle 3\pi/2$ is fulfilled, the customer is the dominant source of the considered harmonic. For $\varphi = \pm\pi/2$ there is no decision about the dominant source of harmonic.

Figure 3 shows a simplified model of electric power network employed in the investigation, the supplier and customer sides are indicated. For the purpose of illustration let us assume the supplier is the dominant source of 5th and 11th harmonics and the customer is the dominant source of 7th and 13th harmonics. The above assumption is valid for both the balanced and unbalanced system (Table 1). Balanced *RL* loads are connected in parallel with non-linear loads represented by currents I_{iS}, I_{iL} for *i* = A, B, C.

Figure 4 summarizes the simulation results for selected cases. In the case of balance for the considered harmonic the method correctly locates the dominant source of disturbance: at the supplier or customer side, also in the case where non-linear loads are connected at both sides of PCC. In the latter case a change in the phase shift angle between the current harmonics generated at the supplier and customer side may, in a certain interval of values, affect correctness of the inference about the disturbance source location. Figure 5 shows the fifth harmonic active power variation at PCC for the case when the customer and supplier fifth harmonic relations were (a) 1:1.2 and (b) 1:1.8, and the phase shift angle between the 5th harmonic currents was varying within the interval 0-360^0. The larger the difference between the values of customer and supplier harmonic currents, the wider is the angle interval in which the inference is correct.

In the case harmonic sources are located at both the supplier and customer side and unbalanced system (Fig. 4), the inference based on this method cannot be correct. Comparison of simulation results with data contained in Table 1 indicates that the party responsible for 13th harmonic distortion was wrongly identified. The dominant party, responsible for the 13th harmonic presence in all phases is the customer, whereas the result of identification indicates the supplier in phases B and C. Thus the method fails also in the case of the considered circuit unbalance.

Table 1. The supplier and customer harmonics – balanced/unbalanced system

h	Phase A				Phase B				Phase C			
	Supplier		Customer		Supplier		Customer		Supplier		Customer	
	I_m[A]	φ_{Ih} [^{o}]	I_m[A]	φ_{Ih} [^{o}]	I_m[A]	φ_{Ih} [^{o}]	I_m[A]	φ_{Ih} [^{o}]	I_m[A]	φ_{Ih} [^{o}]	I_m[A]	φ_{Ih} [^{o}]
5	2.75/2.7	41/41	1.5/1.5	26/26	2.75/2.5	161/74	1.5/1.3	146/33	2.75/5	281/-123	1.5/2.7	266/-150.7
7	1/1	-25/-25	2.3/2.3	-15/-15	1/1.2	-145/-15	2.3/1.6	-135/-22	1/2.2	-265/-160	2.3/3.9	-255/167
11	1.6/1.6	100/100	0.9/0.9	79/79	1.6/1.35	220/199	0.9/1.1	199/96	1.6/1.9	340/-36	0.9/2	319/-91.6
13	0.2/0.2	-75/-75	0.65/0.65	-56/56	0.2/0.3	-195/30	0.65/0.7	-176/-77	0.2/0.3	-315/172	0.6/1.4	-296/112.7

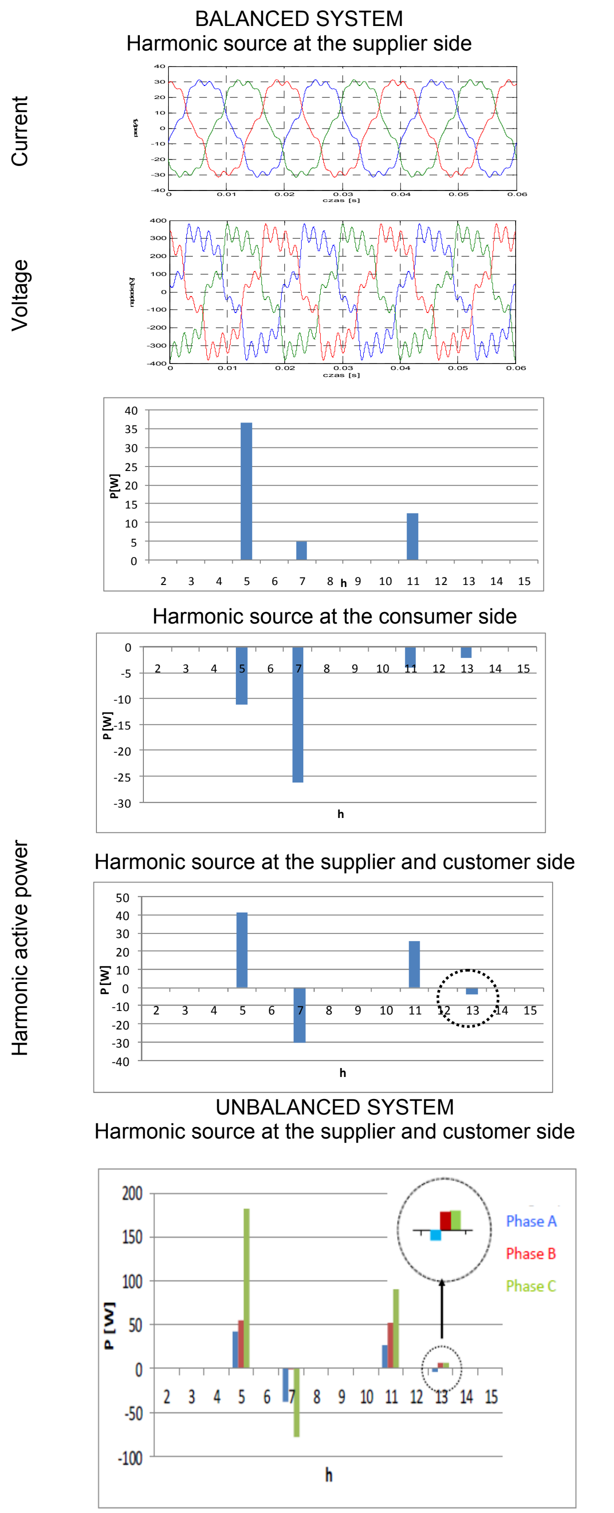
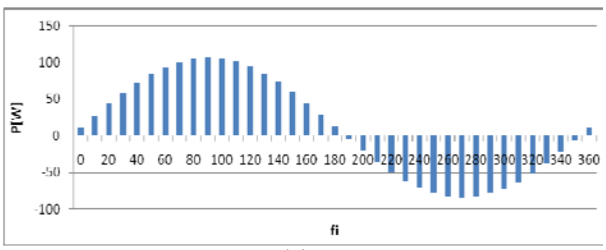
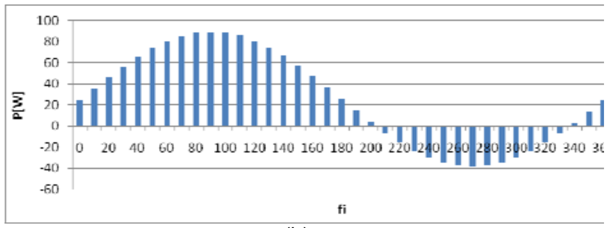


Fig. 4. The active power direction criterion for particular harmonics – example simulation results for the balanced and unbalanced system (Fig. 3)



(a)



(b)

Fig. 5. Variation of the 5th harmonic active power at PCC for different values of the phase shift angle φ between the customer and supplier current and various relations between their rms values: (a) 1:1.2; (b) 1:1.8

Voltage asymmetry

A three-phase power system is called balanced or symmetrical if the three-phase voltages and currents have the same amplitudes and their phases are shifted by 120° with respect to each other. If either or both of these conditions are not fulfilled, the system is called unbalanced or asymmetrical [Fig.6].

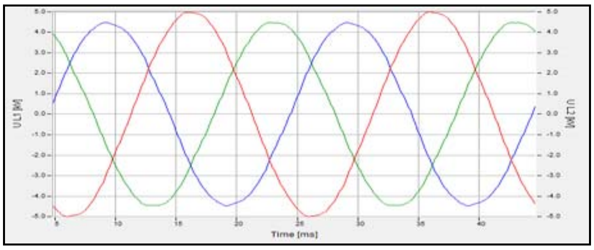


Fig. 6. Waveforms of asymmetrical voltages measured at PCC

Example 2. [54] The basis for locating the source of asymmetry in a power system can be the sign of the negative-sequence component active power measured at the PCC. The positive sign of active power means the dominant asymmetry source is at the supplier side, the negative sign of active power means the dominant asymmetry source is at the consumer' side.

A circuit used to demonstrate the correctness of inference, shown in Figure 7, enables simulation, at the supplier side, of asymmetry of source voltages rms values, phase shift angles between them, and series and parallel equivalent impedances of the supply source. The load is represented by three phase *RL* impedances with equal or different values.

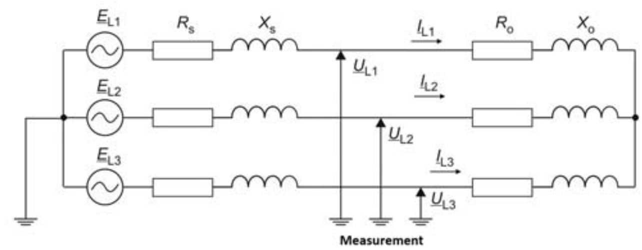


Fig. 7. Circuit diagram for asymmetry source location and identification

The following asymmetry sources were considered:
- unbalanced load side parameters
- unbalanced system side parameters
- unbalanced system phase voltages.

The analysed cases were categorized into three groups: (a) symmetrical source – unbalanced load; (b) asymmetrical source – balanced load; (c) asymmetrical source – unbalanced load. Symmetrical source is understood as the condition in which series impedances and phase voltages' amplitudes are equal to each other and phase-shifted by 120°.

In two cases, the conclusions based on the assumed criterion was not correct:

TEST 1: voltage unbalance in PCC - equality of active power components for negative sequence corresponding to the individual emission of the supplier and the consumer

TEST 2: voltage balance in PCC – different values of active power component for negative sequence corresponding to the individual emission of the supplier and the consumer.

The following symbols are used:

P(2)a – active power component (negative sequence) in PCC occurs in the case of unbalance only on the supplier side

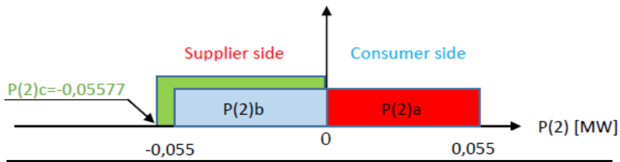
P(2)b – active power component (negative sequence) in PCC occurs in the case of unbalance only on the consumer side,

P(2)c – active power component (negative sequence) in PCC occurs in the case of unbalance on the consumer and supplier side.

Test 1

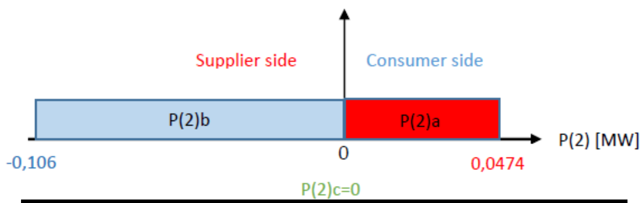
In that case the sources of the asymmetry were on both the supplier and the consumer side with assumption that none of them is dominant, ie. the powers of P(2)a and P(2)b are equal. The test case is shown graphically in Figure 8. It can be seen two equal absolute values of the negative sequence active power P(2) measured in PCC.

In the case under examination, the total power P(2)c in PCC has a negative value. According to the given criterion dominant source of asymmetry should be located on the consumer side, which is not true.



Active power for negative sequence component	Unbalance on the supplier side - P(2)a	Unbalance on the consumer side - P(2)b	Unbalance on the consumer and supplier side - P(2)c
P(2) [kW]	0.0549854	-0.0549978	**-0.0557651**

Fig. 8. TEST 1: Voltage assymetry in PCC - equality under the active powers for negative sequence component corresponding to the individual consumer and supplier emission levels



Active power for negative sequence component	Unbalance on the supplier side - P(2)a	Unbalance on the consumer side - P(2)b	Unbalance on the consumer and supplier side - P(2)c
P(2) [kW]	0.0474	-0.106	**≈ 0**

Fig. 9. TEST 2: Symmetrical voltages in PCC - the various components of the active powers for negative sequence component corresponding to the individual consumer and supplier emission levels

Test 2

System parameters are chosen so that the sources of asymmetry were both at the supplier and the consumer sides, with the assumption that the total power P(2)c is equal to zero. The test case is shown graphically in Figure 9. It can be seen two unequal absolute values of active power P(2) for the negative sequence component measured at PCC.

In that case, the negative components of voltage and current at the PCC are different from zero, the phase displacement between them is ≈-90°, which means that the total active power P(2)c in PCC equals zero. Analysis of individual side emissions showed that the asymmetry occurs on both supplier (dominant) and consumer sides.

Voltage fluctuations

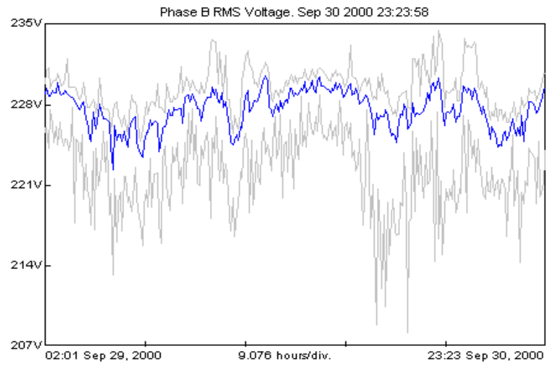


Fig. 10. Example of rms voltage fluctuation

Where only one dominant source of voltage fluctuations (Fig. 10) occurs its identification is usually a simple task. In extensive networks or in the case of several loads interaction, the location of a dominant disturbance source is a more complex process. Where large voltage fluctuations occur in several branch lines it may happen that measurements of flicker severity indices carried out at a power system node, do not indicate disturbing loads downstream the measurement point. The reason is a mutual compensation of voltage fluctuations from various sources.

Example 3. Identification of interharmonic power direction [34]. The method utilises two common observations:

- interharmonics cause flicker – the fundamental and an interharmonic component of a voltage waveform are not in synchronous, therefore the voltage can be represented as the one of with modulated magnitude, which causes flicker.
- flicker cause interharmonics – voltage variations can be treated as amplitude modulation of the voltage, therefore by means of signal analysis the voltage can be decomposed on harmonic and interharmonic components.

Thus, the problem of locating flicker source can be solved by locating interharmonic source. If the customer appears as a source of interharmonics i.e. the active interharmonic power is negative, the customer is also a flicker source. If the customer appears as an interharmonic load i.e. the active interharmonic power is positive, the customer is not a flicker source.

The method is applied as follows:

- a power quality monitor is installed at the branch related to the suspected consumer, and records voltage and current waveforms as flicker occurs.
- Fourier based algorithm is used to investigate main interharmonics i.e. the components that have the maximum magnitude.
- for each of the interharmonic active power is calculated.
- if the consumer produces interharmonic power, he can be identified as interharmonic source and consequently the flicker source.

The frequency of an interharmonic signal depends on operation of the customer's equipment, so it is almost impossible that two devices produce the same interharmonics at the same time. Consequently it is relatively easy to locate the source of interharmonics. This method is fund not to be effective for random flicker source detection.

The method gives correct results under inductive load, and limited capacitive power load. There is also possibility of misinterpretation when a load of constant power demand is considered. In such a case a voltage drop results in increased current flow. When the reaction is considerable it could be misinterpreted as having the flicker source downstream. The described situations, however, seldom arises in most practical situations.

A conception similar to the method of examining the direction of dominant interharmonics active power flow is presented by authors of [2-4]. Similarly to the definition of active power in the time domain there could be introduced so called "flicker power".

Voltage dips

The procedure of locating the dip (Fig. 11) source is usually a two-stage technique. The first part involves inferring whether the dip has occurred upstream or downstream of the measuring point, i.e. at the supplier's or the consumer's side. In the next step the algorithm that precisely computes the voltage dip location is applied. This paper deals with the first stage. Several methods for voltage dip source detection have already been reported. They are based mainly on:

- the analysis of voltage and current waveforms
- the analysis of the system operation trajectory during the dip, e.g. [32]
- the analysis of the equivalent electric circuit, e.g. [52]
- the analysis of power and energy during the disturbance
- the analysis of voltages, e.g. [29]
- asymmetry factor value and symmetric component phase angle, e.g.[40][41][52]
- algorithms for the operation of protection automatics systems, e.g. [35]
  - impedance variation analysis, e.g. [40][50]
  - the analysis of current real part, e.g. [17]
  - "distance" protection, e.g. [40]
- vector-space approach [38]

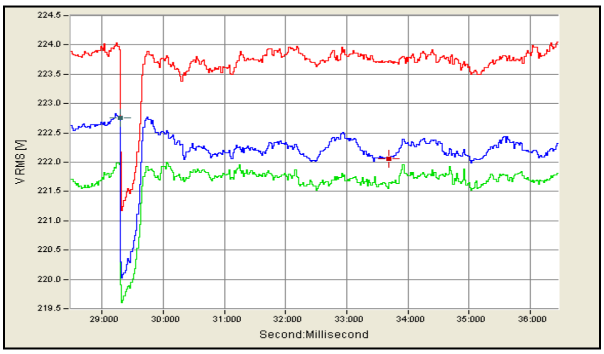


Fig. 11. Three-phase voltage dip

Example 4. The circuit of a short-circuit which has occurred at the consumer's side takes power from the supply network. On the other hand, during a short circuit that has occurred at the supplier's side energy in transient state will flow from the consumer's side. The direction of flow of instantaneous power and energy is determined on the basis of registered voltage and current waveforms.

In the steady state, assuming that the network is a symmetrical one, instantaneous power has practically constant value which changes as a result of variations in voltage and current instantaneous waveforms. The difference in power between the steady state and the disturbance state is the so-called "disturbance power" - DP. According to this definition, in the steady state the DP value approximately equals zero (assuming very brief intervals between subsequent measurements), while during short circuit it is different than zero.

As a result of integrating the DP value, disturbance energy – DE – is determined. Information concerning DP and DE variation makes it possible to locate the voltage dip source, because during a short circuit energy flows towards the place of the short circuit occurrence (Fig. 12) – the increase of DE during the disturbance indicates that the disturbance source is located downstream the measurement point. On the other hand, DE decreases if the disturbance source is located upstream the measurement point [36]. The method requires that a threshold value of energy is assumed; since the reliability of results depends on this value, the method works correctly as long as the value has been accurately chosen.

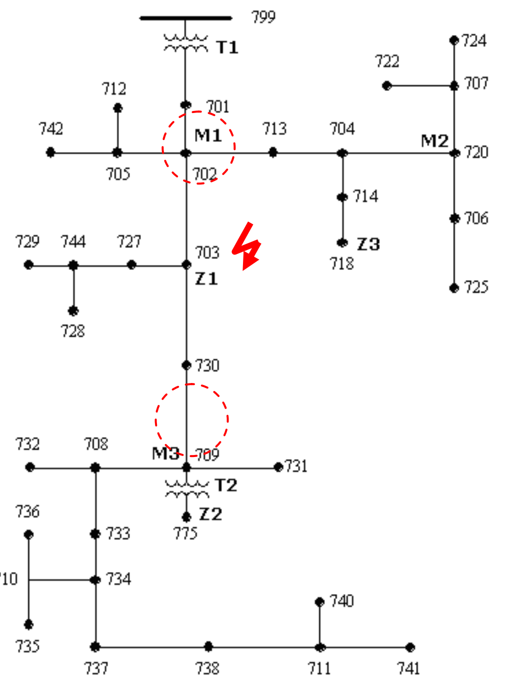


Fig. 12. Supply network model used to investigate the power flow during a short-circuit

Figure 13 shows the results of simulation studies aimed at locating the voltage dip source using the network model such as that in Fig. 12. A three-phase short circuit, which occurred in node 703, has been simulated; the study investigated if the disturbance in nodes 702 and 709 was located correctly. Correct conclusions are guaranteed also in the case of other types of short circuits.

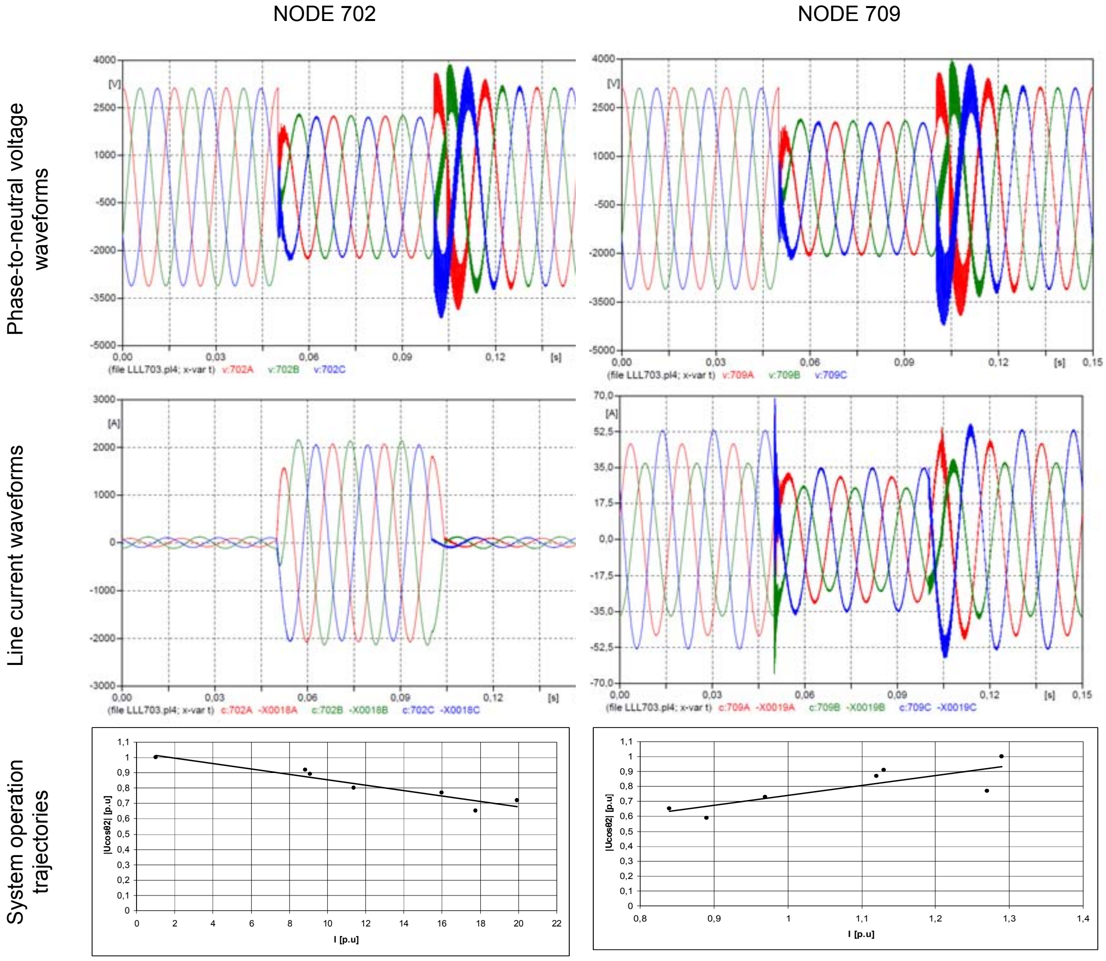


Fig. 13. Example results of a three-phase short circuit simulation in node 703 of 23 network model; waveforms of voltages and currents in nodes 702 and 709 (Fig. 13) as well as system operation trajectories in these points for phase L1 (analogous waveforms in other phases)

Conclusion

Seeking non-expensive, reliable and unambiguous methods for locating disturbances and assessing their emission levels in power system, not employing complex instrumentation, is one of the main research areas which require the prompt solution. Commonly used disturbance source localization method based on direction of power flow study, despite its simplicity, unfortunately, is not always effective. In many cases, it can lead to wrong conclusions.

Acknowledgments

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