Identification of Harmonic Sources

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Abstract: The paper is dealing with the possibility of identifying harmonic sources on the base of on-site measurements, analysing the change of operating point on different type characteristics due to sudden changes utilising the method of monoparameter variation in a multiparameter system.

I. INTRODUCTION

The new European standard EN 50160 gives the guideline of the recommended tolerable levels of several power quality indices. These indices are considered not to be exceeded on the low voltage and medium voltage public networks. Besides the indices and the evaluation methods, the relevant parameters of the measuring equipments are given in addition in the norm EN 61000-4-7.

However the problem of power quality is double sided and EN 50160 gives the guides from one side only. This side ensures that a consumer can not be effected by more than for example 8% THD in voltage, e.t.c.

The electric utility companies are responsible to keep the indices under the limits. However utility company itself usually does not generate disturbances or distortions. The distortions are caused by nonlinear loads, located mainly at the consumer side. The distortion effects of some kind of individual consumers on the supply voltage can be practically summed up like in case of TV sets or fluorescent lamps with electronic ballasts.

The disturbing effect of the conventional power electronic circuits (diode or thyristor rectifiers) or the novel ASD-s based on PWM inverter are time varying regarding the magnitude and phase of generated harmonics. However the disturbance level of the supply network is the resulting distortion caused by the individual nonlinear loads.

The question is (and this is the other side) - what the utility company has to solve -how to share the distortion limits between the consumers in order to keep the THD and the individual harmonics under the limits specified by the standard keeping in mind to be on the safe side regarding the reserve for future loads, and to determine a fair play regarding the allowed distortion portion of one consumer.

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Last but not least the economical solution for both parties is important.

The methods followed by the utility companies are based on the distribution of the limits (THD and individual harmonics as well) between the consumers in function of their fundamental power rate.

The advantage of this method is in its simplicity. The method assumes identical per unit nonlinear load portions of the consumers. In fact this can be very different, and from economical point of view the system is very unefficient, because the allowed limits will not be achieved, only if all the consumers will use their right of contamination.

Assuming that the disturbing portion of one consumer can be determined, the utility companies can allow more freedom for the consumers and time-by-time they have to measure the distortion levels and change the allowed limits of the contracted consumers if necessary. This aspect will be very important in the future with respect to the open market in the power systems, because of the possibility for a utility company to give advantageous conditions regarding harmonic distortion portions for the consumers compared to the other utilities following the above mentioned power proportional sharing method.

The simple method is popular between utility companies because the identification of harmonic sources and their disturbing effect seemed to be rather difficult. The identification method introduced below has been developed during the last years. The method and it's verification is based on the results of numerous on-site measurements performed and evaluated by the authors using TRANSANAL-16, a 16-channel multifunction power quality analyser. The software features of the equipment allow a wide-scale evaluation regarding any kind of functions in form of plots. As it will be proved the identification of harmonic sources and their disturbing effect can be determined evaluating the results of measurements in a proper way.

II. CHARACTERISTICAL INDICES AND FUNCTIONS. THEORETICAL INTRODUCTION

This chapter introduces the theoretical explanations made on the changes of 5th harmonics. The 5th harmonic order was chosen because usually its magnitude is the greatest and it is the main component of the THD. In cases where the dominant component of the THD is not the 5th harmonic, it is recommended to follow the identification procedure with the dominant harmonic.

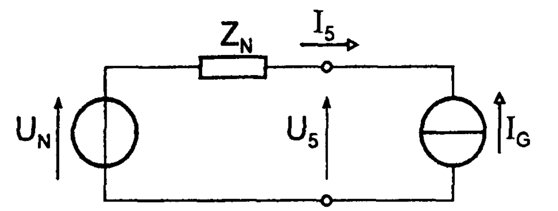

Fig.1. Equivalent model to calculate P_5

A. Harmonic Active Power

The negative harmonic power is considered in the technical literature as an essential evidence of a harmonic source. Below a brief explanation is given that this is true only if the measured nonlinear load is the dominating one causing the harmonic distortion of the busbar. The negative harmonic active power is sufficient but not necessary condition of being an active harmonic source in a branch, that is a linear element cannot produce active power at all but nor does it a nonlinear one in each case.

The one phase equivalent model for a branch having only a single nonlinear element can be seen on Fig.1. The nonlinear load is considered as an ideal current generator (I_G), the supply network with other branches connected to the same busbar is modelled with a Thevenin generator (U_N and Z_N). U_5 and I_5 are the 5th harmonic content of the measured parameters, P_5 is their active power as follows (all the possible parameters are complex phasors):

$$I_G = -I_5; \qquad U_5 = U_N + I_G Z_N$$

$$P_5 = \mathrm{Re}\left[U_5 \hat{I}_5\right] = \mathrm{Re}\left[(U_N + I_G Z_N)\hat{I}_5\right] =$$

$$\mathrm{Re}\left[-U_N \hat{I}_G - I_G^2 Z_N\right] = -\mathrm{Re}\left[U_N \hat{I}_G\right] - I_G^2\,\mathrm{Re}\left[Z_N\right]$$

In the above expression of P_5 the second part is always negative but the first one can be positive or negative as well, because U_N and I_G are independent parameters. Regarding the harmonic current generated by a nonlinear load there is a wide possibility of the phase shift between the harmonic current and the busbar voltage. The phase shift of the harmonic current depends basically on the phase shift between the fundamental voltage and current (e.g. for thyristor controlled rectifiers $\alpha_h \approx h\,\alpha_1$ where α_1 is the firing angle and h is the harmonic order). The magnitude and phase of the harmonic voltage U_N is determined by the sum of other linear and nonlinear loads connected to the network. Hence the effect on the voltage distortion of one nonlinear consumer in question depends on its relative weight related to the other nonlinear loads in the (electric) vicinity. In consequence the harmonic active power will be negative:

- if the branch in question consists of the same type nonlinear loads (e.g. computers or fluorescent lamps in an office building measured on the low voltage busbar), where the effect of the single loads on the voltage distortion is summed up.
- if the nonlinear load to be measured is dominating on its voltage level regarding the caused voltage distortion.

In the above listed cases the existence of the harmonic source can be identified but not its exact disturbing effect on the network, only its presence.

The harmonic active power will be positive in cases when the above conditions are not fulfilled. However even in these cases the existence and the disturbing effect of harmonic sources can be determined following the method given in the paper.

An other example on the sign of the active power question is the case of two 6-pulse bridge rectifiers supplied from 30° shifted transformers separately as it is given in Fig.2. Measuring the active harmonic powers, the sign of side A and B are the opposite in spite of both are harmonic generators.

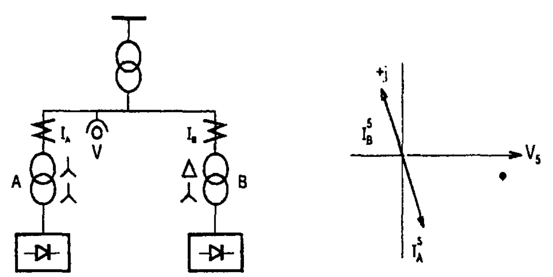

Fig.2. Active harmonic power of 30° shifted transformers

Introducing the assumption, that the nonlinear load has some kind of dynamics (load side or network side), the proper evaluation of the harmonic voltage - current (e.g. V_5 vs I_5) and the harmonic current - fundamental current (e.g. I_5 vs I_1) plot diagrams during the change of the quantities help to identify the harmonic source, and its disturbing effect. Below the theoretical functions will be discussed and later their proof will be given with results of on-site measurements.

B. Plot Diagrams V_5 - I_5 And I_5 - I_1 During Sudden Changes. Method of Monoparameter Variation

These diagrams show the changes of the operating point of typical loads during operation. To solve the identification problem it is essential to find sudden changes of one parameter, while other ones remain stable. Among the numerous technical characteristics, the absolute value of V_5, I_5 and I_1 were chosen, these parameters can be evaluated easily from the on-site measurements. There are

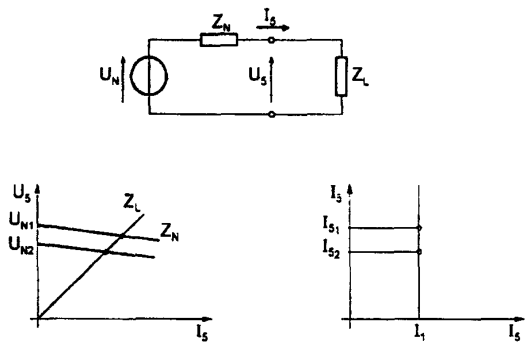

Fig.3. Equivalent model for a linear load

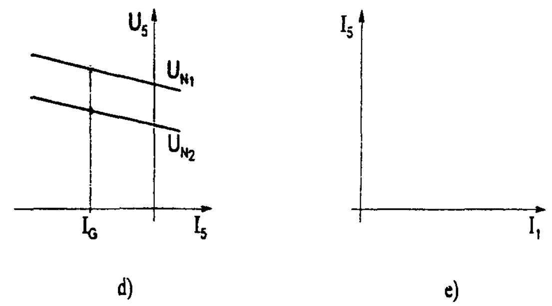

Fig.4 d-e Effect of U_N fluctuation on nonlinear load

a lot of parameters being able to change the operating point, but fortunately there is the possibility to find changes of two consecutive operating points (time sequence Δt = 4s) as a consequence of the sudden change of one parameter.

First consider a linear network element, modelled with a series R-L or R-C (Z_L) circuit for the given frequency. It cannot change nor cause the harmonic distortion of the busbar but suffers it. Therefore its V_5 - I_5 and I_5 - I_1 curves are as seen on Fig 3. The equation describing the behaviour of the linear element on the 5th harmonic is

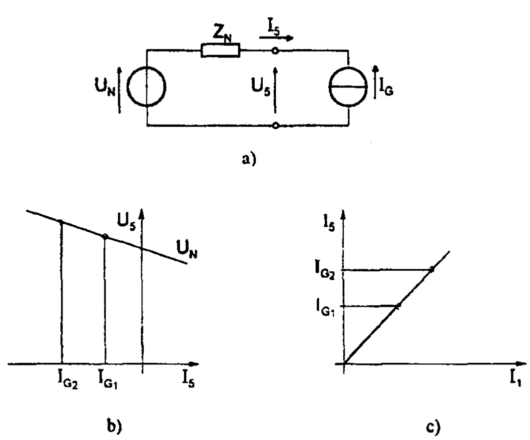

Fig.4a-c Nonlinear load with changing current

$$U_N - I_5 Z_N = U_5 = I_5 Z_L$$

The change of the operating point is caused in most cases by the fluctuation of U_N , the voltage distortion of different nonlinear loads in the vicinity. As a result I_5 changes but I_1 remains the same value if the fundamental voltage does not change.

The behaviour of active elements are to be seen on Fig.4 according to the equation:

$$U_5 = \mathrm{U_N} - I_5 Z_N = \mathrm{U_N} + I_G Z_N$$

This type of load causes partly or totally the THD of the busbar. If the change is caused by the nonlinear load itself (I_G), the operating point is shifted as shown on Fig 4b and 4c, assuming controlled rectifier as nonlinear element. In this case the effect of the nonlinear element on the THD ($I_G Z_N$) can be separated from the distortion effect of other loads (U_N). If the changes origin from other nonlinear elements modelled with U_N, the result is according to Fig. 4d and 4e, and in this operating point the distortion effect cannot be determined separately.

For a branch having linear and nonlinear components as well the corresponding relationship is

$$U_5 = \mathrm{U_N} - I_5 Z_N = (\mathrm{I_5} + I_G) Z_L$$

and the characteristics are shown on Fig.5b-c as a result of the change of I_G and Fig 5d-e as a result of the change of other nonlinear loads (U_N). The parameters Z_N and Z_L can be changed as well by variation of the network configuration and the load.

III. RESULTS OF ON-SITE MEASUREMENTS

The above characteristics can be verified by means of on-site measurements where the nature of the branches is known. Our examples are taken from a measurement on a substation for electric railway supply. There are two active (nonlinear) branches and a filter (passive load) considered according to Fig.6.

The plot diagrams V_5 - I_5 and I_5 - I_1 of a measurement can be seen on Fig.7. for one branch with nonlinear load causing changes in the system, Fig.8. for the other one with constant current, and on Fig.9. for the linear element. Fig.10. shows the sum of the loads, that is indeed a composite load. For the first sight some of them (Fig.7a) seem to be a rather chaotic spread because of the relative long period of the measurement (37 min) and the changes of different origin during this time. A short period was chosen when only one type of change was taken place, the corresponding plots were connected with straight lines.

From the plot diagrams one can establish that simple cases can easily and surely be identified: for a passive element the V_5 - I_5 curve starts at the origo, its slope is the 5th harmonic impedance of the load and the I_5 - I_1 characteristic is a vertical line because I_5 is independent from I_1 . If the active element is the reason of the changes, then its I_5 - I_1 characteristic is directed to the origo because they are in a close correlation and the V_5 - I_5 curve shows the portion of THD caused by this nonlinear element and its tangent is the driving point impedance seen fron the connection point. If the active element does not cause

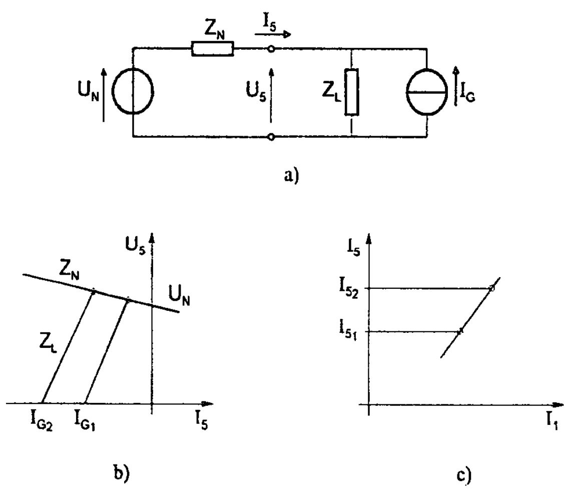

Fig.5a-c Composite load, changing I_G

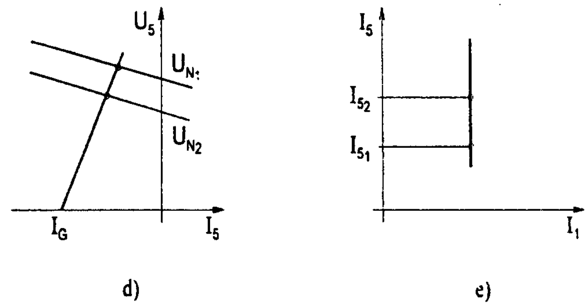

Fig.5d-e Composite load, changing U_N

changes, its I_5 - I_1 characteristic is a single point and the V_5 - I_5 curve is a vertical line. The composite branch can be recognised as well by its V_5 - I_5 curve which is not necessarily directed into the origo - the voltage distortion belonging to the zero 5.th harmonic current is caused by other nonlinear loads - and by the I_5 - I_1 values, which curve - not always a straight line - has an $I_1 \neq 0$ value for $I_5=0$ which is the constant fundamental current of the linear part of the load. The sign of the harmonic active power can help in identifying the type of branches but is not enough itself. And finally we mustn't forget, that the basic equations contain complex parameters; voltages and voltage drops are not in-phase quantities and the currents to be sumed up can have different angles. In the plot diagrams there are absolute values of the phasors, so we can observe only tendencies and this can cause difficulties when analysing the results. However the tangent of the V_5 - I_5 curve is the absolute value of the impedance, and the absolute value of the voltage distortion caused by one nonlinear branch can be easily calculated.

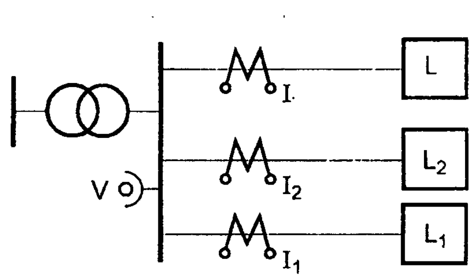

Fig.6. One -line model of the measured substation

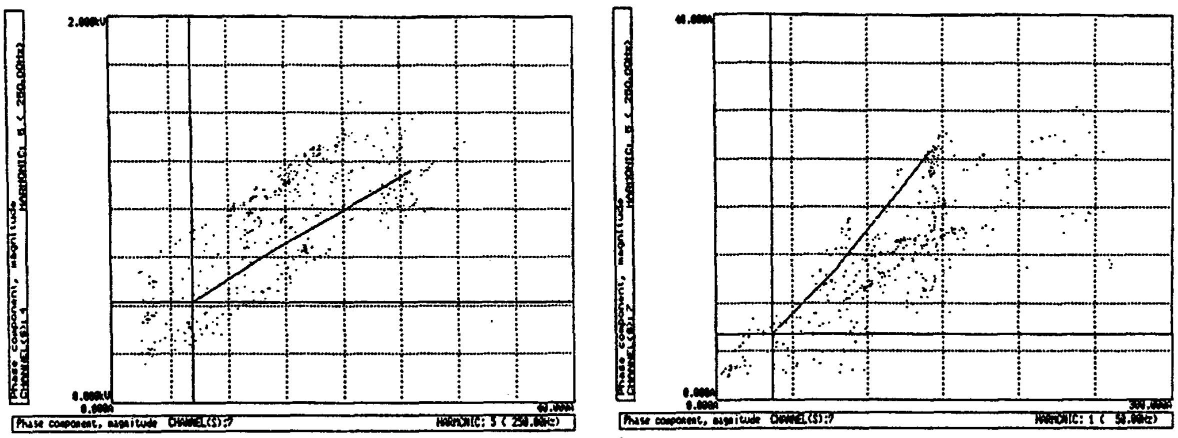

Fig.7. Plots of the nonlinear load, changing current

IV. CONCLUSION

The paper proved that in spite of the uncertanties explained, the method of monoparameter variation is a good way to identify the existence of a harmonic source and to determine the distortion caused by this harmonic source.

V. ACKNOWLEDGEMENT

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V. REFERENCES

[1] EN 50160
[2] EN 61000-4-7
[3] TRANSANAL-16 Operation manual

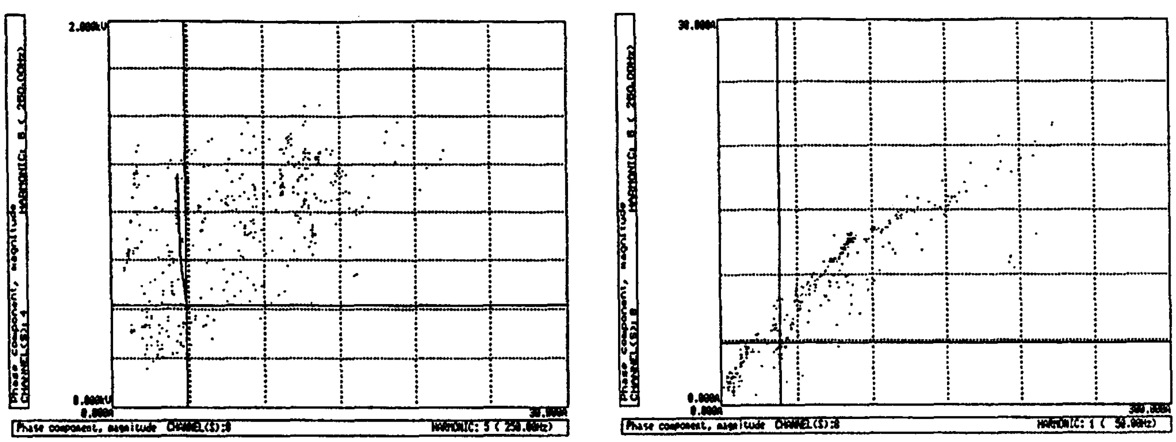

Fig.8. Plots of nonlinear load, constant current

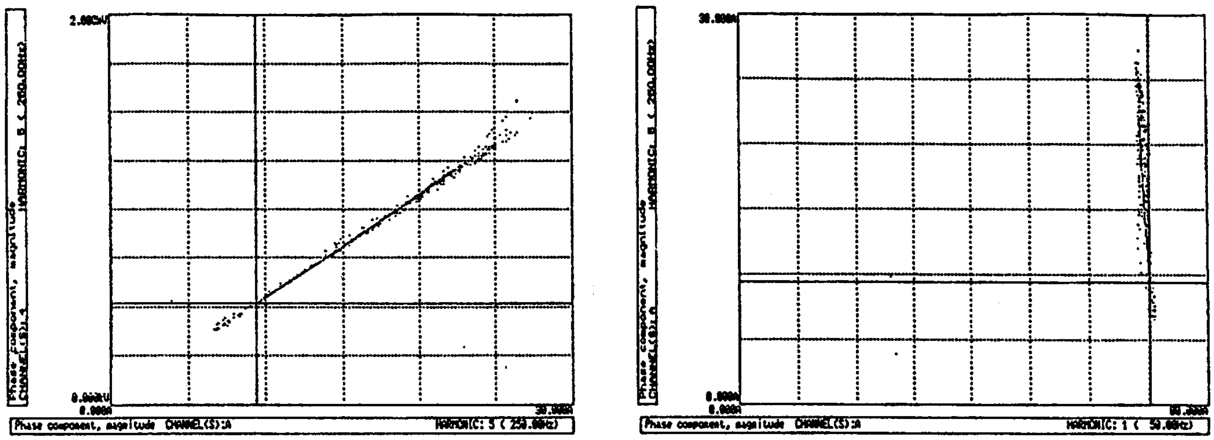

Fig.9. Plots of linear load

VI. BIOGRAPHIES

András M. Dán (SM'90) received MSc degree from Budapest Technical University in 1966, PhD degree in Electrical Engineering from the Hungarian Academy of Sciences in 1983. He has been at Budapest Technical University since 1970 where he currently holds the rank of professor and acts as a consultant for local industry. His expertise is in power electronics, reactive power compensation especially associated with power system harmonics. Dr Dán is a member of the Hungarian Electrotechnical Association.

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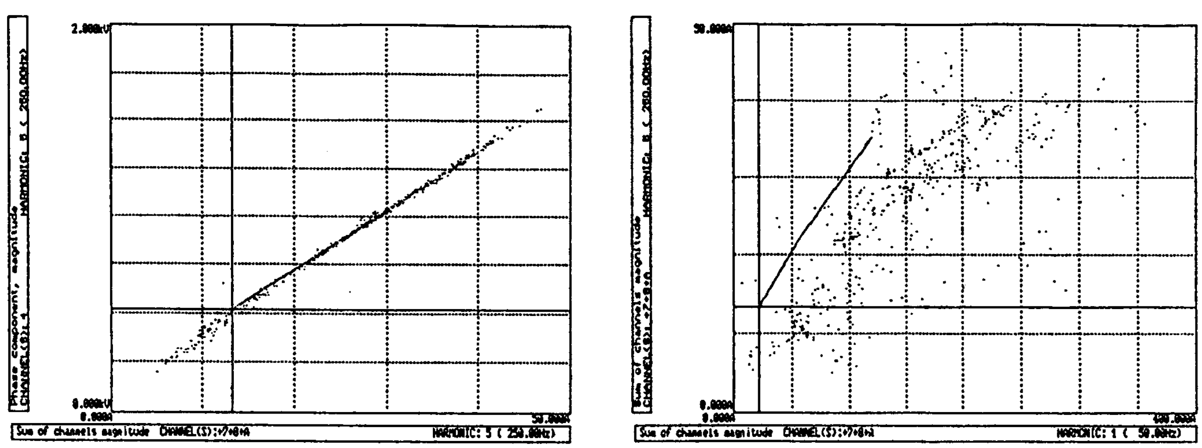

Fig.10. Plots of the composite load