Determining the source of harmonic distortion with a single measuring device

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Abstract - **In today's networks, full of nonlinear loads which generate higher current harmonics, it is important to determine who is the real source of harmonic disturbances. Even if one side has linear load, due to resonant impedance of its network, it can amplify individual current harmonic which are coming from other side. Supply voltage harmonics are mainly caused by higher nonlinear load current harmonics, which are connected to different voltage levels of the network. Various methods dealing with determining of harmonic distortion direction are summarized in two groups, as multi point and single point measurement. This paper presents application of two methods for determining direction of harmonic distortion by measurements taken in single point of common coupling (PCC). Two well know methods, active power method and method based on IEEE 1459-2000 will be used. As both methods do not need impedance values for their calculation, they are ideal for implementation directly into power quality analyzer. Active power method needs values for current and voltage amplitudes of each harmonic order, and phase angles between them. IEEE 1459-2000 method needs same data, with comparison of different reactive powers defined in standard IEEE 1459-2000. In some specific situations, both methods can have problem with generation of accurate results. Nevertheless in many situations they can give valuable informations and engineers can use them as first indication of harmonic distortion source. For measuring equipment advance programmable power quality analyzer will be used. Method algorithms will be implement directly on analyzer, so there will be no need of usage advance software package. Goal of this paper is to create, implement and test on board program for determination of harmonic source. For evaluation of this work, real test system with typical non linear load (six pulse converter) is developed.**

Keywords**: Harmonic, direction, harmonic power flow method, power quality**

I. Higher harmonic and their sources

Harmonic distortion of current and voltage in past 10 years become common term in power system. Higher harmonics are causing distortion of current and voltage, which can result with many type of problems and disturbances, like overload of cable feeders, nuisance tripping of circuit breakers, reduce lifetime of transformers, motors and generators, circuit loses and heating, disruption of electrically controlled equipment, etc.

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Typical source of higher harmonics on utility side are renewable sources, static VAR compensators, HVDC converters, etc. Typically sources on customer side of the network are VSD's, AC/DC converters, pulse converters, arc furnaces, etc.

For the majority of the disturbances in the power system, responsible are nonlinear loads owned by customers (consumers), although supplier of electricity (grid operator - utility) can also contribute to these disturbances. The unwritten rule is that responsibility for maintaining the quality of voltage is on supplier of electricity, while customer (load) is responsible for the quality of the current. Supply voltage harmonics are mainly caused by higher nonlinear load current harmonics, which are connected to different voltage levels of the network. If there is a customer (load) with a negative effect on the network, producing significant amounts of higher harmonic currents, as result there is appearance of higher harmonics of the supply voltage at the point where a network is connected to the customer (point of common coupling). Disturbances in the form of reduced supply voltage quality, due to a significant share of higher voltage harmonics, reflect to all customers connected to the same connection point. Higher harmonics currents produced by nonlinear customer loads will be injected into all other appliances and customers connected to the same connection point. In this case, some customers may receive electrical energy with reduced quality. Since a supplier of electricity is responsible for the delivery of electricity within required quality, the supplier must limit the negative effect of individual customer [1]. To limit the negative effect, determination of responsibility for such disturbances between customer and utility needs to be measured and detected.

II. Determining the source of harmonic distortion

Lots of methods and algorithms for determining the flow/source of harmonic distortion are propose in various articles and researches. We can dived all that methods into two main groups, multipoint measurement and single point measurement. Multipoint measurement methods can be very accurate, but they require knowledge of complete system characteristics with several different measurements such as voltage, current, active and reactive power at each harmonic frequency. Additionally this methods are assuming installing number of advance power analyzers (depend on metering points) with synchronous measurement preformed in different metering section, and implementation of this method can have high costs. Mainly multipoint methods are reserved for big transmission system.

Single point methods are divided into three groups, regarding system characteristic which are sufficient for their calculation. We can divide single point methods on those which are requiring data about system impedance, and those which require only voltage and current measurement at measuring point.

Methods which are requiring system impedance are generally more accurate [4], but far more complicated. In real world it is almost impossible to get impedance value, because methods like frequency scan and switching tests are generally not allowed in practical power system. Second method group, like harmonic vector method HVM [2], and RLC method [3], are using know data for utility impedance (short circuit impedance and last transformer impedance) and they are calculating customer impedance from measured voltage and current values.

Third group methods are "easiest" one for calculation. They require only current and voltage data at the measuring point. Even they are not so accurate as methods from first two groups, they are most used today. Most used method is active power method [9]. Some of methods from third group can be implemented even on standard revenue meters.

A. Implementation of the proposed methods

Goal of this article is to implement two methods from group three directly to power quality analyzer. Both methods are already presented [5], [9], and are proven on numerous tests.

As per standard, algorithm for this methods are made in software package, as Mathlab, Labview, Neplan, etc. Power quality analyzer is used only as measuring/logging device, which is taking snapshots of voltage and current waveforms. After measurement is done, waveforms are transferred to dedicated software, which is processing waveforms and providing calculations.

In this article, we will implement method algorithms directly to measuring device. With this kind of application, engineers will be able to determine direction of harmonic distortion in real time, directly on site. For fixed mounted measuring device, this kind of application will enable permanent measurement of distortion direction, with onboard memory of historical data. By using this kind of metering on numerous points, we can create simple version of multi point measurement, base on single point methods.

B. Methods for determining direction of harmonic distortion

Two methods will be presented in this article. Active power method [9] and method based on standard IEEE 1459-2000 [5]. Both methods are basic one, and they do not require any additional data except current and voltage measurement at measuring point.

Active power method is most used method for determination of direction of harmonic source today. Biggest benefit of this method is its simplicity and easy implementation to any power quality meter. Goal of this method is to calculate power flow for every harmonic order. If value of active power is positive, then the network is main source of harmonic distortion for that harmonic order, and if value of active power is negative, than customer is main source of harmonic distortion. Because method calculation depends only on the difference of the harmonic voltage and current phase angle, and because of possible errors in measurement this method cannot be considered as fully accurate [7]. Although this method is not always accurate, its simplicity can give engineers quick and valuable information about harmonic distortion in that measuring point and can be used as guideline for finding source of higher harmonics.

Algorithms for method based on IEEE 1459-2000 standard are based on different calculation of reactive powers (Q1, Qx and N), defined in [5]. This method is giving relatively correct results, with main disadvantage that results from this method give only share in distortion of whole harmonic spectrum, without knowing the direction and share from individual harmonic orders. General point of this method is difference of three reactive powers. The concept of the method is described in [5] and [8].

Algorithms for both methods will be implemented directly to power quality meter. Algorithms are represented in [8]. Power quality meter has incorporated FFT module, and it already has values for all current and voltage harmonic orders written in its RAM memory. By using this data, we can provide real time calculations and representation of this methods. Results from all four methods will be represented on front LCD screen of ION meters, so engineers can use this meter as local, on site measuring device. Results from bots methods are written in modbus registers, so they can be transferred to any supervisory system. In case of alarm triggering because of high harmonic values crossing over specific level, all results can be stored into onboard memory together with time stamp.

III. IMPLEMENTATION OF METHODS INTO POWER QUALITY METER

For implementation of proposed method algorithms, almost all advance programmable power quality meters (available on the market) can be used. Due to authors availability, advance power quality meter series ION 7650 will be used in this article. This type of measuring device is ideal for on-board implementation of method algorithms, as it has high sampling rate (1024 samples per cycle), and advance programming capability. Power quality meters of this type (from almost all producers) come with standard factory template, which is adapted to analyze power quality based on norms like EN50160 and IEEE 519. Some utility's are using this meter with their own version of metering device template with some additional functions implemented into this meter. Almost all revenue connection points between transmission and distribution system and between two interconnected transmission lines in Croatian Transmission network are monitored with advance power quality meters, that have same or similar characteristic.

Programming language is object oriented architecture, with a core parts named modules, managers, framework, template and node.

Each module provides a specific function to the device. For example typical modules are power meter module, arithmetic module, power quality module, minimum value module, SNMP module, etc. One of the most important module is data acquisition module which is core module for analog/digital conversion of measured current and voltage signals on measuring terminals. Algorithm for all methods in this articles will be created through various arithmetic modules, receiving data from data acquisition module and FFT module. In figure 1 presented is framework and modules for Active power method. For test phase in this article, modules for only odd harmonics are presented on front LCD screen. Front LCD screen is represented with two rows. On left side results from Active Power Methods are represented by values of 1 or - 1. If value for certain harmonic order is 1, than utility is source of that certain harmonic. If value is -1, this indicates that source of that harmonic order is on customer side. On right side of the front LCD, results from method by IEEE 1459-2000 are represented. Harmonic source can be determined by comparing this three results, defined in [5].

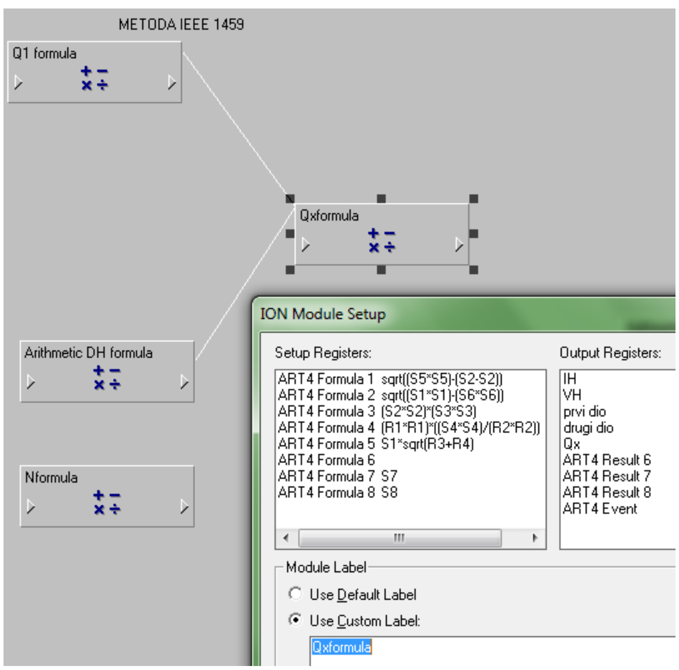

Fig. 1 Algorithm for IEEE 1459-2000 method inside power quality meter

IV. USING THE TWO PROPOSED METHODS TOGETHER

Active power method can give result for direction of each harmonic order separately, but is not giving us the share of contribution of each side in specific harmonic order. Also, this method is not giving data about source of overall harmonic distortion. If we have customer that has relatively small non-linear load compared to network power, producing only some specific harmonics like third or fifth harmonic connected to highly polluted network full of harmonics of all type, result of active power method will show that customer is responsible for specific harmonic which he is typically generating. But in reality contribution of customer non-linear load on harmonic distortion in the network is almost negligible. During connection of new customers or renewable power plants, measurement of THD before and after connection is performed, and this situation is checked, but in case that situation changes during the normal operation, it will not be possible to perform such measurement without customer disconnection.

Similarly , IEEE 1459-2000 method is giving insight only in contribution of overall harmonic distortion. Parallel use of both methods can result with more accurate determination of direction for harmonic distortion. Active power method can show direction of each higher harmonic and IEEE method will show total impact of customer non-linear loads on harmonic distortion in point of common coupling, and respectively in the distribution network.

This situation is common in all distribution nodes where big industrial customers are connected. For example, on same node are connected big industrial plant and small production firm with lot of small non linear loads (single phase AC/DC converters, fluorescent lighting, office computers, etc). Let's assume that big industrial implement huge number of big VSD's without informing distribution company (utility). After wile, small production firm realize that voltage THD on point of common coupling is above recommended limits, and they will make complain to utility. Without knowing of new installation of VSD inside big industrial plant, utility will first provide measurements on PCC with small production plant. In case of determination who is responsible for high voltage THD, utility can check current THD and can use active power method. It will show that for typical higher harmonic responsibility is on customer side. Using method IEEE 1459-2000 it will be evident that despite harmonic generation, customer don not contribute, or its contribution is negligible to the level of THD in the point of common coupling. In this case, utility should not penalized customer (small production firm) for negative detrimental effect on power quality in the network.

Opposite situation is when network is polluted with very specific higher harmonic, for example second order harmonic near customer with arc furnace or arc welders (steel plant, ship yard...). Utility needs to find real source of that specific harmonic, and for this purpose IEEE 1459-2000 method is not adequate. In this case, use of active power method and determination of direction for every individual harmonic can be very useful.

Instead of active power method utility can use some advance methods like HVM method [2]. Result of this method is contribution of both side in each individual harmonic order of current and voltage. Main disadvantages are required knowledge of network impedance which is not always available, and not so easy implementation of method algorithms into existing power quality analyzers. Parallel use of active power method and IEEE 1459-2000 method can be good replacement for advance methods, like HVM method.

V. TEST EXAMPLES

For test example we can use measurement carried out on Faculty of electrical engineering and computing in laboratory for process automation and measurement. This test will represent real conditions in which network is highly polluted and customer type of load has mostly small non-linear loads. Due to the strength of the network in real situation customer has no impact on network harmonic distortion.

Algorithm for both methods are implemented into ION power quality analyzer, and results are shown on front LCD screen, as shown on figure 1.

Customer non linear load is represented with few typical non-linear loads (fluorescent lamp, single phase VSD and computers) connected on phase A, and AC/DC three phase graetz bridge converter with three phase heather as load.. Network/Utility is represented with LV network of faculty.

Due to the large number of computers and electronic devices connected on faculty network, voltage THD level is relatively high with average value of 3 - 4 %, as shown in figure 2.

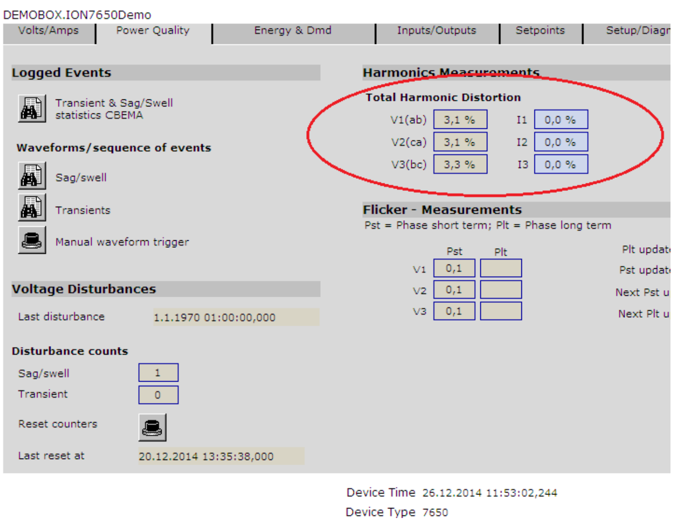

Fig. 2 Harmonic distortion in PCC without any load connected

A. First test - linear load and non linear supply

First test is connection of passive linear load to the polluted network. Linear load is represented with three phase heating device. Total harmonic distortion without connection of any load is around 2,6%, with same value after connection of linear load. Current total harmonic distortion is low as expected, around 3%. In figure 3 results from both methods are represented on front LCD screen of metering device. For all odd harmonics, active power method in left row is showing that network is source of higher harmonics. Equally result from method based on IEEE 1459-2000 are reactive powers with different values close to each other. From this results we can conclude that network is responsible for harmonic distortion in PCC [5]. Results from metering device are checked through advance algorithms created in LabVIEW programming language. Current and voltage waveform is captured with metering device and they are processed in LabVIEW application. Result of LabVIEW application calculation is shown in figure 4.

Fig. 3 Harmonic distortion in PCC with only heather connected

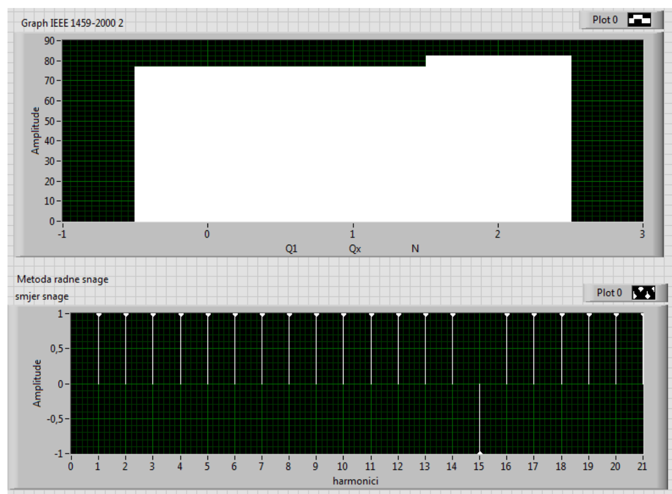

Fig. 4 Results of both methods from LabVIEW application

B. Second test - non-linear load and non linear supply

Second test is representing the connection of small non-linear loads to highly polluted network, from figure 2. After connection of fluorescent lamp, two computer power supply's and mono phase motor powered by single phase VSD all connected on phase 1, THD I1 has rise to 16%, as shown on figure 6. Distorted current waveform in phase1, is represented in figure 5.

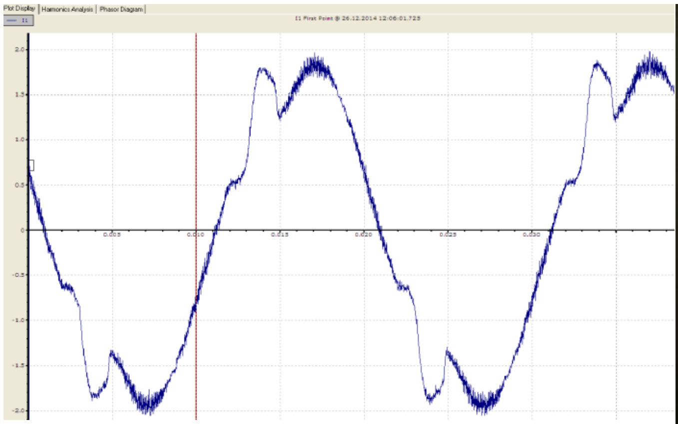

Fig. 5 Current waveform for phase 1

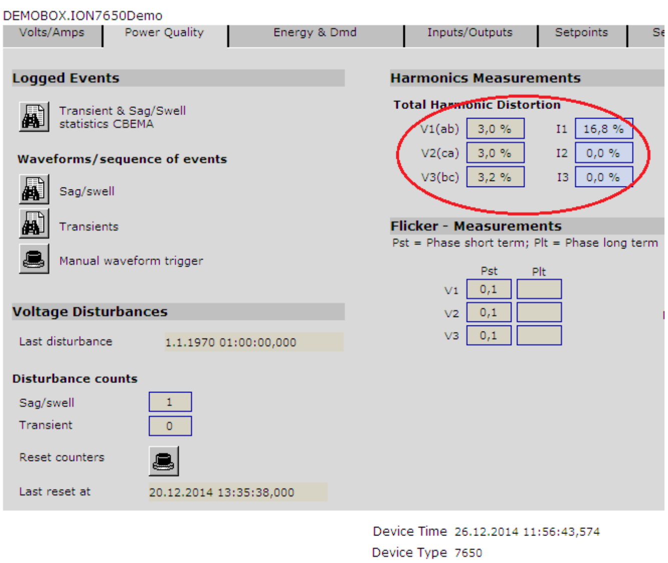

Fig. 6 Harmonic distortion in PCC with non linear load connected on phase 1

Although THD I1 has raised to respectable high level, there is no change in THD V1. It stayed on almost same level. This was expected as load have relatively low power consumption.

If we use active power method to determine source of higher harmonics, we can conclude that source is responsible for almost all odd higher harmonics. Without disconnection the customer, and reviewing only results of active power method, mistake can be made in conclusion that customer is responsible for voltage harmonic distortion in PCC (in phase 1 for this test). Parallel use of IEEE 1459-2000 with active power method this mistake can be easily removed. IEEE 1459-2000 method is showing that responsibility for total harmonic distortion of voltage is on utility side [5]. Result of both method in parallel use is shown in figure 7.

Fig. 7 Results of both method from front LCD screed of PQ measuring device

Active power method can give easy insight in direction of higher harmonics in PCC and IEEE 1459-2000 method will simultaneously give insight who is generally responsible for harmonic distortion. When measurements on PCC with customer with big non linear loads are provided, both method will show their purpose. Active power for direction of each higher harmonic order and IEEE for responsibility on voltage THD in PCC.

VI. Usage of both methods in real power distribution system

Because of their simplicity, both method can be easily implemented in almost all power quality meters. New series of revenue meters, can also be suitable for implementation of both methods. Metering device needs to have ability to measure THD value for current and voltage and to provide FFT calculation, with amplitudes of current and voltage harmonics.

IEEE 1459-2000 method can be implemented in almost all new revenue meters. With this option operator of distribution system will have effective and valuable information of general responsibility for harmonic distortion in all measuring point with newly installed meters (for household and small industrial customers). As the project for implementation of AMI system and replacement of old revenue meters is ongoing in many countries around the world, this is ideal chance for implementation of power quality module into revenue meters. Almost all producers (Iskra, Landis&Gyr, Kamstrup, Echelon, etc...) of revenue meters are offering product with at least measuring of individual harmonics up to 15th harmonic order. This measurements are enough for implementation of IEEE 1459-2000 method, but not for active power method (measurement of phase angle of individual harmonics are missing).

Current practice and laws are defining that all bigger customers and renewable power plants need to have permanent power quality measurement. For that purpose advance power quality meters needs to be used. On almost all this kind of meters implementation of both method will be possible,

Connecting all revenue meters and power quality meters to supervisor software (AMR or SCADA system), operator of distribution system will be able to check responsibility for harmonic distortion on all customer connected to same node.

Operator will be able to check, find and locate all sources of harmonic distortion in distribution system. This will reduce field measurements, traveling of distribution workers from one location to another, engineering working hours on the field and unnecessary disturbing all other customers, except dedicate one. This idea is not intended for usage of revenue power quality metering (for penalization), but only as insight/overview of possible source of harmonic distortion in distribution network.

VII. Conclusion

Harmonic distortion is definitely becoming "hot" theme in today power engineering world. Today power quality is defined by relevant norms and all participants should lower harmonic distortion under recommended limits.

Although used methods in this article are not most effective ones and considering that they can give incorrect results in some situations ([7] and [3]), they can be very useful in determining and locating sites on which additional advance measurements needs to be provided.

For this article both method algorithms are implemented into power quality analyzer, and test system is designed. Test have shown that parallel use of both method can give more accurate results, and mistake of using only one method in specific situations can be avoided. Both algorithms need similar measured data for voltage and current. Meters that are capable of calculating active power method, can also calculate method based on IEEE 1459-2000.

In simulated conditions both methods are giving correct results, but only further use of both methods in real system will show full effectiveness and correctness of both methods.

VIII. References

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