Separate measurement of fundamental and high harmonic energy at consumer inlet – a real way to improve supply network voltage waveform

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Abstract **-High harmonics in power systems are caused by both energy sources and consumers. Harmonics essentially decrease the efficiency of electricity use. Therefore the following questions are rather pressing: what is the source of high harmonics and at whose expense the supply network voltage waveform should be improved? Solving these problems is of both technical and administrative character. Electricity consumers can be divided into two groups. Group 1 includes loads with almost linear voltage-current characteristics. These consumers receive both fundamental and high harmonic energy which is detrimental in the majority of cases. Group 2 includes loads with nonlinear voltage-current characteristics. They generate high harmonics to the network while power supply company bears the costs of implementing the measures on decrease of the high harmonics level in the network. Hence, it is necessary to:**

- **develop a meter to measure separately the energy of fundamental and high harmonics;**
- **determine the way of compensating for the damage caused by high harmonics in supply network to the consumers of group 1 and for the damage caused by consumers of group 2 to power supply company.**

The paper shows the necessity of measuring separately fundamental and high harmonic energy. Measurement of high harmonic energy and settlement of legal issues related to payment for this energy should encourage power supply companies and consumers to take technical and organizational measures to decrease high harmonic level in the network. These measures should lead to the improvement of the supply network voltage waveform which will enhance the efficiency of electric energy use by consumers.

Keywords: efficiency of power use, meter of fundamental and high harmonic energy, high harmonic energy

I. INTRODUCTION

High harmonics caused by nonlinear load lead to many negative consequences. Harmonic voltages and currents affect the components of power supply systems.

The main effects the high harmonics have on power supply systems are increase of harmonic currents and voltages due to parallel and series resonances; decrease in efficiency of electricity generation, transmission and consumption; aging of electric equipment insulation and, as a result, reduction of its service life; malfunction of equipment.

Electric motors break down prematurely due to voltage deviation from its rated values and occurrence of harmonic voltage in the supply network. Harmonic voltages and currents lead to additional losses in stator windings, rotor circuits and in stator and rotor steel. Harmonic losses are distributed as follows: 14% - stator windings, 41% - rotor circuits, 19% - end zones of stator and 26% - asymmetrical ripples [1][2].

The losses caused by high harmonics in the rotating machines result in increase of temperatures in the machines and in local overheating, which is most probable in rotor.

In cable lines harmonic voltages speed up the aging of dielectric, which leads to an increase in the number of cable damages and the cost of related repairs. The aging of cable and wire insulation is accelerated.

In ultra high voltage lines the harmonic voltages for the same reason can cause an increase of corona losses.

High harmonics considerably increase the losses due to rise in eddy currents in power transformers, since these losses are proportional to a squared value of frequency. The increase of losses raises the actual operating temperature of transformer, which essentially reduces its life time.

The wear and premature failure of condensers in the reactive power compensation devices occur faster.

The settings of relay protection are adjusted to the fundamental harmonic currents and voltages of the circuit section to be protected. Higher harmonics in the network can lead to false operation. There can be malfunction of safety devices and automatic circuit breakers due to their additional heating by harmonic currents.

The probability of resonance switching overvoltage that leads to a premature failure of electric equipment increases.

The metering devices are normally calibrated at purely sinusoidal voltage, therefore, even insignificant deviations of a waveform from sinusoidal one increase an error [4]. The value and direction of harmonics are very important since error sign depends on harmonic direction.

The measurement errors caused by harmonics strongly depend on the type of metering devices [7]. The readings of ordinary induction meters are as a rule overrated if consumer has a source of distortion. Such consumers appear to be automatically punished for causing distortion in the network. Therefore, they are interested in installing devices to suppress distortions.

There are no quantitative data on the influence of harmonics on the accuracy of load power measurements. Supposedly the effect the harmonics produce on the accuracy of the load power measurements is the same as on the accuracy of energy measurements [5].

The influence of harmonics on accuracy of verification and calibration of devices at laboratories is seldom mentioned, though this aspect is also important [3].

II. MAJOR PRINCIPLES OF THE APPROACH

According to the requirements established for power quality there are two standards related to high harmonics of the supply network: total harmonic distortion and harmonic factor. However, even if these factors are measured, for example, at inlet of an individual consumer the questions still remain open: what is the source of high harmonics in the network and at whose expense the above power quality parameters should be improved. Solving these problems is of both technical and administrative character.

It should be noted that high harmonics in power system are produced by both energy producers and consumers [6]. For technical reasons it is practically impossible to create a generator that produces purely sinusoidal electromotive force. As far as electricity consumers are concerned they can be conventionally divided into two groups.

The consumers of group 1 do not generate high harmonics to the power system. These are loads with almost linear voltage-current characteristics: lighting equipment, electric heaters, AC motors, domestic load. These consumers receive both fundamental and high harmonic energy. In the majority of cases high harmonic energy is detrimental. We will enumerate the main negative effects of high harmonics: decrease in energy indices of AC motors, lower accuracy of measurements of an effective value of current, malfunction of computer networks, overvoltage due to possible resonance conditions at high harmonic frequencies.

The consumers of group 2 generate high harmonics to the supply network. These are loads with nonlinear voltage-current characteristics: electronic power converters, rectifiers for electrolysis and for dc motors, electric transport, electric arc furnaces, welding, etc. At the same time power supply company suffers loss. This can be costs of the measures to decrease the level of harmonics in the network and expenses related to fines to be paid to consumers of group 1 as compensation for the damage related to the non-sinusoidal voltage in the network.

Thus, it is necessary:

- to develop a meter for separate measurement of: fundamental harmonic energy – W_1, value and sign of high harmonic energy – W_{HH} and total energy – $W = W_1 + W_{HH}$;
- to determine the method of compensation for the damage caused by high harmonics in the network to the consumers of group 1;
- to determine the method of compensation for the damage caused by high harmonics of the consumers of group 2 to the power supply company.

The meter of high harmonic energy should be reversible, i.e. capable to indicate the direction of harmonic energy flow. When harmonic energy is supplied from the network to consumers - the energy has a positive sign and, vice versa, when consumers supply harmonic energy to the network – a negative one.

Any meter of electric energy irrespective of the principle of operation carries out integration of active power with respect to time.

Let us consider a general case (Fig.1 a), where the supply network has high harmonics and they are generated by a nonlinear load. Here a voltage drop in current circuit of meter can be neglected, i.e. $\dot{U}_{kN} = \dot{U}_{kL}$. For simpler analysis we present a conventional one-phase meter with indicated directions of fundamental and high harmonic currents and voltages at the meter inlet and outlet. In Fig.1 $\overset{*}{I}, \overset{*}{U}$ – inputs of current and voltage windings of the meter; $\dot{I}_1, \dot{U}_1$ – complex numbers of effective values of fundamental harmonic currents and voltages; $\dot{I}_{kN}, \dot{U}_{kN}, \dot{I}_{kL}, \dot{U}_{kL}$ – complex numbers of effective values of currents and voltages of high harmonic that comes to the meter from network (*N*) and consumer (*L*), respectively.

Determine the total energy recorded by a conventional meter:

$$W = \int_0^t iudt = \int_0^t \left(i_1 + \sum_{k=2}^{n} i_{kN} - \sum_{k=2}^{n} i_{kL} \right)\left(u_1 + \sum_{k=2}^{n} u_k \right) dt ,$$

where i – meter load current;

u – meter load voltage;

$i_1, \sum_{k=2}^{n} i_{kN}$ – fundamental harmonic current and high harmonic currents of the network, respectively, that come to the meter inlet;

$\sum_{k=2}^{n} i_{kL}$ – harmonic currents whose directions are opposite to the load current;

$u_1, \sum_{k=2}^{n} u_k$ – fundamental and high harmonic voltages, respectively; their directions and values are equal at meter inlet and outlet.

Assuming that the average value of the product of momentary values for sinusoids of different frequency for the period is equal to zero, we obtain:

$$W = \int_0^t i_1 u_1 dt + \sum_{k=2}^{n} \int_0^t i_{kN} u_k dt -$$

$$- \sum_{k=2}^{n} \int_o^t i_{kL} u_k dt = W_1 + W_{HH\ N} - W_{HH\ L}$$

where W, W_1 – total energy and fundamental harmonic energy of the load, respectively;

$W_{HH\ N}$ – high harmonic energy received by consumer from the supply network;

$W_{HH\ L}$ – high harmonic energy transmitted by the nonlinear load to the supply network.

Thus, we have determined that the energy measured by the conventional meter consists of the sum of fundamental and high harmonic energies.

Consider the case (Fig.1b), when the consumer of group 1 is connected to the supply network containing high harmonic *k,* i.e. the high harmonic comes from the system to load. The sign of active power *P* and correspondingly energy *W* depends on the phase shift.

$$\varphi_1 = \Psi_{u1} - \Psi_{i1},\ 0^{\circ} \le \varphi_1 \le 90^{\circ},$$

$$\varphi_k = \Psi_{uk} - \Psi_{ik},\ 0^{\circ} \le \varphi_k \le 90^{\circ},$$

Here φ_1 and φ_k – phase shift between the fundamental and high harmonic voltage and current at the meter inlet, respectively. The angles φ_1 and φ_k are determined through the complex impedance of load. In practice the loads are most frequently active-inductive, i.e. the angles change in the range from 0° to 90°.

$$cos\varphi_1 \ge 0;\ P_1 \ge 0;\ W_1 \ge 0;$$

$$cos\,\varphi_k \ge 0;\ P_k \ge 0;\ W_k \ge 0.$$

In this case the consumer of group 1 pays for the sum of fundamental and high harmonic energies, i.e. pays for high harmonic energy needless for it.

Consider an opposite case (Fig.1c), when the consumer of group 2 generates high harmonic *k*, i.e. the high harmonic comes from the consumer to the system. At the same time voltage of the supply network does not contain harmonics.

$$\varphi_k = \psi_{uk} - \psi_{ik},\ 90^{\circ} \le \varphi_k \le 180^{\circ},$$

Angle φ_k depends on the internal resistance of high harmonic generator.

$$cos\varphi_1 \ge 0;\ P_1 \ge 0;\ W_1 \ge 0;$$

$$cos\,\varphi_k < 0;\ P_k < 0;\ W_k < 0.$$

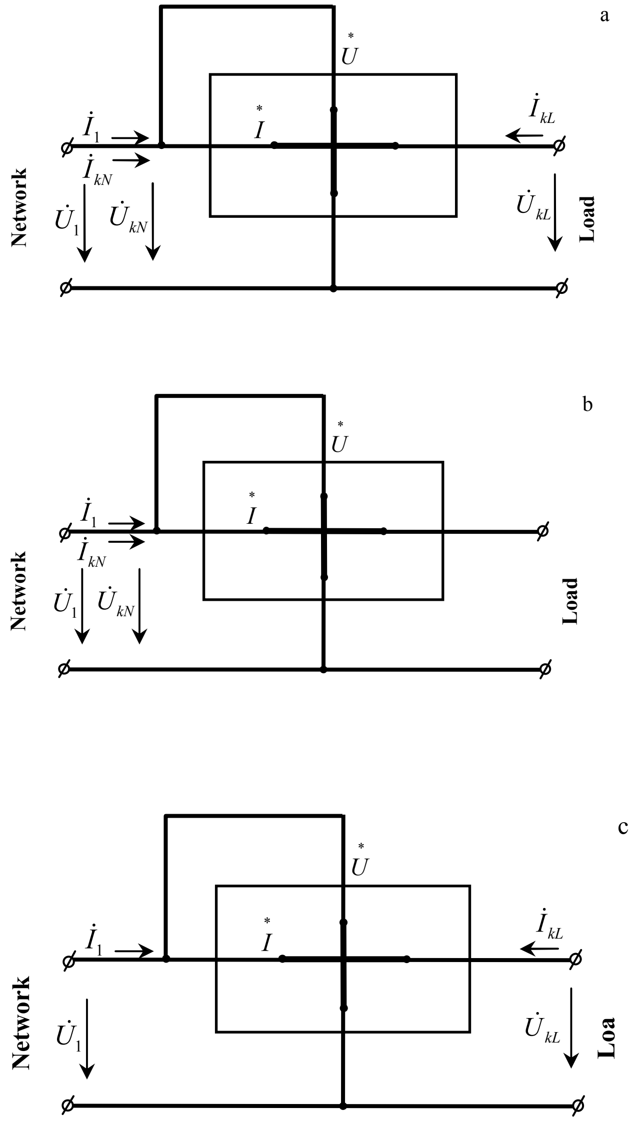

Fig.1. Schemes of meter connection for three cases

The question on the high harmonic energy value and sign remains unsettled. In the works dealing with power quality the question is formulated as determination of the contribution of an individual consumer to the harmonic network composition. There are methods to determine this contribution by measuring a network harmonic level before and after disconnection of some load. Experience shows that the results of such measurements are widely spaced because of unpredictable variations in operation of other consumers. Besides, experts in electricity supply have not demonstrated special interest to spectral composition of network voltage and high harmonic energy distribution among individual harmonics. It is important for them that the high harmonic energy flow from the supply network should be within the limits providing reliable and highly efficient operation of consumer. The authors have the courage to say that the suggested reversible meter of high harmonic energy is a real decision for determination of the contribution of an individual consumer. The following problems remain unsolved:

- metrological – meter calibration;
- economic – estimated cost of high harmonic energy, energy payment.

It is obvious that consumers as a high harmonic energy source are not interested in introduction of the suggested meter.

To explain the above said, consider vector diagrams of both cases. Fig. 2a presents the case, where a high harmonic comes to consumer from the network. As to Fig.2b, it illustrates the case, when a high harmonic comes from the consumer to network. For simplicity sake the resistances of harmonic load and generator will be assumed to be purely active.

The phase shift between current and voltage is known to be equal numerically to the angle shift between the representing vectors of current and voltage in the vector diagram. Here the angle is counted from the current vector counterclockwise in the direction of voltage vector.

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We have obtained a rather unexpected result: in the second case the total active energy is less than the active fundamental harmonic energy by the value of high harmonic energy and the consumer of group 2 pays less than is required.

A consumer that converts electric energy into thermal one (e.g. electric boiler) utilizes both types of energy and should pay for them. Presence of high harmonics in the voltage is not so important for such a consumer as the total energy.

A consumer that converts electric energy into mechanical one by using ac machines (synchronous and asynchronous machines) applies only fundamental harmonic energy. The high harmonic energy is undesirable for them, since it decreases economic indices of machine operation.

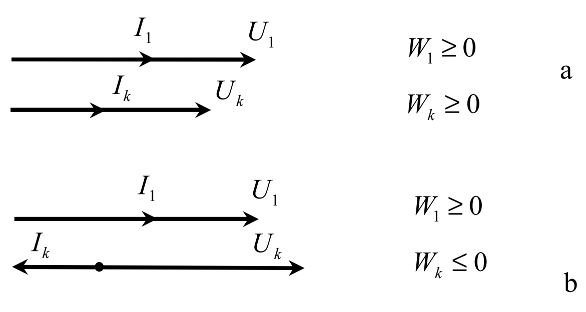

Fig. 2. Vector diagrams

Hence, the requirement to pay for this part of electricity by the consumer is unjustified. It would be more logical to measure this energy component and require that electricity supplier pay for it.

Special attention will be paid to consumers generating high harmonics, whose energy comes to the supply network and is consumed further by all other loads connected to this network.

Thus, in the case “a” the consumer of group 1 pays for the sum of fundamental and high harmonic energies and in the case “b” the consumer of group 2 pays for the difference between fundamental and high harmonic energies. In other words, we face a double inequity.

From the above said follows the necessity for an active energy meter that would allow separate measurement of the total energy, high harmonic energy and fundamental harmonic energy in terms of it direction.

III.GENERALIZED METER DIAGRAM

Several years ago the problem of separate measurement of the fundamental and high harmonic energy would be purely academic, however the current measurement technology makes possible its solution. Clearly the arising metrological problems will require additional scientific comprehension and commercial metering of high harmonic energy needs a legal solution.

Fig. 3 presents a suggested generalized schematic diagram of the single-phase digital meter with separate measurement of the fundamental and high harmonic energy of load. In the diagram: 1 – an analog former of voltages u_u and u_i proportional to voltage u and current i of load L; 2 – a digital meter of total energy; 3, 4 – low frequency filters; 5 – a module for measuring the length of fundamental harmonic period; 6, 7 – analog-to-digital converters (ADC): 8 – a fundamental harmonic energy meter; 9 – a comparator.

Now we consider its work. Module 1 generates measurement information as voltages u_u and u_i proportional to load voltage and current, respectively. Voltage u_u can be obtained by the metering voltage transformer and that in 0.4 kV circuit – by the resistive voltage divider. Voltage u_i can be obtained by the metering current transformer. The fundamental harmonic can be measured by isolation of the fundamental harmonic voltages u_{u1} and u_{i1}. The levels of voltages u_u and u_i are within the dynamic range of ADC. It makes possible the application of active electronic filters of low frequencies to isolate fundamental harmonics that pass fundamental harmonics without decrease and decrease high harmonics practically to zero.

Conventional meter 2 measures the total fundamental and high harmonic energies of load L. Modules 3 and 4 are low frequency filters passing fundamental harmonics u_{u1} and u_{i1}. Module 5 measures the length of high harmonic period for voltage and generates clock pulses that control work of digital devices of the meter, namely modules 6, 7, 8, 9 of the meter.

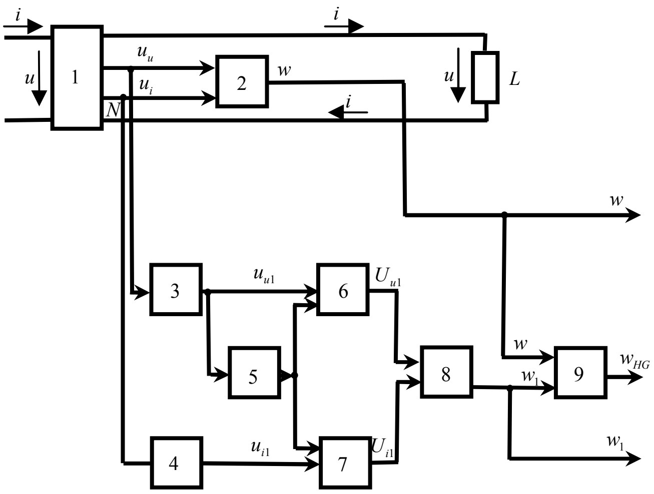

Fig. 3. Generalized schematic diagram of high harmonic energy meter

Modules 6 and 7 generate in a digital form voltages proportional to fundamental harmonic voltage and current of load, respectively. Conventional meter 8 measures the fundamental harmonic energy of load. Its specific feature is the entry of digital signals with a small step of sample at its inlet. The sample step is determined by the high harmonic frequency that makes a real contribution to high harmonic energy. Module 9 is a comparator that determines the absolute value and the sign of difference $W - W_1 = W_{HH}$. Signals W , W_1 and W_{HH} are transmitted by the communication channels to the dispatching center, where they are further processed in order to take administrative and engineering measures.

Note two possible results: W_{HH} >0 and W_{HH} < 0. The first result indicates that the high harmonic energy comes from the supply network to load; the second shows that the high harmonic energy comes from load to the supply network. Hence, the meter measures simultaneously three active energies: W – total energy that is used as a basis for making settlements with consumers neutral to harmonic levels (electric boilers); W_1 – fundamental harmonic energy that is applied for making settlements with consumers; W_{HH} - high harmonic energy, for which consumers of group 1 get compensation from the power supply company and consumers of group 2 incur a fine in favor of the power supply company.

Measurement of high harmonic energy that comes from the supply network to the consumer and resolution of legal issues concerning payment for this energy should create incentives for the power supply company to take technical and organizational measures on power quality improvement.

Measurement of high harmonic energy coming from the consumer to the supply network and payment for this energy should encourage in turn consumers to take technical and organizational measures on power quality improvement. Taken together these measures would lead to improvement of the voltage waveform for the supply network.

IV. CONCLUSION

The authors have shown the necessity of separate measurement of fundamental and high harmonic energies. Measurement of high harmonic energy and resolution of legal issues concerning payment for this energy should encourage both power supply companies and consumers to take engineering and organizational measures on increasing the high harmonic energy level in the network, which would lead to improved efficiency of electricity use. A digital meter is suggested to measure fundamental and high harmonic energies of load separately. Measurement of the high harmonic energy will be an incentive for taking technical and organizational measures on decrease of high harmonic level in the supply network.

V. REFERENCES

[1] Arrillaga, Jos. Power system harmonics /J. Arrillaga, N.R. Watson. -2nd.ed. – Chichester: Wiley, 2003

[2] DeKeulenaer, Hans, Power Quality&Utilisation Guide, Leonardo Energy, 2006

[3] Heriakian, Isabelle, Power quality critical sectors: Power Quality for healthcare facilities, Leonardo Energy, 2009

[4] Key, T and I.S.Lai “Cost and Benefits of Harmonic Current Reduction for Switch-Mode Power Supplies in a Commercial Building” in Con! Rec. of IEEE IAS Annual. Mtg., Orlando, FL, Oct. 1995, pp.1101-1108

[5] Lai, S. and T.S.Key “Cost Effectiveness of Harmonic Mitigation Equipment for Commercial Office Buildings” IEEE IAS Annual Mtg., San Diego, CF, Oct.1996.

[6] Rusdy, Hartungi and Liben, Jiang “Investigation of Power Quality In Health Care Facility” International Conference on Renewable Energies and Power Quality (ICREPQ’10) Granada (Spain), 23rd to 25th March, 2010

[7] M. Bollen, I. Gu, Signal processing of power-quality disturbances. New York: IEEE Press, 2006.