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From Smart Metering to Smart Grid

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The paper deals with evaluation of measurements in electrical distribution systems aimed at better use of data provided by Smart Metering systems. The influence of individual components of apparent power on the power loss is calculated and results of measurements under real conditions are presented. The significance of difference between the traditional and the complex evaluation of the electricity consumption efficiency by means of different definitions of the power factor is illustrated.

Keywords: Smart Metering, Smart Grid, efficiency, power factor, power loss.

1. INTRODUCTION

The world is changing and so are the conditions and circumstances in the energy industry. The concentration of population in cities and their vicinities are growing and the demands for comfort are increasing. We are observing global warming and natural disasters, we suffer from a dependence on the owners of fossil fuels, we want and have to deal with environmental pollution, renewable sources, risks related to nuclear power and minimizing of CO_2 production. There are complications with electric networks, lacks and surpluses of electricity, its capacity and quality parameters are changing, the risks of problems and possibly smaller and bigger energy blackouts are increasing.

In relation to the liberalization of the single European electricity market and promoting the use of distributed renewable electricity sources, often unstable and less predictable, resulting in an increasingly complicated electricity flow, the requirements for a cost-effective implementation of new production sources and electricity distribution, network stability and secure supply of increasing and fluctuating electricity amounts all the way to the end consumer are becoming more and more difficult to fulfil.

2. METERING STATUS QUO

Measurement of the amount of electricity produced, transmitted, distributed and consumed has been a natural part of the electricity business for years. The means of measurement are changing according to the technology advancement, new theoretical analyses are published, however, the quantities measured, the period of measurement, and the way of processing and presentation of data by the electricity system operators are almost the same as many years ago.

The world is changing and so is the European and national energy legislation, resulting in the Third Energy Package, the 2020 European strategy objectives in power industry and climate EU 20/20/20 rules, to name only a few. Apart from the energy efficiency, probably the terms most often used are Smart Metering (SM) and Smart Grid (SG) as synonyms for the solution of (all) problems of (mainly electrical) energy industry [1], [2].

Smart Metering should provide much more useful information (not only data) to all members of the electricity (gas, water...) market to strengthen the customers' position, to facilitate a greater integration of renewable energy sources into distribution networks, enable the development of electro-mobility and electricity storage, to help increase energy efficiency and decrease the power loss, along with a contribution to environmental protection and overall sustainability.

3. IS SMART METERING SMART (ENOUGH)?

Smart Metering is generally defined as an "electronic system capable of measuring energy consumption with more additional information than a conventional meter and transmitting and receiving data using some form of electronic communication". The emphasis is mostly given on the bidirectional communication alone and more information is often understood only as readout with much higher frequency [3].

But this is a very limited approach. To fill the data servers of the Distribution System Operators (DSO) with a huge amount of redundant data is surely not smart. We neither doubt the need of a fast and reliable bidirectional communication with the meters nor the usefulness of data compression algorithms adjusted to the requirements of SM and SG [4], but the communication speed and data processing

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have to be adjusted with the sense, kind of use and presentation of the data. We would like to present our view on measurements in the electricity industry and to propose the possibilities of enhancing them in order to give the words "with more additional information" in the upper definition a qualitative rather than quantitative sense.

The active power P is generally defined as a mean value of the product of the instantaneous values of voltage v and current i.

$$P = \frac{1}{T}\int_0^T v.idt \tag{1}$$

In a three-phase system the active power is the sum of them over the three phases.

$$P = P_1 + P_2 + P_3 \tag{2}$$

The active power consumption (energy) we all pay for is an integral of this power over quite a long period of time – most often one year or one month. To get the information about the power consumption in a more detailed way, e.g., once a day in a quarter of an hour step, surely gives the customer a better view on his/her "mode of operation" and enables him/her to optimize the power consumption, to adjust it to the electricity tariffs, etc.

Of course the evaluation of power efficiency is nothing new. The reactive power Q is also measured at large customers to be able to evaluate the power factor $\cos\varphi$. Although these two terms are used generally and for a long time, the first ambiguities just appear. The total reactive power is most often defined as the sum of the reactive powers of all harmonics.

$$Q = \sum_{k=1}^{\infty} V_k I_k \sin\varphi_k \tag{3}$$

However, the reactive power $Q(1)$ of the first harmonic is very often measured, because it is easier to do and it creates the most significant part of the total Q. Nevertheless, this does not cause any major problems.

In a three-phase system the reactive power is the sum of them over the three phases.

$$Q = Q_1 + Q_2 + Q_3 \tag{4}$$

The more imprecise situation is with the power factor $\cos\varphi$. It is generally defined as a ratio of the active power P and the apparent power S.

$$\cos\varphi = \frac{P}{S} \tag{5}$$

But in the electrical power industry the apparent power is mostly not measured and evaluated at all and, more importantly, there are too many definitions of the apparent power in a three-phase system. The apparent power S in a one-phase system is simply a product of the RMS values of the voltage and current.

$$S = V.I \tag{6}$$

For sinusoidal waveforms of both voltage and current the following equations can be easily derived.

$$S = \sqrt{P^2 + Q^2} \tag{7}$$

$$\cos\varphi = \frac{P}{\sqrt{P^2 + Q^2}} = \cos\left(\operatorname{atan}\frac{Q}{P}\right) \tag{8}$$

The apparent power in a three-phase system is most often calculated by means of the formula (7) with P a Q given as sums of particular powers over all three phases according to the formulas (2) and (4). To avoid later misunderstanding we use the term geometrical apparent power S_g for this three-phase apparent power definition.

$$S_g = \sqrt{P^2 + Q^2} \tag{9}$$

Similarly, the formula (8) for the power factor $\cos\varphi$ is widely used.

The reactive power consumption (reactive energy) is evaluated as an integral of the reactive power Q or $Q(1)$ over the same period of time as the active energy. Afterwards, the formula (8) for the calculation of a power factor is used, except that energies are used instead of powers.

The more frequent measurement of the reactive energy and the more frequent calculation of the power factor have the same implication as with the active energy: more data without more qualitative information.

So what is missing in this "historical" approach? What do these simplifications cause or hide? What can be revealed by a measurement of all power and quality parameters of electricity? How can the electricity measurement be truly smart? What should the "correct" definition of the apparent power of a three-phase system look like?

The first step (actually the second one [5], but we want to show and compare only the significantly different approaches) to get "a better definition" of apparent power was to calculate it as a sum of apparent powers of the three phases resulting in an arithmetic apparent power S_a.

$$S_a = S_1 + S_2 + S_3 \tag{10}$$

The apparent powers S_i of individual phases (i = 1, 2, 3) calculated by means of the general formula (6) involve not only active and reactive powers P_i and Q_i, but also the distortion power D_i as introduced by Budeanu [6].

$$S_i = \sqrt{P_i^2 + Q_i^2 + D_i^2} \tag{11}$$

Thus, the arithmetic apparent power definition describes the influence of all imperfections within individual phases ignoring the relationships between the three phases.

Although there is no complete agreement in the definition and physical meaning of different components of the three-phase apparent power, we consider as the most appropriate (comprehensive) the approach of Nedelcu [7] and others that in our opinion describes the power and efficiency relationships in a general three-phase system in the best way. The well-known formula for the "true" or "effective" three-phase apparent power (Rechtleistung [8]) is

$$S_r = \sqrt{\left(V_1^2 + V_2^2 + V_3^2\right)\left(I_1^2 + I_2^2 + I_3^2\right)} \quad (12)$$

or rewritten as

$$S_r = \sqrt{P^2 + Q^2 + D^2 + A^2 + B^2} \quad (13)$$

The active and reactive powers under nonsinusoidal conditions are usually defined as sums of respective powers over all harmonic components and over all phases.

$$P = \sum_{i=1}^{3} \sum_{k=1}^{\infty} V_i^{(k)} I_i^{(k)} \cos \varphi_i^{(k)} \quad (14)$$

$$Q = \sum_{i=1}^{3} \sum_{k=1}^{\infty} V_i^{(k)} I_i^{(k)} \sin \varphi_i^{(k)} \quad (15)$$

where k is the order of the harmonic component, i is the phase number.

The power quantities introduced in [6] and [7] are

- distortion power of a one-phase system

$$D_i = \sqrt{\sum_{k=1}^{\infty} \sum_{\substack{l=1 \\ l \neq k}}^{\infty} \left[\begin{array}{l} V_i^{(k)^2} I_i^{(l)^2} - \\ - V_i^{(k)} I_i^{(l)} V_i^{(l)} I_i^{(k)} \cos(\varphi_i^{(k)} - \varphi_i^{(l)}) \end{array} \right]} \quad (16)$$

- distortion power of a three-phase system

$$D = \sqrt{\sum_{i=1}^{3} \sum_{k=1}^{\infty} \sum_{\substack{l=1 \\ l \neq k}}^{\infty} \left[\begin{array}{l} V_i^{(k)^2} I_i^{(l)^2} - \\ - V_i^{(k)} I_i^{(l)} V_i^{(l)} I_i^{(k)} \cos(\varphi_i^{(k)} - \varphi_i^{(l)}) \end{array} \right]} \quad (17)$$

- power of asymmetry

$$A = \sqrt{\sum_{i=1}^{3} \sum_{\substack{j=1 \\ j \neq i}}^{3} \sum_{k=1}^{\infty} \left[\begin{array}{l} V_i^{(k)^2} I_j^{(k)^2} - \\ - V_i^{(k)} I_j^{(k)} V_j^{(k)} I_i^{(k)} \cos(\varphi_i^{(k)} - \varphi_j^{(k)}) \end{array} \right]} \quad (18)$$

- asymmetrical distortion power

$$B = \sqrt{\sum_{i=1}^{3} \sum_{\substack{j=1 \\ j \neq i}}^{3} \sum_{k=1}^{\infty} \sum_{\substack{l=1 \\ l \neq k}}^{\infty} \left[\begin{array}{l} V_i^{(k)^2} I_j^{(l)^2} - \\ - V_i^{(k)} I_j^{(l)} V_j^{(l)} I_i^{(k)} \mathbf{cos}(\varphi_i^{(k)} - \varphi_j^{(l)}) \end{array} \right]} \quad (19)$$

where k and l are orders of the harmonic components, i, j are the phase numbers.

If we agree to the definition of apparent power as some kind of product of voltage(s) and current(s) ((6) and (12)), then it has these consequences

- the apparent power is well measurable under all conditions
- the apparent power has more components than P and Q, as used now (7), because of higher harmonics and asymmetry of voltages and currents ((11) and (13))
- the apparent power and the power factor have a direct association with the power loss and thus with the efficiency of the transfer of electricity (actually the apparent power definitions were derived under this assumption)

To avoid the confusion between the most often used power factor $\cos \varphi$ (8) and its generally valid definition (5) for the latter the designation power factor λ or P/S is used.

$$\lambda = \frac{P}{S} \quad (20)$$

What is the physical meaning of the power factor λ? Power line loss P_J in a one-phase system is equal to

$$P_J = R_l . I^2 \quad (21)$$

where R_l is the power line resistance. This formula can be simply modified as follows.

$$P_J = R_l . \frac{S^2}{V^2} = R_l . \frac{P^2}{V^2} . \frac{1}{\lambda^2} \quad (22)$$

The minimum value of power loss in a given system (V, R_l) transmitting the active power P can be achieved when the power factor λ is equal to 1.

$$P_{J\,\min} = R_l . \frac{P^2}{V^2} \quad (23)$$

So we can conclude that the power factor λ is equal to the square root of the ratio of the minimum possible and the actual power loss for the given active power.

$$\lambda = \left(\sqrt{\frac{P_{J_{\min}}}{P_J}} \right)_{P=const} \quad (24)$$

It seems to be appropriate to rearrange the last formula in a more straightforward form to be able to evaluate the power transmission efficiency. The result is a power loss increase factor k_z equal to the ratio of the actual power loss and the minimum possible one for the actual active power [9].

$$k_z = \frac{P_J}{P_{J_{\min}}} = \frac{1}{\lambda^2} = \frac{S^2}{P^2} \qquad (25)$$

In accordance with (11) the sources of the power loss increase in a one-phase system can be identified.

$$k_z = \frac{P^2 + Q^2 + D^2}{P^2} = 1 + \frac{Q^2}{P^2} + \frac{D^2}{P^2} \qquad (26)$$

The power loss increases by a factor of Q^2/P^2 due to the phase shift between voltage and current (reactive power) and by a factor of D^2/P^2 due to the voltage and current distortion (distortion power). Because every saving costs something, also the use of power efficient appliances (light bulbs, power sources in TV sets, PCs, mobile phones and nowadays practically everything else) causes a distortion of current resulting in typical power loss increase factor in the range between 2 and 4. In extreme cases (stand-by) this factor can reach some hundreds [10].

In a three-phase system the formula (13) should be applied into (25) resulting in an even more complex power loss picture.

$$k_z = \frac{P^2 + Q^2 + D^2 + A^2 + B^2}{P^2} = \\ = 1 + \frac{Q^2}{P^2} + \frac{D^2}{P^2} + \frac{A^2}{P^2} + \frac{B^2}{P^2} \qquad (27)$$

Here the power loss increase caused by asymmetry A and distortion asymmetry B has to be added. Because theoretically reasonable splitting of these two quantities does not bring much practical benefits, we suggest to sum them up and call the result a total asymmetry power N. It can be derived as

$$N = \sqrt{\sum_{i=1}^{3} \sum_{\substack{j=1 \\ j \neq i}}^{3} \sum_{k=1}^{\infty} \sum_{l=1}^{\infty} \left[V_i^{(k)^2} I_j^{(l)^2} - P_i^{(k)} P_j^{(l)} - Q_i^{(k)} Q_j^{(l)} \right]} \qquad (28)$$

and

$$k_z = \frac{P^2 + Q^2 + D^2 + N^2}{P^2} = 1 + \frac{Q^2}{P^2} + \frac{D^2}{P^2} + \frac{N^2}{P^2} \qquad (29)$$

The minimum power loss according to (23) can be achieved in the ideal case when there is no phase shift between voltage and current, no voltage and current distortion and no voltage and current asymmetry. Then the power loss increase factor k_z is equal to one. The influence of individual imperfections increasing the power loss is as follows.

- reactive power

$$k_{zQ} = \frac{Q^2}{P^2}.100\% \qquad (30)$$

- distortion power

$$k_{zD} = \frac{D^2}{P^2}.100\% \qquad (31)$$

- power of asymmetry

$$k_{zN} = \frac{N^2}{P^2}.100\% \qquad (32)$$

In this way the amount of increase of power loss for individual sources can be evaluated and proper measures for avoiding them can be taken.

Different measurements taken so far show clearly that individual appliances cause significant distortions of electric current and individual consumers often have significant asymmetry of consumption, both resulting in an increase of the power loss. Some typical situations are presented in the following figures.

4. REAL MEASUREMENT RESULTS

"All theory, dear friend, is grey, but the golden tree of life springs ever green." J. W. Goethe

To get a first glimpse at what we are writing about, let us show the results of one-day measurements of an office building. For clarity's sake we measured the power ("instantaneous") quantities, although for the real evaluation energy (integral) quantities are used. This simplification has no influence on the aim of this article.

First of all let us show the power efficiency evaluation used until now. Only active and reactive powers P and Q are measured (Fig.1.) and the power factor $\cos\varphi$ according to formula (8) is calculated (Fig.2.).

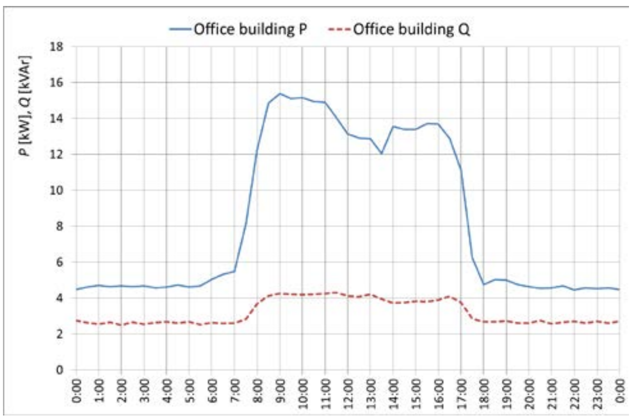

Fig.1. Traditional power measurement of an office building during one day.

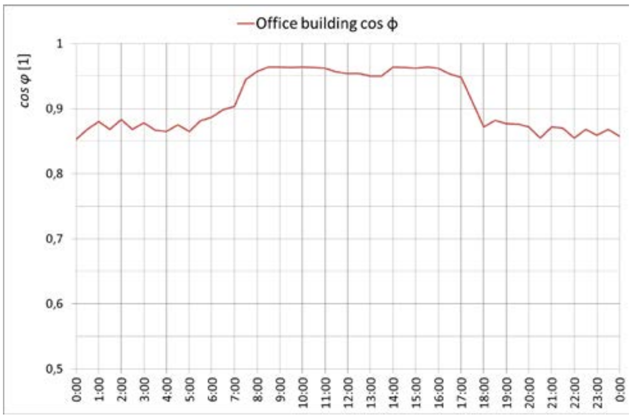

Fig.2. Traditional *cos φ* evaluation of the same office building during one day.

Next, let us add the other power components D and N (Fig.3.). Are they negligible? In this particular measurement D is small, but N is much bigger than the reactive power Q.

How does it influence the different apparent powers (Fig.4.)? There are visible differences, but are they significant enough to bother with them?

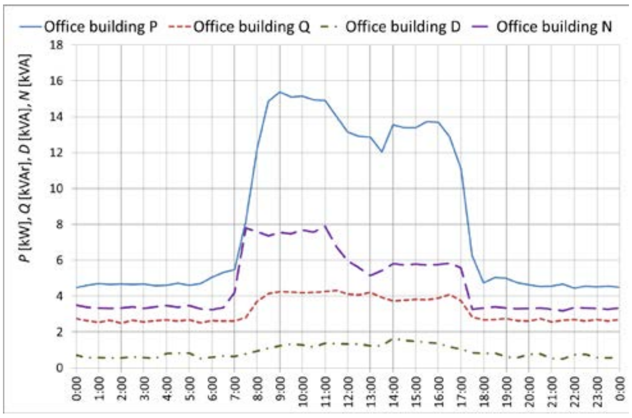

Fig.3. Measurement of all power components of the same office building during the same day.

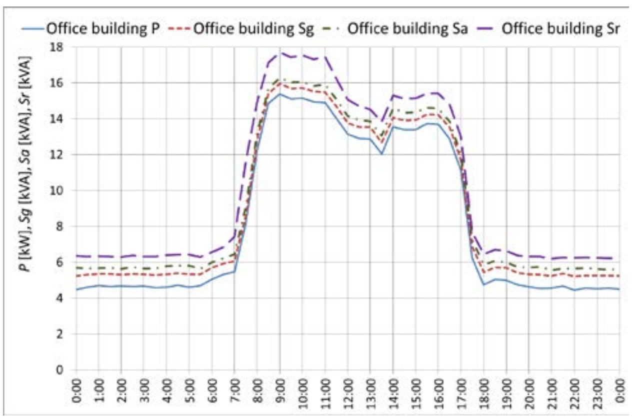

Fig.4. Evaluation of different apparent powers of the same office building during the same day.

Let us compare the power factors *cos φ* (8), λ_a and λ_r (20) using S_a and S_r, respectively (Fig.5.). The results are not that good.

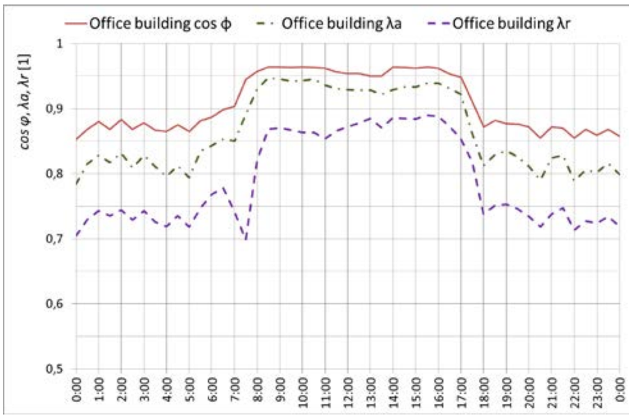

Fig.5. Evaluation of different power factors of the same office building during the same day.

What about the power loss? Look at the power loss increase factors k_{zg}, k_{za} and k_{zr} calculated by (25) using the apparent powers S_g, S_a and S_r (Fig.6.).

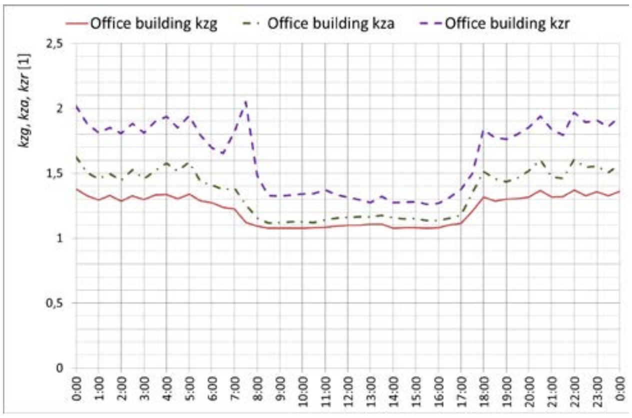

Fig.6. Evaluation of different power loss increase factors of the same office building during the same day.

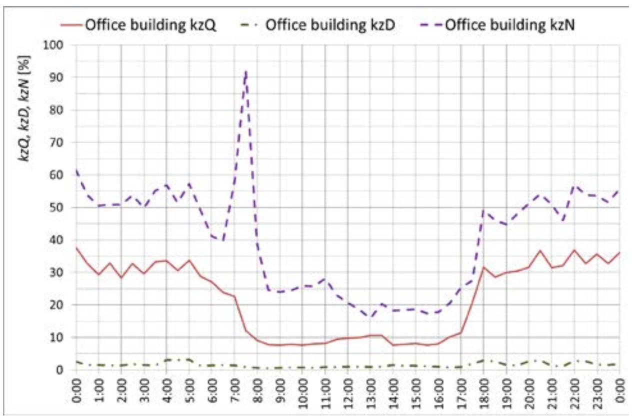

Fig.7. Evaluation of different power loss increase factor components of the same office building during the same day.

Whereas k_{zr} reveals the power loss being up to twice as big as in an ideal case ($S = P$), the other two hide significant portions of it. The sources of the power loss increase are presented in Fig.7.

Results achieved by real measurements not only present the meaning of different power associated quantities, but also illustrate that there are significant portions of power related quantities, including the power loss, hidden, when using the "traditional" simplified evaluation of power distribution efficiency.

5. Smart grid - a label or a real need

Smart Metering is undoubtedly the topic of many power-engineering projects all over the world. It should provide

- energy savings,
- fraud reduction,
- detailed consumption information to the utility,
- detailed consumption feedback to the customer,
- remote tariff switching,
- remote disconnection/reconnection,
- remote control of appliances for load management,
- easier supplier switching,
- and much more …

It looks like Smart Metering can solve almost every problem of the electrical power business. However, Smart Metering is only a means of getting more useful information and a possibility of presenting and efficiently using them.

But the ever increasing number of distributed energy resources (DER) that are very often centralized in small areas, the support of electrical automobiles, the need of power storage and other reasons cause that the processes in electrical grids become much more complicated than we were used to take into account for many years.

Power flows change their direction, the amount of energy produced is hardly predictable, and so is the energy overproduction/shortage. The distortion of voltages and currents, power asymmetry and other power quality issues are more and more frequent. The distribution, sources and possibilities of limitation of power losses is another important problem not taken into account so far. Only a complex analysis of these (and other) processes, quantities and circumstances can bring wide useful results for a better, higher quality and more efficient electricity grid. These tasks are generally described as a Smart Grid.

Although the measurement itself may not be very simple (as shown in previous parts of this paper), it is still only a source of (preferably correct) measurement results. Smart Metering may provide more information, but the real power of it can reveal only the higher level – Smart Grid. Is there a will to invest a lot of hard effort to proceed?

6. Conclusion

We tried to present our view to the measurement part of Smart Metering. We do not believe that only more frequent measurements of the same basic power quantities as used for a long time can enhance the evaluation of electrical grids operation, efficiency, reliability, power loss, etc. We proposed the use of nonstandard calculations that clearly describe more detailed relationships within the electricity grid. Graphical presentations of our calculation results show that new evaluations fundamentally change the view of the electrical grid parameters.

We would like to extend our efforts to more complicated grid models to get a more complex view of the usefulness of these new evaluation methods mainly from the point of view of distribution network operators. We are preparing some sets of measurements of different types of electricity consumer groups like an apartment house, a large office building, an industry area, etc. to analyze the transfer of the imperfections of individual power consumptions as described above into the power parameters of the group as a whole. The aim is to use best the possibilities of Smart Metering for the benefits of Smart Grid.

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