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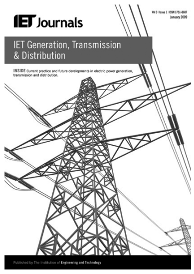

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Working, reflected and detrimental active powers

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Abstract: The active power P is one of the best established power quantities, commonly regarded as the useful power. There is awareness in the electrical engineering community, however, that some components of this power in systems with non-sinusoidal and asymmetrical voltages and currents are not useful for customers. Owing to an increase in cost of energy, increase in expectations towards the supply reliability and security, electrical power system technology faces a need of extensive changes. Even the best established concepts can be challenged and revised. Therefore the concept of the active power is revised in this study. It is shown that the active power P can be decomposed into three components of different usefulness, referred to as working, reflected and detrimental active powers. It is shown, that energy accounts based on the working, instead of the active energy, might create economic incentives for reducing harmonics and asymmetry both on the energy provider and the customer sides. This idea challenges deeply rooted standards; therefore the study can be regarded only as an initiation of a debate on the very sensitive issue of rationalisation of energy accounts in systems with non-sinusoidal and asymmetrical voltages and currents.

1 Introduction

All bills in power systems are eventually paid by energy users. Nonetheless, financial accounts between the energy provider and the user should contain some economic incentives that would promote an efficient use of electric energy and its transfer. Such efficiency is linked to the supply and the loading qualities, and thus these financial incentives should promote enhancement of these qualities. Some approaches are discussed in [1–6].

Financial accounts for energy are currently based on the cost of active energy, that is, on an integral of the active power P. Moreover, large customers usually pay for a low power factor. It will be shown in this paper that in the presence of the voltage and current harmonic distortion and asymmetry the accounts based on the amount of delivered active energy do not promote any improvement in the supply and the loading qualities, however.

This paper introduces concepts of the working power and the working energy. It will be shown that financial accounts based on the cost of the working energy, instead of the active energy, can create natural incentives for improvement of the supply and the loading qualities.

A need for such incentives may grow with increase in the number and power of sources of harmonic distortion and asymmetry. According to [5–7], along with handling increasing complexity and distributed generation in power systems, the security and supply reliability [8], the smart grids and the advanced measurement infrastructure (AMI) technologies should contribute such incentives development.

The subject of this paper touches a very well-established area of electrical engineering, settled by decades of university teaching, papers, books, conventions and standards. At the same time, power systems will face a need of very fundamental changes, however. In this situation, questions on even very fundamental and settled issues can be justified. This paper can be regarded as a voice in a discussion on the concept of the active energy as the fundamental of energy accounts. Maybe a revision of this concept would be beneficial for future Smart Grids.

2 Active power

For the first few decades of the power systems development the energy was provided almost exclusively from synchronous generators with almost sinusoidal voltage; loads in a great majority were linear, time-invariant and, consequently, voltage distortion was rather not observed. Data on the system performance were provided by analogue meters. The concept of the active power P was a perfect one for such systems. It was developed when electrical power systems and customer loads were substantially different from systems and loads we have now, however. This difference will be even greater in the future, when increase in the cost of energy, distributed generation and intelligent tools, implemented under Smart Grids concept [5], may change power systems dramatically.

The concept of the active power P is simple. It is the average rate of energy flow from a supply source to a load, calculated over the period T. The active power has a clear physical meaning and it is a fundamental power quantity in electrical engineering. It is an important power quantity for power system equipment design, for evaluation of systems and loads performance. An integral of the active power over payoff interval, usually a month, is the active energy and it is a fundamental quantity for financial accounts between energy provider and its user. The active power is regarded as a useful power. It stems from an opinion that the energy absorbed by loads is a useful energy.

It is known in the electrical engineering community, however, that excluding purely resistive loads, the energy conveyed by the voltage and current harmonics and/or their negative-sequence components can disturb or overheat electronic equipment and motors. Thus, the active power P in systems with non-sinusoidal and asymmetrical voltages and currents has components that are not useful but are detrimental. The active power, apparently simple, is in fact a compound quantity. It is not a synonym to the useful power. With an increase in the cost of energy, the difference between the active energy and the useful one can become increasingly important.

3 Trends of changes

There are several symptoms of evolution in power systems that resulted in the concept of Smart Grids, discussed in [1, 5, 6], as a new approach to power system technology. There are several permanent trends of changes in power systems. For the subject of this paper the following trends are relevant:

1. The active energy is a useful energy, for sure, if it is converted, on purpose, into heat and light. Resistive heaters and incandescent bulbs are such energy converters. Such loads do not produce current harmonics and are immune to disturbances by the supply voltage harmonics. These are traditional loads. Their share declines as compared with electronic and power electronics-driven equipment [9, 10], however. Residential and commercial customers use now more and more often non-linear and/or electronically driven devices. Fluorescent bulbs, videos and computer-like appliances are examples of such equipment, which are present in large numbers in our homes and commercial buildings. Industrial customers use, moreover, power electronics drives, digital instruments, control and protection systems. There are also innumerable electrical motors in customers' loads.

The energy conveyed by harmonics or by symmetrical components of the negative and zero sequence to some of such loads, mainly three-phase induction motors, is evidently not useful energy. For other loads such as electronically driven devices, the issue of the usefulness of the energy conveyed by harmonics and negative-sequence component is debatable. There is awareness in the electrical engineering community, however, that the supply voltage harmonics and its asymmetry can disturb the normal operation of some devices or at least degrade their performance [11–16].

2. The voltage distortion in conventional power systems occur mainly as a response to the load-generated harmonics, whereas original sources of electric energy, meaning synchronous generators, provide almost sinusoidal voltage. Distributed generators that exploit renewable energy, mainly from wind, wave or solar cells, are very often connected to power systems by power electronics converters. They can be sources of voltage and current harmonics and high-frequency (HF) noise. Moreover, the time distributions of availability of renewable energy and customer demand do not fit each other. Systems with such generators may need energy storage facilities. Such facilities are usually interfaced with the power system through power electronics converters, potential sources of voltage harmonics and HF noise.

3. Cost of electric energy increases. Not only does the amount of easily available fossils decline, but their demand also grows at a fast rate. Also the public concern with environmental impact and global warming makes production of electric energy much more expensive now than it was before. Production of so-called 'clean electric energy' is usually much more expensive than the traditional one. Elevated public expectations as to the supply reliability and energy security may contribute to this cost as well.

4. Gradual replacement of conventional cars by electrical ones may bring deep changes in distribution systems. Overnight charging a car battery may require charging power several times higher than the average power of a residential family home. Such homes have often a single-phase supply and consequently, battery charging rectifiers may increase not only harmonic distortion, but also the load imbalance [17]. Charging the car battery at a charging station, in the time comparable with that needed for refueling common cars, meaning in a few minutes, needs charging power of the order of megawatts. It is not clear now as to how this issue would be solved in the future, but it is likely that energy storage/release systems with power electronics converters will be needed for that.

Thus, taking these trends into account, it is very likely that electronic and power electronics devices will become much more common in future power systems, both on the providers' and customers' sides. Such devices are sources of harmonics and HF noise. At the same time, their performance is sensitive to harmonics and HF noise in the supply voltage.

Current harmonics and HF noise produced by electrical devices as well as immunity of such devices to the supply voltage harmonics and noise can be reduced by adequate construction of these devices. Such construction usually elevates their cost, however. To carry extra costs, economic incentives are needed. According to [6] such incentives, built into energy accounts, should be linked to detrimental effects of harmonics upon revenues of the energy providers and consumers. The same applies to asymmetry. The AMI, one of the key concepts [1, 7] in the smart grid technology, might provide a platform for such economic incentives. A possibility of the development of such incentives can be hidden in the concept of the active power P, which in systems with non-sinusoidal and asymmetrical voltages and currents occurs to be a much more complex quantity than commonly regarded.

4 Active power of harmonic generating loads

To reduce a risk that a circuit complexity would obscure results, let us analyse the simplest possible single-phase resistive circuit with a harmonic generating load (HGL), shown in Fig. 1, assuming that the distribution voltage e is sinusoidal, while the load is a source of current harmonics j.

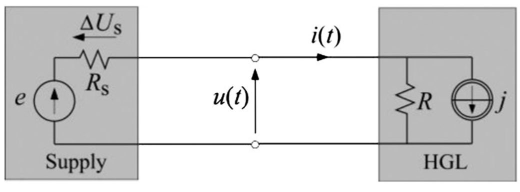

Fig. 1 *Resistive circuit with HGL*

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Let us assume, for simplicity sake, that the load generated current j does not contain dc component, and thus the load current can be expressed the form

$$i(t) = \sum_{n \in N} i_n = i_1 + i_\mathrm{h} \tag{1}$$

where N denotes the set of all harmonic orders n. In a response to distorted load current, the load voltage is distorted and has the form

$$u(t) = \sum_{n \in N} u_n = u_1 + u_\mathrm{h} \tag{2}$$

The active power at the load terminals is equal to

$$P = \frac{1}{T}\int_0^\mathrm{T} u(t)i(t)\,\mathrm{d}t = \sum_{n \in N} P_n = P_1 + P_2 + P_3 + P_4 + \cdots \tag{3}$$

The load-generated current j is composed of harmonic of the order $n > 1$, and thus for the fundamental harmonic the load is passive; hence

$$P_1 = U_1 I_1 > 0 \tag{4}$$

The active power of other harmonics, for $n > 1$, is equal to

$$P_n = U_n I_n = (-R_\mathrm{s} I_n) I_n = -R_\mathrm{s} I_n^2 < 0 \tag{5}$$

thus all of them are negative. Thus

$$\sum_{n \notin 1} P_n = P_2 + P_3 + P_4 + \cdots \stackrel{\mathrm{df}}{=} P_\mathrm{h} < 0 \tag{6}$$

Therefore formula (3) can be rewritten in the form

$$P = P_1 + P_\mathrm{h} \tag{7}$$

This formula shows that the apparent power, P, of HGLs contains two substantially different components. The first of them, P_1, stands for the average rate of energy flow from the supply source to the load. The second term, P_h, stands for the average rate of energy flow back from the load to the supply source, where this energy is dissipated on the source internal resistance. Since power P_h is negative, thus $P_1 > P$, which means that the HGLs have to be supplied with higher power than measured at the load terminals active power P. It has to be supplied with power P_1. Part of energy delivered to such a load by the fundamental harmonic is converted to energy of higher harmonics and is reflected back to the supply source. This energy is not, however, recovered in the supply source, since its voltage e is sinusoidal, but it is dissipated on the supply source resistance. Therefore the power P_h can be referred to as a reflected active power.

Illustration 1: Fig. 2 shows a structure of a single-phase dc battery charger, simplified to a purely resistive circuit with ideal lossless diodes. The rectifier is supplied with a sinusoidal voltage e of the root-mean-square (rms) value $E = 230$ V, and provides the active power $P = 5000$ W to the dc side.

Analysis of this circuit results in the complex rms (crms) value of the supply voltage and current fundamental harmonic equal to

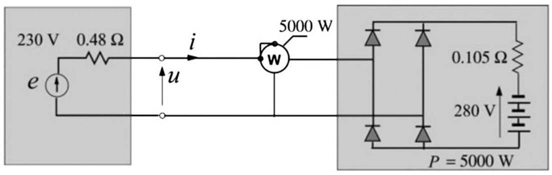

Fig. 2 *Structure of battery charger simplified to a resistive circuit*

$$U_1 = 218.5\ \mathrm{V}, \quad I_1 = 24.99\ \mathrm{A}$$

which are in-phase, so that the active power of the fundamental harmonic is equal to $P_1 = 5242$ W. The reflected active power is equal to

$$P_\mathrm{h} = P_1 - P = 242\ \mathrm{W}$$

Thus, the rectifier has to be supplied with a power, which is a few per cent higher than the active power P, measured by the wattmeter at the load terminals.

To operate such a load, it has to be supplied with power P_1. Therefore power P_1 can be referred to as a working active power and denoted by P_w, that is, $P_1 = P_\mathrm{w}$. It means that a part of energy delivered to the load by the voltage and current fundamental harmonics is transformed, owing to the load non-linearity, into energy of harmonics and sent back to the supply system, where it is dissipated on the supply source resistance.

Harmonics in the circuit analysed in this illustration have occurred owing to the load non-linearity. They can occur also in linear loads with periodic switches, meaning in linear loads with time-variant parameters. Both non-linear and time-invariant loads can be regarded as HGLs.

The relation between the working and reflected active powers, P_w and P_r, and the active power P in a single-phase, resistive system with HGLs is observed in Fig. 3.

Symbol i_w in this figure denotes a working current, that is, the minimum current needed for providing the working power P_w to the load. In single-phase systems this current is identical with a component of the fundamental harmonic which is in-phase with the voltage fundamental harmonic, $u_1(t)$.

5 Active power of unbalanced loads

Let us consider a three-phase, three-wire system with purely resistive, but unbalanced load and symmetrical sinusoidal supply voltage, shown in Fig. 4.

The vector of the load currents in such a system is composed of the vector of the positive- and negative-sequence

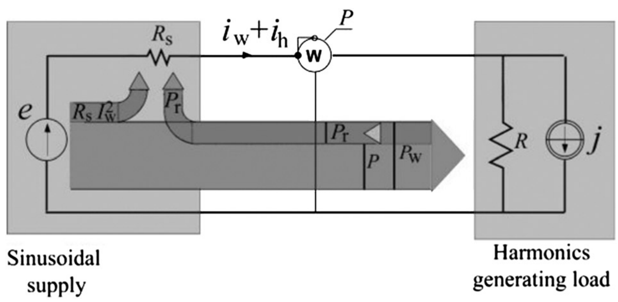

Fig. 3 *Diagram of energy flow in a resistive system with HGL*

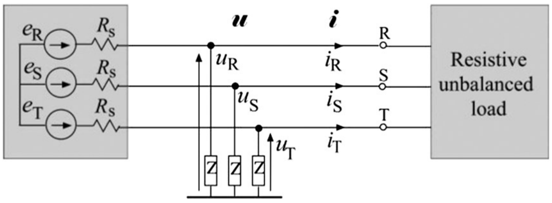

Fig. 4 *Three-phase system with resistive unbalanced load supplied with symmetrical sinusoidal voltage*

components, $\boldsymbol{i}^{\mathrm{p}}$ and $\boldsymbol{i}^{\mathrm{n}}$

$$\begin{bmatrix} i_{\mathrm{R}} & i_{\mathrm{S}} & i_{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} \stackrel{\mathrm{df}}{=} \boldsymbol{i} = \boldsymbol{i}^{\mathrm{p}} + \boldsymbol{i}^{\mathrm{n}} \tag{8}$$

Since the load voltage, owing to asymmetrical currents, is asymmetrical, it also contains the positive- and negative-sequence components

$$\begin{bmatrix} u_{\mathrm{R}} & u_{\mathrm{S}} & u_{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} =^{\mathrm{df}} \boldsymbol{u} = \boldsymbol{u}^{\mathrm{p}} + \boldsymbol{u}^{\mathrm{n}} \tag{9}$$

The positive- and negative-sequence quantities are mutually orthogonal, that is, their scalar product, defined for three-phase quantities x and y [18, 19] as

$$(\boldsymbol{x}, \boldsymbol{y}) \stackrel{\mathrm{df}}{=} \frac{1}{T}\int_0^{\mathrm{T}} \boldsymbol{x}^{\mathrm{T}}(t)\boldsymbol{y}(t)\,\mathrm{d}t \tag{10}$$

is equal to zero, meaning $(\boldsymbol{u}^{\mathrm{p}}, \boldsymbol{i}^{\mathrm{n}}) = 0$ and $(\boldsymbol{u}^{\mathrm{n}}, \boldsymbol{i}^{\mathrm{p}}) = 0$; hence, the active power at the load terminals is equal to

$$P = (\boldsymbol{u}, \boldsymbol{i}) = (\boldsymbol{u}^{\mathrm{p}}, \boldsymbol{i}^{\mathrm{p}}) + (\boldsymbol{u}^{\mathrm{n}}, \boldsymbol{i}^{\mathrm{n}}) = P^{\mathrm{p}} + P^{\mathrm{n}} \tag{11}$$

It was assumed that the distribution voltage $\boldsymbol{e}$ is symmetrical; therefore the negative-sequence voltage at the load terminals occurs only as a result of the voltage drop of the negative-sequence current at the supply source resistance; therefore

$$P^{\mathrm{n}} \stackrel{\mathrm{df}}{=} (\boldsymbol{u}^{\mathrm{n}}, \boldsymbol{i}^{\mathrm{n}}) = (-R_{\mathrm{s}}\boldsymbol{i}^{\mathrm{n}}, \boldsymbol{i}^{\mathrm{n}}) = -R_{\mathrm{s}}||\boldsymbol{i}^{\mathrm{n}}||^2 < 0 \tag{12}$$

The active power of the negative-sequence component of the load voltages and currents is negative, meaning that it is the average rate of energy flow from the load back to the supply source, where this energy is dissipated on the supply source resistance. It can be regarded as a reflected active power P_{r}

$$-P^{\mathrm{n}} = -(\boldsymbol{u}^{\mathrm{n}}, \boldsymbol{i}^{\mathrm{n}}) \stackrel{\mathrm{df}}{=} P_{\mathrm{r}} \tag{13}$$

Thus, the energy needed for supplying an unbalanced load with the active power P is higher than the integral of that power. The energy provider has to supply such a load with the average rate of energy flow equal to the active power of the positive-sequence component, P^{p}. Just this is the power needed for operating an unbalanced resistive load at power P. It can be referred to a as the working power

$$P_{\mathrm{w}} \stackrel{\mathrm{df}}{=} P^{\mathrm{p}} = P - P^{\mathrm{n}} > P \tag{14}$$

Illustration 2: Parameters of the system shown in Fig. 5 with sinusoidal and symmetrical distribution voltage $\boldsymbol{e}$ and unbalanced load, were selected in such a way, that at the

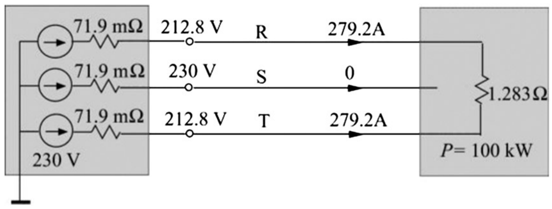

Fig. 5 *Three-phase resistive system with unbalanced load*

line-to-ground voltage of rms value $E = 230$ V, the load active power is $P = 100$ kW.

Assuming that the crms value of the distribution voltage is

$$\boldsymbol{E}_{\mathrm{R}} = 230\mathrm{e}^{\mathrm{j}0}\ \mathrm{V}$$

the crms values of the line currents are equal to

$$\boldsymbol{I}_{\mathrm{R}} = -\boldsymbol{I}_{\mathrm{T}} = 279.2\mathrm{e}^{-\mathrm{j}30^\circ}\ \mathrm{A}$$

and consequently, the crms values of their symmetrical components

$$\begin{bmatrix} \boldsymbol{I}^{\mathrm{p}} \\ \boldsymbol{I}^{\mathrm{n}} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha* \\ 1 & \alpha* & \alpha \end{bmatrix}\begin{bmatrix} \boldsymbol{I}_{\mathrm{R}} \\ \boldsymbol{I}_{\mathrm{S}} \\ \boldsymbol{I}_{\mathrm{T}} \end{bmatrix} = \begin{bmatrix} 161.2\mathrm{e}^{\mathrm{j}0^\circ} \\ 161.2\mathrm{e}^{-\mathrm{j}60^\circ} \end{bmatrix}\mathrm{A}$$

with

$$\alpha = 1\mathrm{e}^{\mathrm{j}120^\circ}$$

The crms values of the load voltage are

$$\boldsymbol{U}_{\mathrm{R}} = \boldsymbol{E}_{\mathrm{R}} - R_{\mathrm{s}}\boldsymbol{I}_{\mathrm{R}} = 212.8\mathrm{e}^{\mathrm{j}2.7^\circ}\ \mathrm{V}$$

$$\boldsymbol{U}_{\mathrm{T}} = \boldsymbol{E}_{\mathrm{T}} - R_{\mathrm{s}}\boldsymbol{I}_{\mathrm{T}} = 212.8\mathrm{e}^{\mathrm{j}117.3^\circ}\ \mathrm{V}$$

and consequently, the crms values of their symmetrical components

$$\begin{bmatrix} \boldsymbol{U}^{\mathrm{p}} \\ \boldsymbol{U}^{\mathrm{n}} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha* \\ 1 & \alpha* & \alpha \end{bmatrix}\begin{bmatrix} \boldsymbol{U}_{\mathrm{R}} \\ \boldsymbol{U}_{\mathrm{S}} \\ \boldsymbol{U}_{\mathrm{T}} \end{bmatrix} = \begin{bmatrix} 218.4\mathrm{e}^{\mathrm{j}0^\circ} \\ 11.6\mathrm{e}^{\mathrm{j}120^\circ} \end{bmatrix}\mathrm{V}$$

The working active power of the load is

$$P_{\mathrm{w}} = P^{\mathrm{p}} = (\boldsymbol{u}^{\mathrm{p}}, \boldsymbol{i}^{\mathrm{p}}) = 3U^{\mathrm{p}}I^{\mathrm{p}} = 105.6\ \mathrm{kW}$$

while the reflected active power of the load

$$P_{\mathrm{r}} = -P^{\mathrm{n}} = -(\boldsymbol{u}^{\mathrm{n}}, \boldsymbol{i}^{\mathrm{n}}) = -3\mathrm{Re}\{\boldsymbol{U}^{\mathrm{n}}\boldsymbol{I}^{\mathrm{n}*}\} = 5.6\ \mathrm{kW}$$

This is power of energy loss on the supply source resistance.

The relation between the working and reflected active powers, in three-phase, resistive systems with unbalanced loads is observed in Fig. 6.

The phenomenon of energy reflection back to the supply source by non-linear, time-variant and/or unbalanced loads exists, of course, in common systems with inductance both on the customer and the supplier side. It is hidden behind other phenomena as the phase-shift and the presence of the reactive power, however.

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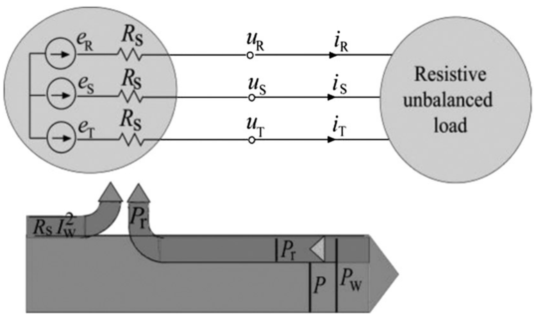

Fig. 6 *Diagram of energy flow in a resistive system with unbalanced load*

6 Working and detrimental active powers

The relation between the active power and the working active power was analysed above for situations where the load-generated harmonics or asymmetrical current degraded the quality of the customer load from the energy provider perspective. The voltage harmonics and asymmetry exist usually also on the energy provider side, in the distribution voltage, which degrades the quality of the supply from the customer perspective.

The effect of distribution voltage harmonics, asymmetry and HF noise upon various energy receivers has been a focus of attention of electrical engineers for a few decades and, consequently, there is a huge number of reports on the issue, special journals and conferences on various aspects of the power quality. These studies are mainly focused on the equipment performance deterioration and/or disturbances in the presence of degraded supply quality, rather than on energetic aspects of their operation.

Some negative effects of degraded supply quality, in particular, the effect of the voltage asymmetry upon induction motors, are well known [11–14] in electrical engineers community. These effects are the most transparent just in such motors. They consume a great deal of electric energy in power systems; therefore specification of this consumption in terms of working energy might be beneficial for objectives of this paper.

Let us assume that induction motor, shown in Fig. 7, is supplied from a source of sinusoidal, but asymmetrical internal voltage $\boldsymbol{e}$, that is, the voltage composed of the positive- and negative-sequence components, $\boldsymbol{e}^{\mathrm{p}}$ and $\boldsymbol{e}^{\mathrm{n}}$.

In response to asymmetrical supply voltage, the motor current $\boldsymbol{i}$ contains positive- and negative-sequence components, $\boldsymbol{i}^{\mathrm{p}}$ and $\boldsymbol{i}^{\mathrm{n}}$.

The active power at the motor terminals

$$P = (\boldsymbol{u}, \boldsymbol{i}) = (\boldsymbol{u}^{\mathrm{p}}, \boldsymbol{i}^{\mathrm{p}}) + (\boldsymbol{u}^{\mathrm{n}}, \boldsymbol{i}^{\mathrm{n}}) = P^{\mathrm{p}} + P^{\mathrm{n}} \qquad (15)$$

but only the active power of the positive sequence P^{p} can be converted, with some losses in the motor, into a mechanical

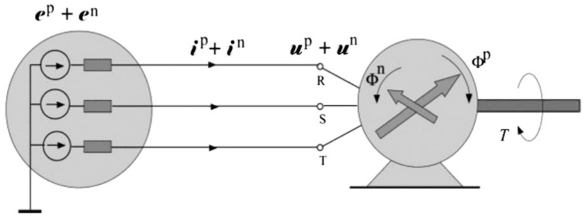

Fig. 7 *Induction motor supplied with asymmetrical voltage*

power on the motor shaft. The negative-sequence current $\boldsymbol{i}^{\mathrm{n}}$ creates rotating magnetic field Φ^{n} which rotates in the direction opposite to the direction of the shaft rotation and it reduces the motor torque T. The energy delivered to the motor by the voltage and current negative-sequence eventually is dissipated in the motor as the heat, which raises its temperature and reduces the lifespan.

Thus, the active power of the negative-sequence component P^{n} should be regarded as a detrimental active power. It will be denoted by P_{d}. It is not justified to charge the motor owner for this energy. Only the active power of the positive-sequence component provides the energy to mechanical loads; thus, only this component of the motor active P can be regarded as the motor working power, that is

$$P_{\mathrm{w}} \overset{\mathrm{df}}{=} P^{\mathrm{p}}$$

The active power measured by a wattmeter at the motor terminals is the sum of working and detrimental power

$$P = P^{\mathrm{p}} + P^{\mathrm{n}} \overset{\mathrm{df}}{=} P_{\mathrm{w}} + P_{\mathrm{d}} \qquad (16)$$

When the distribution voltage contains a harmonic of the nth order, then if this is a harmonic of the positive sequence, for example, the seventh order, it creates a rotating magnetic field which rotates at angular velocity approximately $(n-1)\omega_1$ with respect to the rotor, which rotates at the angular velocity approximately equal to ω_1. At such a velocity of the magnetic field rotation, the motor behaves as if in a permanently starting mode. The energy is mainly dissipated as a heat in the motor winding.

Magnetic flux created by a voltage harmonic of the negative sequence, for example, the fifth-order harmonic, rotates in the direction opposite to the rotor at angular velocity of $(n+1)\omega_1$. Energy of such harmonics is entirely converted into heat which increases the motor temperature. Thus, the active power P_{n} of the voltage harmonics contributes to the detrimental active P_{d} power rather than to the working active power P_{w}.

Thus, if P_{h} denotes the active power of all higher-order harmonics, then the detrimental active power of induction motor increases to

$$P_{\mathrm{d}} = P^{\mathrm{n}} + P_{\mathrm{h}} \qquad (17)$$

Apart from situation like that with induction motors, where effects of distribution system harmonics and asymmetry are very distinctive, their effect on other equipment is not so clear, difficult to detect and usually cannot be described easily in economic terms.

7 Supply and loading qualities

Power systems are composed of two domains: the domain of the energy provider and the domain of the energy users. These two domains are separated by a measurement point, as shown in Fig. 8.

In research on the energy loss at its delivery, the power system is very often treated, however, as one entity where this loss and the cost of energy transfer should be minimised. In fact, there are ‘two players in the game’ with different goals. Confined only by regulations, each of them attempts to maximise its own profit. These profits may depend on the partner in the game, however.

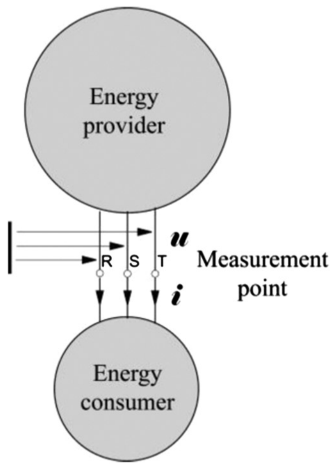

Fig. 8 *Power system separated into energy provider and energy consumer domains*

Apart from other factors, the effectiveness of energy conversion by customer loads depends on various parameters of the supply voltage, such as harmonic distortion, noise, asymmetry, the rms variability, that is, on the supply quality. The cost of electric energy transfer to a customer on the delivery side depends on various properties of the load that affect the supply current, meaning on the loading quality. Thus, financial losses or profits of the energy user may depend on the supply quality, which is under control of the energy provider. Losses or profits of the energy provider may depend on the loading quality, which is under control of the energy user.

Although the supply and the loading qualities depend on number of other features of voltages and currents, the focus in this paper is only on harmonic distortion and asymmetry.

8 Incentives for supply quality and loading quality improvement

Customers are charged currently for the active energy, equal to in a payoff, suppose 1-month, interval

$$\int_0^{\text{month}} P\,\mathrm{d}t = W \tag{18}$$

and measured by common energy meters. Large customers can pay, moreover, a fine for a low power factor. It means that in spite of all detrimental effects, energy users are billed for detrimental energy, carrying, moreover, all extra costs of these detrimental effects. At the same time, the energy provider carries financial burden of the presence in the supply current of harmonics and negative-sequence currents produced by low quality loads. We can formulate this as follows, however.

When charged for the active energy, the energy user with harmonics and/or asymmetrical currents generating load is not financially responsible for the cost increase on the provider side. Such energy user does not have any financial motivations for reducing harmonics and asymmetry in the supply currents. He can reduce them only if this is required by regulations and standards.

At the same time, when charged for the active energy, the energy provider which supplies distorted and asymmetrical voltage to the customer is not financially responsible for the cost increase on the user side. Such a provider is paid by the user even for the energy the user is not able to convert to a useful work. Such provider does not have any financial motivations for reducing harmonics and asymmetry in the supply voltage. He can reduce them only if this is required by regulations and standards.

Thus, in both situations, the level of the loading and the supply qualities relies only on regulations, standards and possible fines, when some regulations are violated [3, 20]. There is the lack of any natural financial incentives for reducing harmonics and asymmetry both on the provider and the user sides.

Financial accounts based on the working energy W_{w}, in 1-month payoff interval equal to

$$\int_0^{\text{month}} P_{\mathrm{w}}\,\mathrm{d}t = W_{\mathrm{w}} \tag{19}$$

modify this situation in a right direction. For energy users with low loading quality, that is, harmonics and asymmetrical currents generating loads

$$W_{\mathrm{w}} > W$$

and this increases the bill for energy. For energy providers with low supply quality, meaning with harmonics and asymmetry in the voltage provided to energy users

$$W_{\mathrm{w}} < W$$

and this reduces the bill for energy sold to a customer.

Thus, switching accounts between the energy provider and its user from that based on the cost of the active energy to the accounts based on the cost of the working energy creates natural financial incentives for improving the supply quality and the loading quality. Unfortunately, such switching is only apparently simple.

All these conclusions challenge deeply rooted fundamentals, regulations and standards, all based on the concept of the active power [21]. Any attempt to change them may be naturally faced by enormous inertia. Nonetheless, a debate on the need of fundamental changes has started and there are opinions like this, [6] ‘Pressure on improved grid reliability and power quality is increasing as more regulators think about attaching penalties and rewards against performance’. This opinion is in-line with conclusions of this paper on a need of some changes in energy accounts, aimed at shifting supply- and loading quality-related costs to the parties responsible for the power quality problems.

There might be a right climate now for such a debate and changes. This is owing to increasing penetration of renewable sources of energy and associated penetration of power electronics converters, meaning sources of harmonics, as well as owing to a trend of increase in the cost of energy. Smart grid technology and the idea of ‘smart meters’ for DSP-based energy measurement, might embrace also a new approach to energy accounts.

A lot of questions have to be answered first. The most important are the following:

1. Would such incentives be sufficiently strong to be effective?
2. How should existing conventions on violation of present standards on the level of harmonic distortion and asymmetry be handled to avoid double penalties?

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3. How can the concept presented in this paper be implemented in energy meters?

Answers to these questions are beyond the scope of this paper, however. They need much more studies to answer them. These answers are not unique, moreover.

Benefits from switching account fundamentals might be most visible, of course, in systems with poor supply and loading qualities. Small power systems are good candidates for that. Usually, these are isolated systems and in particular, islanded micro-grids, with high penetration of generators, driven from renewable sources of energy and interfaced to the power grid with power electronics converters. Also large individual customers, with monthly bills for energy at the level of hundred thousand or million dollars, with amount of energy measured by a single meter, might negotiate and reach a consensus with utilities over benefits from a revision of fundamentals of energy accounts.

9 Conclusions

Financial accounts for energy between its provider and user, based on amount of the active energy, are daunting for any improvement both of the supply quality on the provider side and any improvement of the loading quality on the customer side. At such accounts, the provider does not carry any financial responsibility for the quality of the supply and the customer does not carry any financial responsibility for the quality of its load. Improvements in the supply and in the loading qualities can rely only on conventions, standards and prospective fines.

Such accounts based on amount of the working energy create financial incentives for the supply and the loading qualities both at the provider and the user side. Switching to such accounts fit well present trends of changes in power systems and concern with the supply and loading quality degradation as well as an increase in the cost of energy. Such accounts can be implemented in ‘smart meters’, developed under the concept of the Advanced Metering Infrastructure.

The suggestion that the fundamental of energy accounts should be modified challenges a century long deeply rooted tradition. A lot of studies that would confirm advantage of such a change and a debate over it would be needed. This paper can be regarded as a voice in such a debate.

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