БЪЛГАРСКА АКАДЕМИЯ НА НАУКИТЕ • BULGARIAN ACADEMY OF SCIENCES

ПРОБЛЕМИ НА ТЕХНИЧЕСКАТА КИБЕРНЕТИКА И РОБОТИКАТА, **63**
PROBLEMS OF ENGINEERING CYBERNETICS AND ROBOTICS, **63**

София • 2011 • Sofia

Reactive Power in Wind Generator Farms and Introduction of Flicker in a Power Line

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Abstract: *The paper discusses the role of reactive power in electric energy transfer and the functioning of the consumers, connected with the formation of electric and magnetic fields. The problem of reactive power in wind generator farms is considered, as well as the use of additional reactive power in order to maintain voltage variations within admissible limits. A parameter, reflecting the short time stability of voltage – a flicker, is introduced in the power line of wind farms.*

Keywords: *Wind generator farms, reactive power, flicker.*

1. Introduction

The transfer of electric energy and the functioning of consumers of this energy is connected with the formation of electric and magnetic fields. In constant current networks the energy charge of these fields occurs only once, while turning on. During turning off this energy goes back and special circuits are usually used for its dissipation. In alternating current systems there starts a constant process of bidirectional movement of energy between the source and the fields. Two complete cycles of energy exchange with a null average value occur in each network period. This process has been noticed at the mere beginning of alternating current energy usage. The first presentation reported is from 1888. After that adequate description has been created and since 1914 [1], this oscillating energy is compensated. The intensity of this exchange is estimated by its power, as usually. In engineering practice some more generalized indicators are preferred for work, instead momentary values, in analogue to active power. For linear consumers and sinusoidal currents and voltages it is accepted that the intensity is defined as reactive power, equal to the maximal power (the product of current and voltage), when accumulating energy in the fields, or given back by them. As a result of the research work of many investigators in the following decades, reactive power theory has been formulated. For sinusoidal currents and voltages it remains almost unaltered. For non-sinusoidal values, or for arbitrary forms, there were not found any convincing physical reasons to introduce the old definition of reactive power. For non-strict sinusoidal currents and voltages different definitions are used for reactive power, depending on the necessities. In order to obtain comparable results when using different definitions, some authors propose all the test measurements to be realized with sinusoidal currents and voltages [1, 2]. However, all the definitions must meet the following requirements:

- for sinusoidal currents and voltages all the definitions must give one and the same result;
- the average value of the momentary reactive power must be zero. The averaging interval is usually the period of the network frequency, but it may be longer, as in the case of active filters.

The reactive power is unavoidably present with the active one, both in a transmission (and distributing) network, and in consumers. It must be continuously generated and supplied for the network and for the consumers as well. For the network it is a factor of its stability, of the voltage maintenance, of its quality also, including continuity of the energy supplied. The big failures in the electrical supply of several western countries, USA and Canada in 2003, are due to a great extent to shortage of reactive power [3]. Though the energy in the fields is reversible, its bidirectional movement causes losses in the generator and in the transmission line. Its null average value enables potentially its supply by a separate source, with almost zero power and stored energy for fields charging. In the classical variant a lossless element is connected with a supplementary field type (electric/magnetic or vice versa), parallel to the known type of field. In the interval of energy charging of the first type of field, energy is released in the additional field and in case of appropriate dimensioning, the exchange is realized between the two fields and no supplementary (reactive) current is running through the line.

The direct generation of momentary reactive power by a bidirectional inverter is also possible. The contemporary power electronic components and the microprocessors possibilities to control them in conformance with sufficiently complex laws, enable efficient generation with insignificant losses. Such a generator is adjustable both referring to the value of the reactive power and to its type – inductive or capacitive. Moreover, such an approach is universal, it is not connected with the fields and can be set up for an arbitrary form of the momentary power with the constraint for null average value, and also naturally conformed to the extended interpretation of reactive power.

The source, feeding the generator of reactive energy obtains and releases energy successively in portions, with a null average value. Each portion may be of a too large value, of the order of hundreds and more joules. The source must possess the capacity to get and give out this energy. For the special, but most significant case of tri-phase energy generation, this serious requirement can be considerably lightened, using a common source for the three phases. The momentary sum of the phase currents in a symmetric network remains constantly zero and for this limit case no conditions for accumulation are set on the source. For a real network certain accumulation will be necessary, but not in the dimensions needed for separate compensation of each phase.

2. Reactive power in Wind-Generator Farms (WGF)

2.1. Problem formulation

The transfer of electric energy is connected with energy storage in the electric and magnetic field along the power lines and in the prevailing part of consumers. In constant current systems this energy is accumulated only once and it is altered only during loads changing. In alternating current networks there occurs cyclic recharging with its frequency, connected with reactive power. This energy is reversible – it is accumulated for every semi- period and almost completely restored for the generator, but its momentary value, the power, has got large values, commensurable with the useful power consumed, so it must be provided by the generator. During energy transfer through a cable of high voltage, considerable energy is accumulated in the electric field. In such cases it might prove for big distances more efficient to realize the transfer at constant current, in spite of the necessity for converters. This actual problem appears in the offshore wind-generator farms. The wind-generator farms in their prevailing part are asynchronous – with a cage or a wound rotor, with or without use of energy, inducted in the rotor. The cage generators work at constant revolutions, but they can support the voltage without any external energy and are consumers of large reactive power for formation of the magnetic field in the inter-iron part. The necessary reactive power increases considerably at initial switching on of the generators and during fall in synphase with the network, to which they are connected.

For compensation of the reactive energy some nodes are built in the WGF or in the separate Wind Turbine Generator (WTG). Their power is comparable to the active power supplied. They must be in a condition to supply reactive power in all possible modes of a WTG farm and the network, towards which they are attached – stationary mode, connection to the network, different transition modes, including short circuits. Different types of reactive energy compensators are used. The conventional condenser batteries are usually attached to anti-parallel connected diode-thyristor groups for limiting the initial charging diodes, since after the transition mode (lasting usually about 0.2-2 s) they are shunted by contactors in order to decrease the losses. The batteries control is continuous, dependent on the necessary reactive energy.

The contemporary WTG are of asynchronous type, Double Feeding Asynchronous Generators (DFAG) and more seldom they are asynchronous. They operate at variable revolutions which enables better extraction of the energy from wind, depending on its speed. DFAG require conversion of the energy from the rotor coil, which allows self supply of the necessary magnetic energy for the inter-iron part. The development of the methodologic and technologic bases of Power Electronics (PE) allows highly effective conversion of large powers, and a new stable tendency towards complete conversion of the power from DFAG is established – of the stator and rotor winding. The synchronous type of a generator with variable speed requires complete conversion. The conversion unbinds to a great extent the WTG from the network and assigns it new features, the use of which can increase to a high degree the stability of the network, towards which it is connected [4].

With the introduction of appropriate control, DFAG can work in a 4-quadrant mode – generator/consumer of active and reactive power [5, 6]. The phase difference between the voltage and the current can be controlled within the bounds 0-360°. The alteration of the mode for a standard DFAG may happen too quickly, within the limit of 100 ms [4].

The operation mode of a generator with complete conversion can be presented by the vector diagram on Fig. 1.

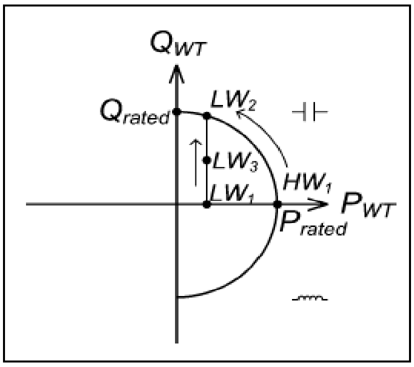

Fig. 1

The generated active power P is indicated along the absciss, and the reactive power Q – along the ordinate. The capacitive power is accepted for positive reactive, while the inductive – for negative power. The generator nominal power is set as fictitious – as the product of the nominal current and voltage, no matter of their phase relations. On the diagram it is presented by a circle with a radius $S = \sqrt{P^2 + Q^2}$. The active power is determined by the extracted wind power. The current, injected by the generator can rise to the nominal one

$$I_\varphi = I_{\max} e^{j\varphi}, \qquad \varphi = \arccos \frac{P}{S} .$$

2.2. Use of additional reactive power

By the introduction of additional reactive power, the network voltage is raised and the use of greater power is possible, while reserving the variations of the voltage in feasible bounds. Let us consider the network, shown on Fig. 2 as an illustration. It is fed by a source with stable voltage and unlimited power, at the far end of which WTG is connected, and a basic load with active power P and reactive power Q. Two successively built equivalent schemes are shown on the same figure.

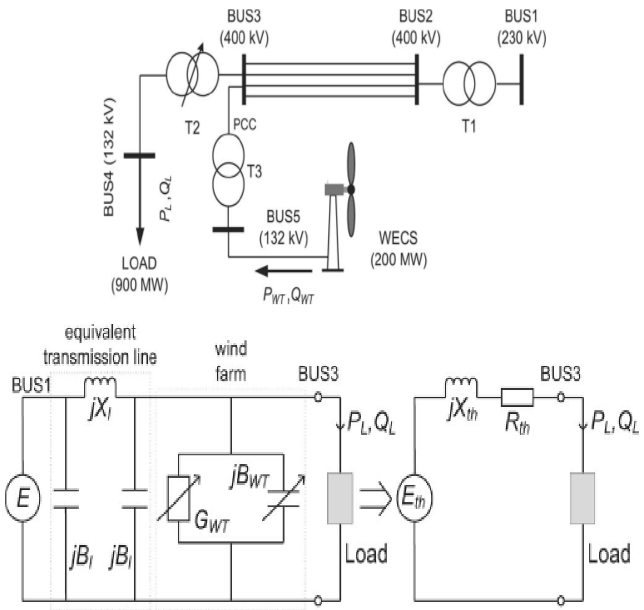

Fig. 2

The transmission network is presented by a Π-shaped quadripole with longitudinal inductive resistance jX_1 and cross capacitive conductivities jG_1. In order to simplify the expressions, the active power generated by WTG is represented by the negative active conductivity G_r, and the reactive capacitive power (it is assumed that the compensating power must be such) – by the conductivity jG_c. In order to simplify the expressions in the following exposition, the cross capacity of the line jG_1 is included in jG_c.

The second equivalent scheme represents the network as composed of a source with equivalent voltage U and equivalent internal resistance Z_i, determined according to Tevenen’s theorem

$$U = \frac{E}{1 - X_1 G_c - jX_1 G_r},$$

$$Z_i = \frac{jX_1}{1 - X_1 G_c - jX_1 G_r}.$$

It can be shown that the maximal active power, which can be obtained by the load $z_T = Be^{j\varphi}$, is

$$P_{\max} = \frac{\cos\varphi}{\sqrt{(1 - X_1 G_c)^2 + X_1^2 G_r^2} - X_1 G_r \cos\varphi + (1 - X_1 G_c)\sin\varphi} . \frac{E^2}{2X_1},$$

and for the same maximal power the voltage over the load is obtained as [7]

$$U = \frac{1}{1 - X_1 G_c - jX_1 G_r} . \frac{E}{\sqrt[1,41]{1 + \dfrac{(1 - X_1 G_c)\sin\varphi - X_1 G_r \cos\varphi}{\sqrt{(1 - X_1 G_c)^2 + X_1^2 G_r^2}}}}.$$

Despite the complex expressions it is obvious that the introduction of reactive power $U^2 G_c$ increases the voltage on the load *U*, and together with it – the power consumed. This means in fact that the consumed power is increased, preserving the feasible deviations in the voltage, without introduction of the additional active power by a WTG. Naturally, the introduction of supplementary active power $U^2 G_r$ also increases the load capacity of the network, but the analysis above given has the purpose to emphasize the role of the introduced reactive power.

3. Flicker introduction in the power line of WTG

3.1. Flicker definition

The requirements towards the quality of the supplied electric energy have increased particularly in the last decade. This is connected with the wide distribution of equipments and systems, sensitive to disturbances in the network, such as information and communication, or with definitely nonlinear properties, such as different types of converters and the use of the network as communication media. The limits on the variability of such parameters, like constancy of voltage and frequency, and harmonics content, are narrowed. One characteristic parameter, often ignored or underestimated, is the short-term stability of the voltage in intervals within the limits of 30 ms up to 20 s, named light flicker [Φ]. It is connected with the physiological perception of the illumination, supported by the electrical power line. The restrictions implied on this indicator are different and in the common case – stricter, than the more general ones, mainly energy restrictions on voltage constancy and content of other fluctuations, harmonics, sub- and interharmonics (with a frequency, which is not multiple to the network one).

As a measurable value, the flicker evaluates the degree of changeability of the network voltage, taking into account:

1. The shape of the voltage fluctuation. In the standard accepted it is presented by the spectrum of the square of its effective value.

2. The fluctuation of the light flow, caused by voltage fluctuation. This obviously depends on the type of the lamps used. In the now existing standard a

lamp with an incandescent filament is used, gas filled, with power of 60 W, supply of 230 V. It is evident that the dependence between the two fluctuations will be different for fluorescent, energy saving or halogen lamps, also fed by the network, but through a reducing transformer.

3. The physiological perception by the eye and the brain reaction.

3.2. Flicker in the electrical line of WTG

The flicker is caused by load commutations in the network, by the nature of some types of loads, such as electric welding tools, invertors, by generators, connected to the network, which trace the balance between the consumed and generated power, by commutations of some network branches. The loads are a dominating factor for the flicker in a conventional network. The connecting of WTG to a network leads to an increase in the flicker level. On one hand, this is connected with the nature of the wind energy – characterized by strongly expressed dynamics. The energy, obtained in the network, is considerably and rapidly changing. On the other hand, a new source of flicker is entered in the network – interharmonics. The interharmonics are periodic fluctuations with a frequency, that is not integer multiple to the network one. The presence of such voltages, which is not noticeable at first glance, introduces fluctuations in the effective value of the voltage with low frequency, which already causes optical flicker.

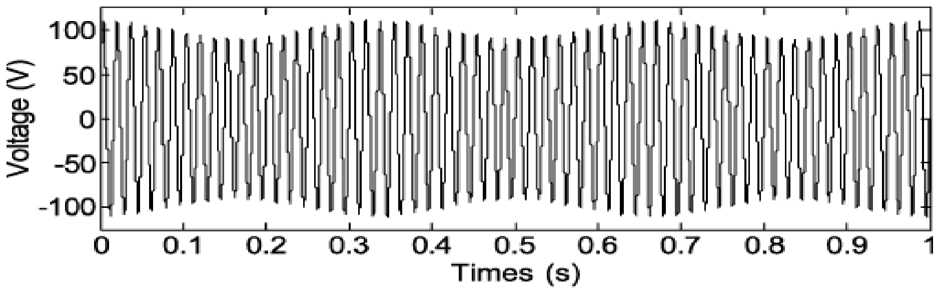

Fig. 3

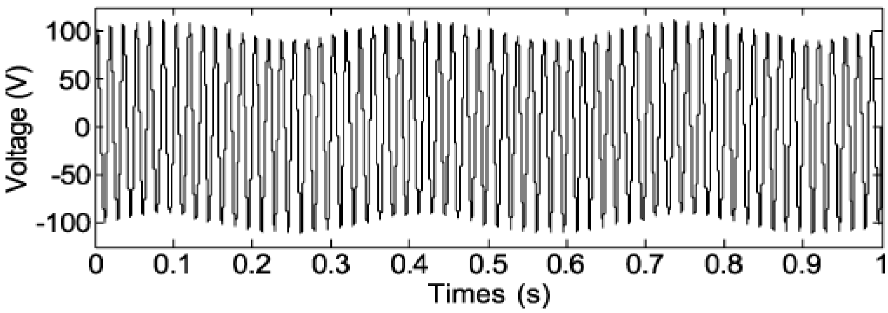

Fig. 4

The larger part of WTG work at variable speed and frequency conversion, which injects interharmonics of variable frequency in the network.

The flicker is defined as a result of the measurement with a measuring scheme, standardized by EN 61000-4-15 – a flicker meter of a 10-minutes sample of the voltage investigated. The equipment is built on an analogue concept. Thus it measures correctly the flicker (set for a lamp with an incandescent filament of 60 W, 230 V and human perception of illumination), as well as for fluctuations of the type of amplitude modulation of the network voltage, and also in the presence of sub- and interharmonics.

The flicker appears in two main forms – as a result of amplitude modulation of the network voltage and as a result of beating between the different frequencies, not integer multiple one to another. Fig. 3 shows the shape of the voltage with flicker of amplitude modulation. The alteration of the power, and hence – of the light flow produced, is clearly visible.

Fig. 4 shows the shape of the summed voltage of two frequencies – 100 V, 60 Hz and 10 V, 117 Hz. The resultant voltage appears visually as a sum of the main voltage and such with a frequency of 3 Hz difference – between the available voltage 117 Hz and the not existing second harmonic of 60 Hz. The presence of flicker with a frequency of 3 Hz is evident.

The realization of a flicker meter of analogue type, as fixed in the standard, is too engaging. The real execution of flicker meters [8-11] is digital, the analogue functions being approximated by digital. This enables the development of flicker meters with different degree of complexity, accuracy of measurement of other illumination sources, not considered in the standard. Fig. 5 shows the functional scheme of a flicker meter EN 61000-4-15.

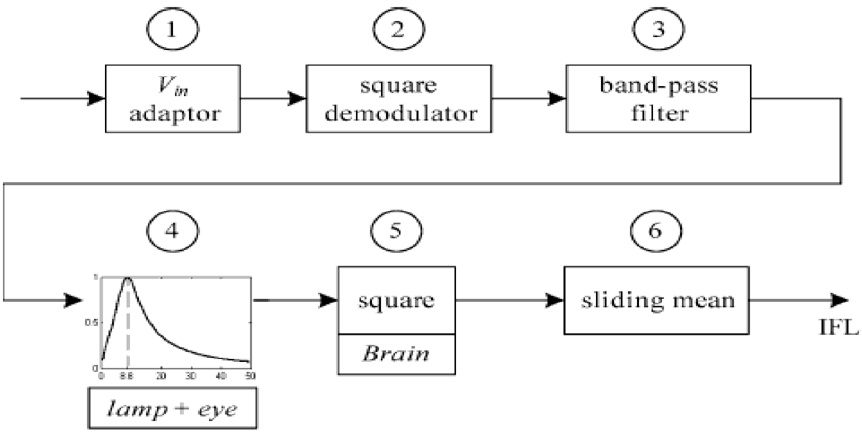

Fig. 5

Primary processing of the voltage investigated is done in block 1 – normalization, galvanic separation. Other functions can also be realized – for example, testing, calibration, etc.

Block 2 is a quadratic demodulator, which separates the variable component in the basic fluctuation. The band filter in block 3 is for frequency bandwidth of 0.05-35 Hz, within which the human eye perceives the illumination fluctuations. The constant component is separated and used to determine the relative alteration in the input voltage.

Frequency weighting is done in block 4. The shape of the frequency weight function, determined in the standard, is shown on Fig. 6 [12]. The value of the flicker depends both on the frequency, with which the illumination is modulated, and on its depth. For frequencies above 35 Hz the human eye is insensitive, regardless of the alteration intensity. The dependence of the accepted flicker level on frequency and depth of modulation, is shown on Fig. 7 [13].

The amplitude-frequency relation of the flicker is obtained from the beating between the main frequency 50 Hz and the interharmonic, with a frequency, altering between the limits 0-150 Hz and amplitude, altering between the limits 0-2.5%. The white fields show the areas amplitude (modulation)/frequency below the threshold of eye sensitivity.

After raising to power of two in order to obtain the power of the variable component of illumination and creeping averaging by a filter of first order, with a cut frequency of 0.53 Hz in blocks 5 and 6, the output signal $U_{f_{\mathrm{m}}}$ is defined as momentary flicker.

The distribution function is determined by the obtained values of the momentary flicker for a 10-minutes sample. The short-term one is then calculated from it according to the expression:

$$F_{\mathrm{st}} = \sqrt{0.0314F_{0.1} + 0.0525F_{1.0} + 0.0657F_{3.0} + 0.26F_{10} + 0.18F_{50}},$$

Here F_i is the value of the momentary flicker, for which the distribution function has a value of *i* %. In order to accomplish these calculations, a large volume of data is used. After quantization with speed of 1 kHz, 600 k discretes are obtained from the 10-minutes sample.

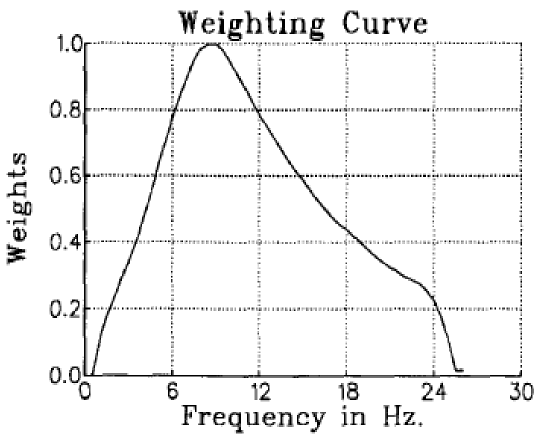

Fig. 6

The coefficients for the weighed sum thus introduced tolerate the strong short-term filter and the lasting, but low power flicker.

For more integral evaluation of the flicker, a creeping cubically averaged short-term estimation is used according to the expression: $F_{\mathrm{lt}} = \sqrt[3]{\frac{1}{n}\sum_{i=1}^{n-N} F_{\mathrm{st}}^{3}}$. The cubic averaging gives additional priority to the weak flickers and emphasizes the strong ones.

For realization of the weighed frequency function, UIF recommends the use of a 4-polar filter with the following transfer function [12]:

$$H(s) = \frac{k w_1 s(1 + s / w_2)}{(s^2 + 2\lambda s + w_1^2)(1 + s / w_3)(1 + s / w_4)},$$

$$k = 1.74802, \qquad w_2 = 2\Pi \times 2.27979,$$

$$\lambda = 2\Pi \times 4.05981, \qquad w_3 = 2\Pi \times 1.22535,$$

$$w_1 = 2\Pi \times 9.15494, \qquad w_4 = 2\Pi \times 21.9.$$

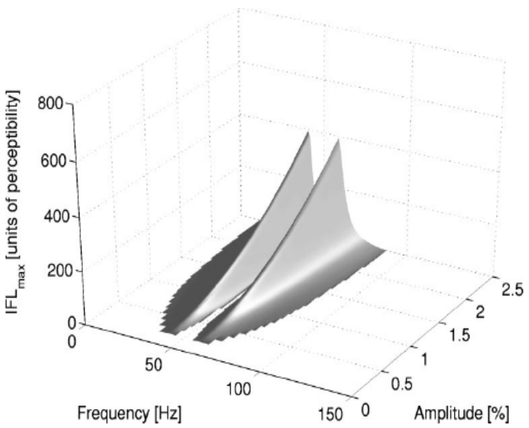

Fig. 7

In extended form the transfer function becomes as follows:

$$H(s) = \frac{100s(1 + 0.0698s)}{(s^2 + 51s + 3309)(1 + 0.1299s)(1 + 0.007267s)}.$$

WTG can inject flicker in the network both due to variability of the generated power, and also due to the frequency conversion completed. They cause two types of flicker – as a result of the amplitude modulation and as a result of the beating between the basic frequency and the interharmonics.

Specific attention is paid to the flicker, obtained in WTG farms, regardless of that, obtained by other sources in the network. A possible approach for such measurement is proposed in [14]. It is assumed, that in the distant end of the network, where a generator is connected to preserve the frequency, the voltage is constant with respect to the shape and also with respect to the phase, and the line impedance is known. The voltage at the network input (near to WTG) is determined analytically from the measured current, and then the network flicker is defined.

For digital realization of a flicker meter the quantization frequency and the filters order are significant parameters. The frequencies used for flicker meters quantization vary in wide bounds from 450 Hz up to 15 kHz [12, 14, 15, 16].

In [16] the frequency weighting function is approximated by two successively connected digital filters of second order with pulse reaction of unrestricted length:

$$F_1(z) = \frac{0.21z^{-1} - 0.21z^{-2}}{1 - 1.877z^{-1} + 0.898z^{-2}},$$

$$F_2(z) = \frac{0.142z^{-1} - 0.138z^{-2}}{1 - 1.720z^{-1} + 0.724z^{-2}}$$

with a quantization frequency of 450 Hz, a smoothing filter of first order with a time constant of 300 ms, which corresponds to a bound frequency of 0.53 Hz.

In order to study the complete frequency range of 0.05-35 Hz with a resolution of 0.05 Hz, 20 × 35 = 700 spectral components must be obtained.

4. Conclusions

The network considered (see Fig. 2) is a partial case – a new source of active and reactive power in the distant end of a network. It can be generalized for networks with distributed sources and consumers. These are already another type of networks, the theory of which is in the process of development. With the introduction of different alternative sources of electric power, it is expected the existing networks to be transformed in a similar type. The direction of the energy flow in their sections alters, depending on the place and the value of the power consumed/injected by the separate loads/generators.

The injecting of reactive power contributes strongly to the increase of the short-term network stability. A large part of the consumers in transition modes – during switching on, stress loading for short intervals of 0.1-2 s, usually use bigger current than the nominal one, at that reactive. A typical consumer of this type is the asynchronous motor with a cage rotor. Its characteristic “revolution moment-slipping” is equivocal with a narrow interval of stable operation and at initial starting with a load there is probability not to be able to pass in a stable operation zone. The short term injection of reactive energy in the transition mode – up to 2 s, obviously increases stability. It also contributes to the improvement of another qualitative indicator for the network, that is often underestimated – the flicker.

The study of flicker’s influence on man shows that its fluctuation, rather than its absolute value, causes certain discomfort. The human eye, with its system of circular (sphincter) and radial (dilators) muscles possesses large potential to adapt to different degrees of illumination, altering the pupil aperture. However, this reaction is not sufficiently quick. The reaction of the channel eye-brain is too complex. The discomfort caused depends on the time relation to light fluctuation, on its amplitude, spectral content, continuation, on the individual, their age, emotional status, the spectral constitution of light and other less significant factors. The unpleasant perception of the fluctuation when reading, watching TV, work with an electronic-ray screen, is discussed. The human sensitivity to light illumination is really high, of the order of 0.25%.

The individual feeling of discomfort may vary from weak irritation to a sharp reaction. Nowadays the flicker level is accepted as one of life qualitative indices.

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Реактивная мощность в ветерно-генераторных парках и введение фликера в электрической сети

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(Р е з ю м е)

В работе обсуждается участие реактивной мощности при трансфере электрической энергии и функционирование консуматоров этой энергии, связанное с формированием электрических и магнитных полей. Рассматривается проблем реактивной мощности в ветерно-генераторных парках и использование дополнительной реактивной мощности для сохранения вариаций напряжения в допустимых границах. Дефинируется параметр коротковременной стабильности напряжения – фликер, и обсуждается введение фликера в электрическую сеть ветерных генераторов.