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SIMULATION OF THE CIRCUIT WITH A RECTIFYING ELEMENT FOR ANALYSIS OF THE PHENOMENON OF POWER PARADOX

Valeriy Yahup[1], Kateryna Yahup[1], Yevhen Diakov[1], Yuriy Sayenko[2],

O. M. Beketov National University of Urban Economy in Kharkiv[1],
Pryazovskyi State Technical University[2]

Abstract: An electrical system is considered in which the resistive load is powered through an ideal electrical valve from a sinusoidal voltage source. It is shown that when simulating such a system for measuring power at the source and load in the SimPowerSystem using a PQ power meter, this leads to inadequate results. Similarly, the paradoxical discrepancy between the results gives the use of virtual meters that estimate the power based on the effective values of the current and voltage of the element. A virtual power meter based on the instantaneous power of the element has been substantiated and proposed. The adequacy of power estimates when using it in a system with a valve is illustrated.

1. INTRODUCTION

The issues of power evaluation in electrical systems invariably attract considerable attention of developers and researchers in the field of electric power industry. These issues are related to the need for proper assessment of the amount of electricity consumed and the quality control of electricity in power supply systems [1]. Mathematical estimates of power give the opportunity to adequately develop penalties to consumers for the making of asymmetry in the modes of three-phase power supply systems [2]. Modern concepts of reactive power compensation are also based on the determination of the components of total power [3], and a decrease in reactive power in an electrical network means a reduction in losses and an increase in efficiency. The last is a key problem in the power industry. Estimates of power are complicated for cases of power supply through non-linear elements. Even in the simplest case of connecting a resistive load to a source of sinusoidal single-phase voltage through an ideal uncontrolled or controlled valve, the ambiguity of estimates of the levels of power consumed and given off appears.

2. ESTIMATION OF POWERS IN VISUAL MODELING

2.1. Analysis of recent research and publications

The mutual inconsistency of various concepts of power in the electrical system and its various components has been repeatedly discussed in the scientific literature [4 – 6]. The intensity of these discussions is not reduced at the present time. Of particular interest are the interpretations of power components applied to nonlinear systems, in particular, to electrical energy conversion systems with electric valves [7, 8]. In such systems, the voltage currents are subjected to distortion of a sinusoidal shape, which is due, on the one hand, to the nonlinearity of the current-voltage characteristics of the electric valves, on the other hand, the ability to control the unlocking and locking moments of the controlled valves. Thus, the relatively well-balanced theory of AC power, known from the classic textbooks of theoretical electrical engineering, is directly violated in its direct formal application. A vivid example of the discovery of such contradictions is the publication of V.T. Dolbnya [9]. It is devoted to the definition of energy ratios in an extremely simple system with a valve. The power supply of the load, represented by a single resistance resistor, is considered through an ideal uncontrolled valve from a sinusoidal voltage source with a single amplitude. Further studies are extended to the same system provided that the uncontrolled ideal valve is replaced with a partially controlled thyristor with a variable angle of control of the thyristor unlocking moment. The paradox observed and described in article [9] is the inequality of the mode, consumed by the load and given by the source of electrical energy. This is against the well-known law of power balance [5, 6]. The attractiveness of the work [9] consists primarily in the simplicity of the system under consideration and in the presence of specific numerical values of the studied parameters. This immediately suggests to conduct a computer experiment using SimPowerSystem (SPS) tools [11].

2.2. Object of the article

Consists of a study using computer experiments on a visual model of an electrical system with uncontrolled and controlled ideal electrical valves to determine the power delivered by the source and the power consumed by the load in various ways of constructing virtual power meters.

2.3. Use of virtual power meter system SPS

Figure 1 shows the virtual model of the system under investigation with standard virtual power meters of the SPS system itself.

In the model, the voltage source e(t) generates a sinusoidal voltage with an amplitude of 1 V and a frequency of 0.5 Hz. The diode Diode is represented by a piecewise linear model with resistances of 0.00001 Ohms in the forward direction of conductivity and 100000 Ohms in the opposite direction. This ratio allows us to put the valve close to ideal. The power dissipated on such a valve is close to zero, which allows us to consider the balance of power only in relation to the source and load. The load is represented by the active resistance of the resistor R with a resistance of 1 Ohm. Virtual instruments VMe and VML measure voltages at the source and load, respectively. The CMe and CML virtual instruments measure source and load currents, respectively. The voltage and current of the source are recorded by a ScopeE virtual oscilloscope, and the voltage and load current are recorded by a ScopeL virtual oscilloscope. The corresponding time diagrams of voltages and currents according to the simulation results in the model time interval from 0 to 2 s with an integration step of 0.001 with the Rosenbrock method are shown in Fig. 2

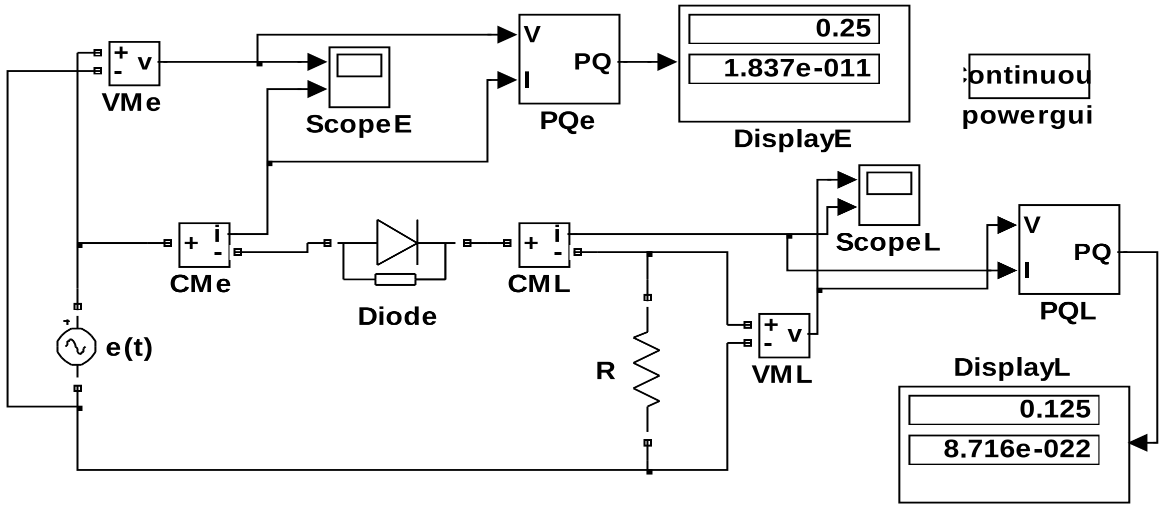
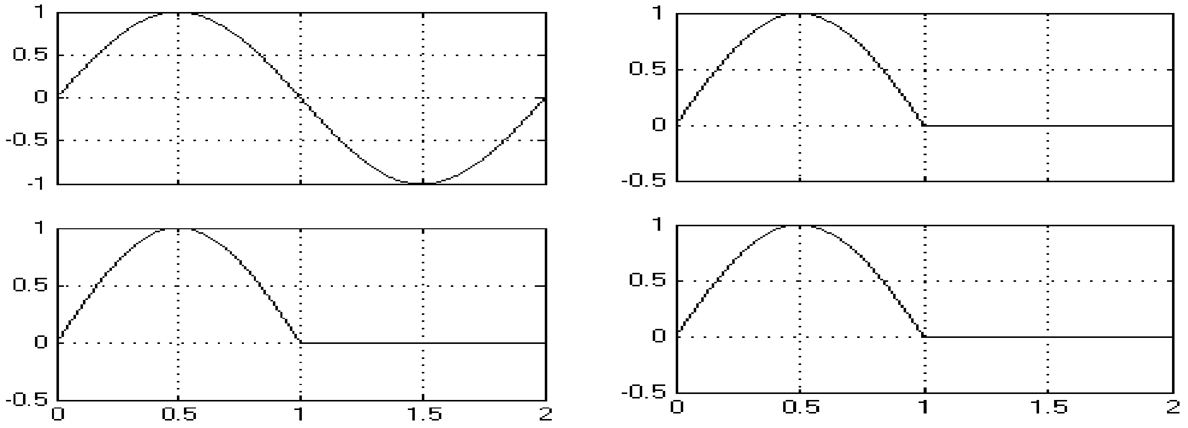


Fig.1. System model with virtual SQ PQ power meters



a *б*

Fig.2. Time diagrams of voltage and current: a – source; b – load

These time diagrams show the adequacy of the model. Indeed, the source voltage is sinusoidal, and the current from the source is consumed only during the first half period. In the load, both current and voltage are consumed only in the first half period.

What are the indicators of the virtual power source and load meters? The source power meter indicates the presence of active power S = 0.25 V, and the active power P = 0.125 V is consumed in the load. The phenomenon of the paradox [9], consisting in the inequality of power consumed by the load and given by the source, was manifested in the simulation using a virtual power meter of the SPS system. Note, however, that the values of the power source and load are different from those specified in [9], where they are equal to 0.3536 and 0.25 Watt, respectively, and give a ratio of 1.4. In our simulation case, this ratio is 2.0. Let us analyze the structure of the virtual power meter system SPS. It is shown in Fig. 3 and obtained using the context menu option Look Under Mask.

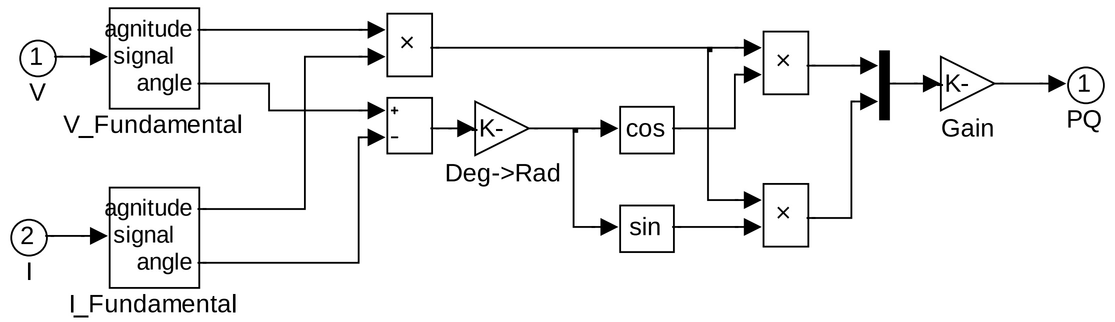


Fig. 3. Virtual SPS power meter

As can be seen from fig. 3, the voltage and current causing the measured power are fed to the V_Fundamental and I_Fundamental blocks, which are analyzers of the harmonic components of a given order. The structure of the model of the first virtual device is shown in Fig. 4.

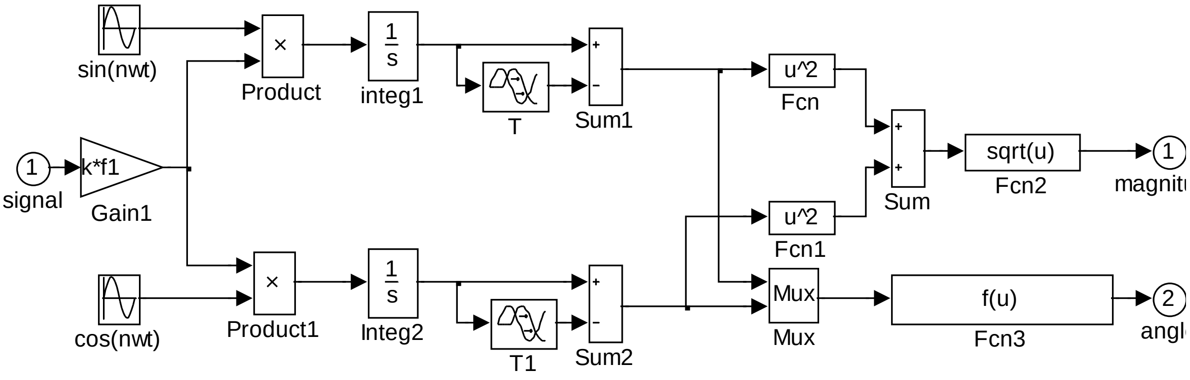


Fig. 4. Virtual harmonic analyzer of system SPS (V-Fundamental)

Here, the input signal is multiplied by the sine and cosine components of a given frequency. The received signals are integrated and the values of definite integrals in the interval of the last period are selected. Using the amplitudes of the sine and cosine components found in this way, the module and phase of the harmonics taken from the output of this virtual analyzer are calculated. Returning to the power meter in fig. 3, we note that after processing the voltage and current signals with harmonic analyzers, the amplitudes and phases of the main harmonics are distinguished. From the results obtained, the product of the amplitudes of the voltage and current harmonics is calculated, representing the double total power module. The phase calculates the angle between current and voltage and the corresponding sigus and cosine. Active power is determined by the product of the module by the cosine, and the reactive power, by the product of the module by the sine of the difference angle. Before outputting signals corresponding to active and reactive power, they are multiplied by 0.5 to reduce to values equal to the half-outputs of the voltage and current modules using the well-known formulas of classical electrical engineering for alternating current power.

From the adduced analysis it becomes clear that the standard virtual meter PQ-power system SPS actually measures the power due to the main harmonics of voltage and current. The voltage source takes into account the full voltage source during the period with a single amplitude and the main harmonic current with an amplitude of 0.5 A. Taking into account the need to divide the product of the amplitudes of voltage and current by two, we obtain a fixed source power value S = 0.25 W. For the load, the amplitudes of the main harmonics of voltage and current are 0.5 V and 0.5 A, respectively. Their semi-production gives the value of power fixed by the device P = 0.125 W. From this we can conclude that the standard virtual PQ-power meter provides adequate indication only at sinusoidal voltages and currents that create power at an alternating current. The presence in the system of nonlinear elements that distort the sinusoidal form of voltages and currents, leads to erroneous results.

2.4. The use of virtual power meters at effective values of voltages and currents

Let us turn to the conclusions of the article [9], which describes the power paradox. As follows from the above mathematical calculations, the power is calculated by multiplying the effective voltage value by the effective current value. Thus, to calculate the power, the formula is actually used:

$$P = \sqrt{\frac{1}{T}\int_0^T u^2 dt}\,\sqrt{\frac{1}{T}\int_0^T i^2 dt}. \tag{1}$$

The model of the researched system, in which the measurements of the power source and load by the effective values of voltage and current are implemented, is shown in Fig. five.

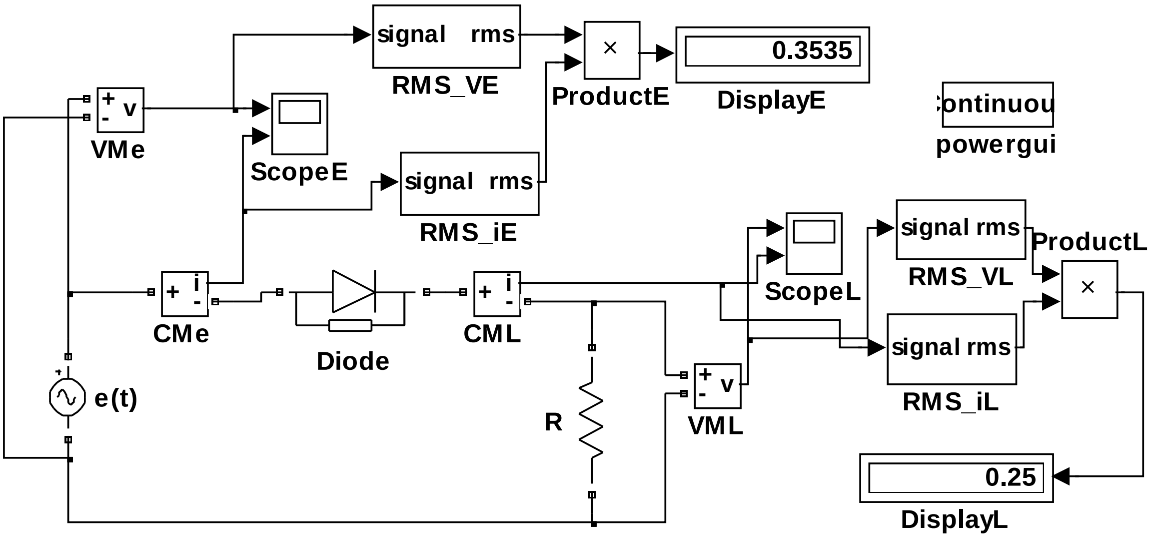


Fig. 5. Model of a system with virtual power meters of effective values of voltage and current

Here, the SPS RMS virtual device is used to calculate the effective values of voltages and currents. The structure of this device is shown in Fig. 6

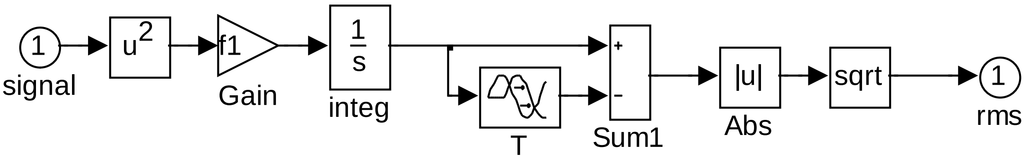


Fig. 6. Virtual calculator of the effective value of the SPS system

From the structure of the RMS calculator, it is clear that the input signal is squared, the obtained value is processed by the integrator and the calculation of a definite integral over the period of the fundamental frequency is provided. The resulting value is averaged over the period and then the square root is extracted from this result. The presence of the Abs block seems to be redundant here, since the signal is squared before calculating the integral. To calculate the power such a way after calculating the effective values of voltage and current, they are multiplied by the Product_E blocks for the source and Product_L for the load (Fig. 5).

The simulation results show exactly those values of capacities that were obtained in [9], thereby confirming the analytical calculations by numerical calculations on the SPS-model and directing the researcher to think about the power paradox.

2.5. Use of virtual instantaneous power meters

What are the causes of the power paradox, manifested in both previous cases of modeling the system under study? We draw attention to the fact that in the second half-period, both in the load and in the source, the work is not performed. In the load, this seems more obvious, because in the second half-period both the voltage on the load and its current are zero. This circumstance affects the calculations of both the amplitudes of the main harmonics of voltage and current in the first model (Fig. 1) and the effective values of voltage and current in the second model (Fig. 5). When calculating the source power, the voltage in both considered cases is taken into account in two half-periods. However, in the second half-period, the power delivered by the source is absent, since there is no current consumed from the source.

It is possible to suggest the following elementary interpretation of adequate calculations of active power for the case of periodic non-sinusoidal voltages and currents of the element under study. We divide the period T by n intervals of duration Δt = T/n. During each k- interval, we will consider the voltage and current to have constant averaged values on the interval uk and ik. Then the work Ak performed by the electric current on the k-th interval is determined by the expression Ak = Δt uk ik.

Summing up all the elementary work on the period and averaging the obtained value of the total work on the interval of the period, we find the active power

$$P = \frac{1}{T}\left(\sum_{k=1}^{n} u_k i_k \Delta t\right). \tag{2}$$

Replacing the sum with an integral with an unlimited increase in the number of intervals n leads this expression to an integral form:

$$P = \frac{1}{T}\int_0^T uidt. \tag{3}$$

The last expression is a known expression of active power in terms of instantaneous power, which is the product of the instantaneous voltage and current values of the element under study [10]. It is instantaneous power that takes into account the absence of power consumption in cases where only one of the quantities that determine power, that is, either voltage or current, is zero. Such cases are typical for valve converters. An example of a current cut-off and is considered in [9] when analyzing a half-wave single-phase rectifier. Another example is the use of a valve, which shunt an active-inductive load in pulse-width converters of direct current. When the shunt valve is unlocked, the voltage at the load becomes zero. The load does not consume power, although it continues to flow current, which is locked through the shunt valve.

Based on the above considerations, you can create a virtual active power meter based on the integration of instantaneous power. Such a meter is presented in Fig. 7

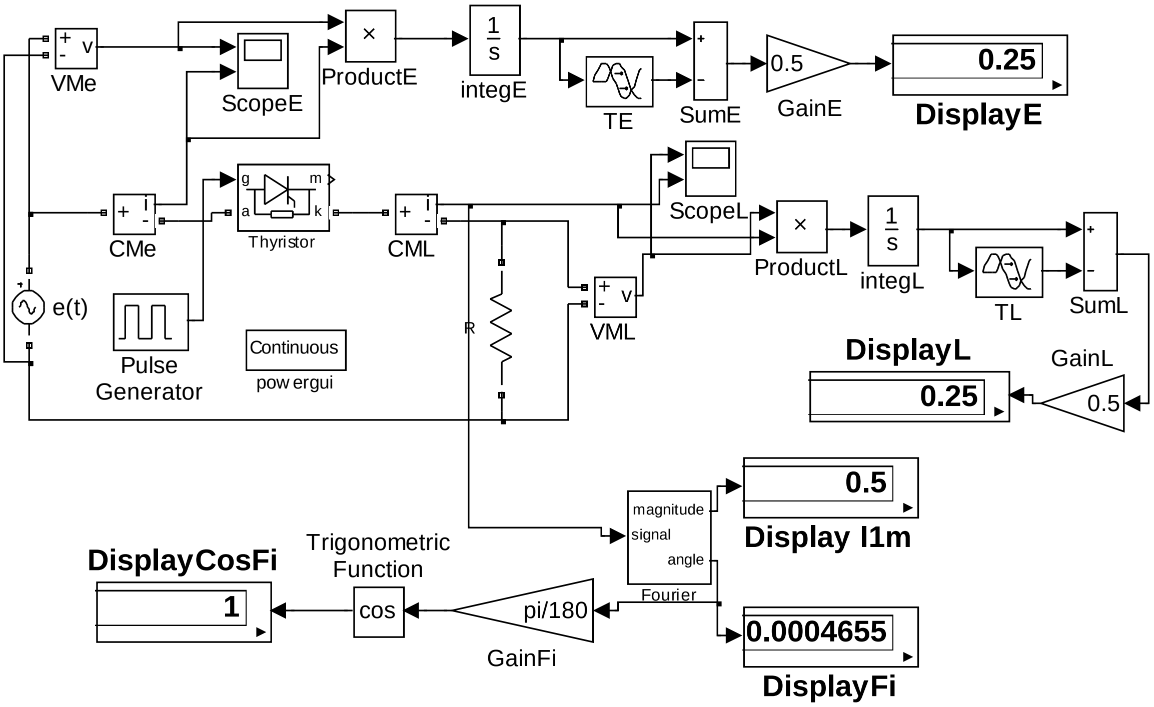


Fig. 7. System model with virtual power meters based on instantaneous power

Virtual power meters are complied here on the use of the concept of instantaneous power. The voltage and current at the element under study e(t) are fed to the virtual multiplier ProductE and thus the time dependence of the instantaneous power is formed. Next, the IntegE integrator performs continuous integration of instantaneous power. SumE adder using the delay unit TE provides the calculation of a definite integral over the period interval, respectively (3). Amplifier GainE averages the value of a certain integral over the period. At its output is given the value of the measured active power. In the model in fig. 7 the diode is replaced by a thyristor controlled from a pulse source Pulse Generator. This allows you to repeat the analysis of the system when changing the angle of control of the thyristor. The blocks at the bottom of the model determine the amplitude and phase of the first harmonic of the current and the corresponding cosine of the phase angle. In fig. 7 in this case, the control angle is zero, which actually turns the thyristor into a diode. Thus, the latter model is equivalent in the behavior of the power section to the previously considered two models (fig. 1 and fig. 5). As can be seen from the presented in fig. 7 models, the indications of virtual instruments in determining the power of (3) are completely identical and completely non-paradoxical. Both powers are 0.25 watts.

The study of a system with controlled thyristor in this case also does not lead to the paradox of inequality of output and consumed power. The results of the change of the control angle within the values given in [9] are displayed in the table 1.

The results of simulating a system with a thyristor when the control angle is changed indicate that there is no discrepancy between their values when using the instantaneous power for the generated and consumed powers. The increase in the power ratio S/P with increasing control angle, noted in [9], is therefore, that at the same time increases the interval of zero current in the load and in the source. This circumstance is correctly taken into account in the load, since here the interval of zero current and voltage coincide. In the source, the voltage throughout the whole period is assumed to be non-zero, and when voltage and current are separately taken into account according to expression (1), this leads to incorrect results. These erroneous results are contained in row S of the table in [9], which represents the active power of the source. In fairness, we also note that fig. 2, b in [9] contains an inaccuracy in the display of the graph of the first harmonic of the thyristor current. The phase angle of the first harmonic coincides with the angle of control of the thyristor only for the case of its zero value. As the control angle increases, the phase angle of the harmonic will always be ahead of the control angle. This is evidenced by the results of calculations concluded in both tables of both the article [9] and the present work.

Table 1. The results of the simulation system with thyristor

Control angle α	0	30	60	90	120	150
1st harmonic amplitude I_{m1}	0,5	0,487	0,420	0,296	0,154	0,042
1st harmonic angle φ (el. d)	0	-4,68	-16,5	-32,5	-50,7	-70,1
Cos φ	1	0,997	0,959	0,844	0,634	0,341
Source power S	0,25	0,243	0,201	0,125	0,049	0,0072
Load power *P*	0,25	0,243	0,201	0,125	0,049	0,0072
Ratio	1	1	1	1	1	1

3. CONCLUSIONS

When modeling electrical systems containing non-linear elements in the form of uncontrolled and controlled electrical valves, it is necessary to take a critical approach to the system power estimation capabilities using standard virtual PQ- power meters. The inadequacy of the readings of these virtual instruments is due to the fact that their readings are based on the isolation of the main harmonics of the current and voltage of the element under study. This estimate does not take into account the presence of zero-current intervals in systems with valves.

Similar inadequate results are provided by virtual meters, in which the power is determined by the product of the effective values of voltage and current of the element under study.

The use of instantaneous power, determined by the product of the element voltage and its current, followed by integration and averaging, allowed us to create a virtual active power meter for use in simulating a system with a valve. The results obtained here are absolutely adequate and correctly take into account the behavior of systems with valves.

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Prof, Dr. of tech. sc., Valery Yagup
O. M. Beketov National University of Urban Economy in Kharkiv
str. Bajanova, 17, Kharkiv, 61002, Ukraine
e-mail: yagup.walery@gmail.com

Associate Prof., Dr. of tech. sc., Kateryna Yagup
O. M. Beketov National University of Urban Economy in Kharkiv
str. Bajanova, 17, Kharkiv, 61002, Ukraine
e-mail: kata3140@gmail.com

Associate Prof., Ph/ D.., Yevhen Diakov
O. M. Beketov National University of Urban Economy in Kharkiv
str. Bajanova, 17, Kharkiv, 61002, Ukraine
e-mail: dyakov_ed@meta.ua

Prof, Dr. of tech. sc., Yuriy Sayenko
Pryazovskyi State Technical University[2]
Electrical Engineering Department
Universytets'ka 7,
87555 Mariupol, Ukraine
e-mail: yls62@i.ua