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ALGORITHM OF POWER LINE CURRENT FORMATION AT LOAD NODE

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Abstract. *The paper is devoted to devices and methods for the automated regulation of power flows in the Smart Grids. A description of the method of the current vector control of the power transmission lines electrically combined in a general load power supply system by introducing an additional voltage and applying a line reactor with specified electrical parameters is given. A vector diagram of voltages and currents of the power system is presented, explaining the principles of forming the current parameters of a line reactor installed in an adjustable power line. A virtual tool made in the LabVIEW graphical programming environment based on the CompactRIO platform is described. It is used as an element of a voltage converter control system that implements control of electrical potentials on a line reactor. The effect of the initial phase shift between the voltages of the connected nodes of power lines is observed. The results of the analysis of the voltage vector system in the regulated power system when measuring the initial phase shift between the voltages of power lines and the formation of a predetermined nature of the current of the network choke are shown and the change in the value generated / consumed by the inverter active power voltage is shown.*

Keywords: *control system, LabVIEW, line reactor, micro grid, smart grid, vector current regulation, voltage inverter.*

The development of intelligent electrical grids in Russia, including the expansion of distributed generation, assumes the development of active and adaptive devices, ensuring the automatic regulation of electrical grid parameters and the effective integration of small and medium renewable energy sources into the power system [1-3]. The implementation of these functions is connected to the development of technical solutions in the domain of electric power flow regulation. Special attention should be paid to electrical grids of medium and low voltage, as they do not have devices capable of effectively performing the outlined functions.

The authors propose a method of vector regulation of the transmission line current [4-8] by means of the installation of a regulator in the common load node (Fig. 1), which helps regulate power flows between generation sources and the final power users.

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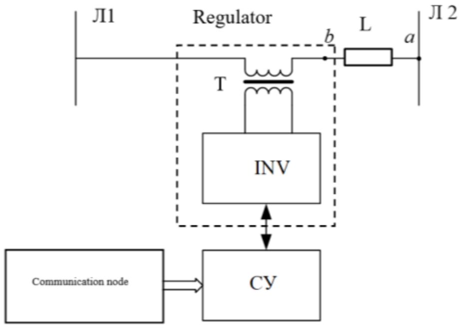

Fig. 1. Area of the electric grid with regulator installed on the transmission line

Figure 1 presents a structural diagram of the electric grid section with two transmission lines, L1 and L2. Transmission line 1 can be connected using an autonomous power source or local area network (MicroGrid, NanoGrid). Transmission line 2 can be connected to the centralized electric grid or any other local area network.

The lines are connected in the load node by means of a regulator that includes: a series transformer (T), network throttle (L), voltage inverter (INV), control system (CS), and a communication node with a control center [9, 10].

A voltage inverter INV is connected to the primary winding of the series transformer T, which allows the inputting of additional e.m.f. into transmission line L1, changing the potential difference (a, b) on network throttle L. Thus, knowing the parameters of network throttle L, the current of line L1 can be generated with the set amplitude and phase angle. The inverter power supply can be performed from an auxiliary direct voltage source or from the working line by means of a rectifier.

The regulation of the voltage value and phase angle on the network throttle allows changing of the value and nature (phase angle) of the current in transmission line L1 and the ratio of currents in both lines L1 and L2, including the “switching off” of any of the transmission lines (line current is equal to zero) without using switching units.

A vector diagram of the electric grid voltage and current with a regulated transmission line explaining the main concepts of establishing the set parameters of the network throttle current is presented in Fig. 2.

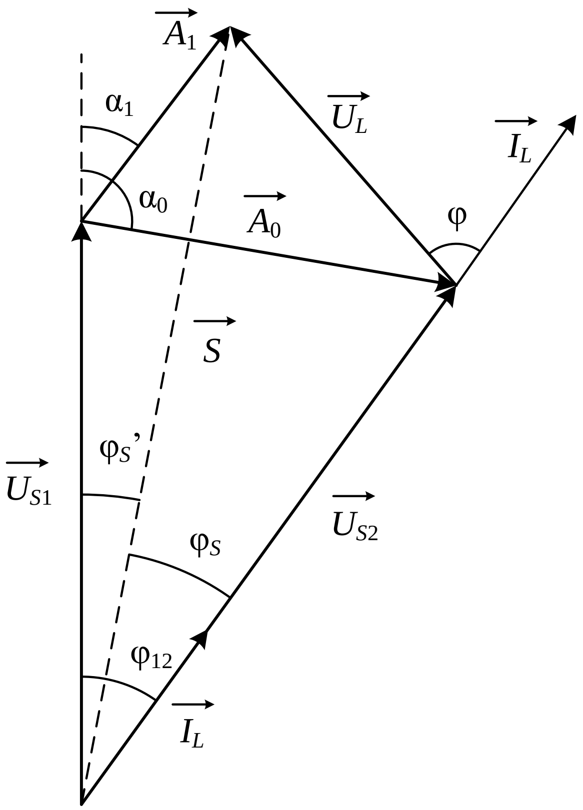

Fig. 2. Vector diagram of the current and voltage with regulation of the current parameters of the power transmission line

$\overline{U}_{S1}$-voltage vector of transmission line L2; $\overline{U}_{S2}$-voltage vector of transmission line L1; $\overline{U}_L$-voltage vector of network throttle; $\overline{I}_L$-current vector of network throttle; $\overline{A}_0$-voltage vector of series transformer corresponding to zero consumption current of transmission line L1; $\overline{A}_1$-voltage vector of series transformer corresponding to the set consumption current of transmission line L1 (current of the network throttle); α_0-phase angle of the series transformer vector corresponding to zero consumption current of transmission line L1; α_1-phase angle of booster transformer vector corresponding to the set consumption current of transmission line L1 (current of the network throttle); φ_{12}-phase shift between the voltage vectors of transmission lines L1 and L2; φ-phase angle between the vectors of current and voltage of the network throttle.

Auxiliary vector $\overline{S}$, as well as its phase angles relative to the voltage vector of transmission line L1 (φS’) and that of transmission line L2 (φS), is introduced for the simplification of calculations and geometric constructions when establishing the set parameters of the network throttle current.

The vector diagram provided in Fig. 2 demonstrates that the introduction of additional e.m.f. into the transmission line L1 by means of voltage inverter INV ensures the following:

- establishment of the mode of the current zero value between L1 and L2;
- establishment of the mode of compensation of reactive power of any nature;
- performance of controlled splitting of the load between L1 and L2;
- performance reverse of power from transmission line L2 to L1.

The parameters of any above-described mode can be determined by measurement of the current parameters of transmission line voltage, as well as by establishing the set parameters of the network throttle current vector. The results of the calculations are the vector of additional e.m.f. $\bar{A}0$ is the setting signal for the PWM generator of voltage inverter INV [11-14].

Platform CompactRIO (cRIO) can serve as one of the possible implementations of the converter CS guided by the network, automatically correcting the parameters of the output voltage of the regulator under the conditions of continuously changing parameters of transmission line voltage. This hardware complex consists of a high-efficiency, field-programmable logic device, real-time controller, a set of protocols for remote communication, as well as expansion modules for the forming and receipt of logic control signals, as well as for digital–analog and analog–digital conversion (Fig. 3).

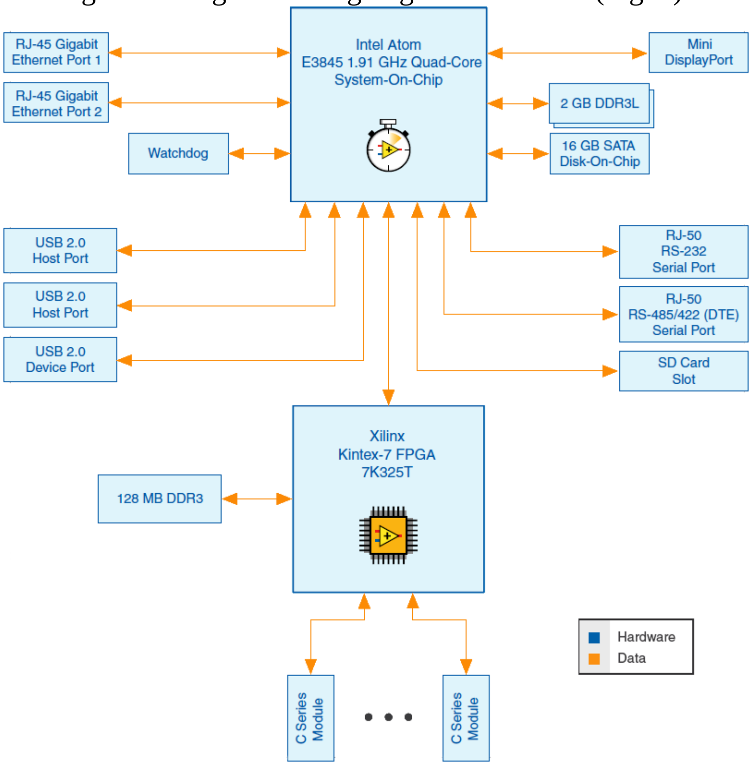

Fig. 3. Structure of platform *cRIO*

Monitoring and CS based on platform cRIO includes the set of elements that implement the exchange of the measured values and parameters of the modes of operation with remote monitoring and CSs using the network protocol TCP/IP, RS 232/485, USB. Integrated solid-state drives allow the keeping journal of measurements and received commands, which further simplifies the analysis.

Platform cRIO includes a regulator server with a fixed IP-address and port reserved for connection and awaits a client connection, which is the remote monitoring and CS in the diagram.

Program components that implement control of platform cRIO shall be developed using graphic programming LabVIEW and have the names of virtual instruments (virtual instruments (VI)). These elements are analogs of subprograms of the text-based programming languages. The use of graphic programming languages allows for the significant simplification of development and the adjustment of CSs.

Control boards of virtual instruments included in the overall CS allow the local operator to monitor the availability of connections with remote operators, tracking the quality of transferred data, performing a manual reset of the connection, fixing availability of errors in operation and those of the subsystems of the receipt/transfer.

The algorithm of vector control of the voltage inverter is implemented in the form of the virtual tool VECTOR, whose task is to repeat the plotting of the vector diagram (Fig. 2) and simplify perceptions of operation of the regulator by the adjuster and operator (Fig. 4) [15, 16].

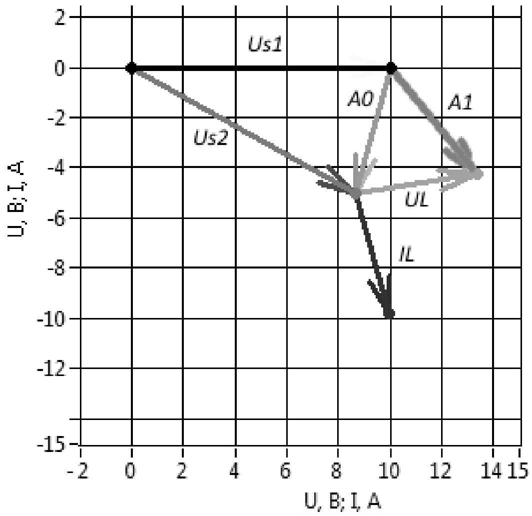

Fig. 4. Virtual instrument *VECTOR*

Figure 4 presents a vector diagram with the set angle of the generated current of 45 electrical degrees of the leading nature relative to the voltage of the transmission line 2, amplitude 5 A. For perception convenience, the line voltages are provided with amplitude values of 10 V.

Graphic code is made by means of standard library elements included in the set LabVIEW 2015.

The output parameters (amplitude of the measured or set current and voltage, as well as their phase angles) are converted into coordinates of the sections' ends by means of blocks of data conversion of the polar coordinate system in the rectangular one (Cartesian)–PolartoRe/Im (library Mathematics>Numeric>Complex).

The use of tools for operation with geometric objects allows the shifting and turning of plotted sections proportionally to the set or measured parameters (library Mathematics>Geometry).

Thus, virtual instruments using known vector values form sections on the coordinate plane, which correspond to the voltage of active rectifier and output voltage inverters.

The obtained coordinates of the sections are converted into parameters of amplitude and phase angles of the formed voltage by means of blocks making reverse conversions from the rectangular coordinate system into the polar one (library Mathematics>Numeric>Complex).

To reduce the graphic code, all of the values are transferred between the estimated nodes in the form of local variables (LocalVariable). The ExpressionNode (library Numeric) blocks perform the function of radian conversion into electrical degrees, which simplifies the calculations and operator's interaction with the control panel.

All the vector values, both set and calculated, are inputs to the tool of the graphic display XYGraph (library Modern>Graph). All of the established sections are combined in the uniform array (Array) by means of the BuildArray (Library Arrays) block.

Elements of the graphic code implementing the calculation of parameters of the voltage vector on network throttle L are provided in Fig. 5. The determination of the parameters of the rest vectors will be performed using similar graphic structures. For the sake of convenience of the vector diagram reproduced on the virtual instrument, the beginnings and ends of the vectors corresponding to each other are connected. This effect is achieved because the calculated coordinates of one set of vector ends are the initial basis for the other. This is implemented by means of local variables X and Y having their own indices that correspond to each vector used in the tool.

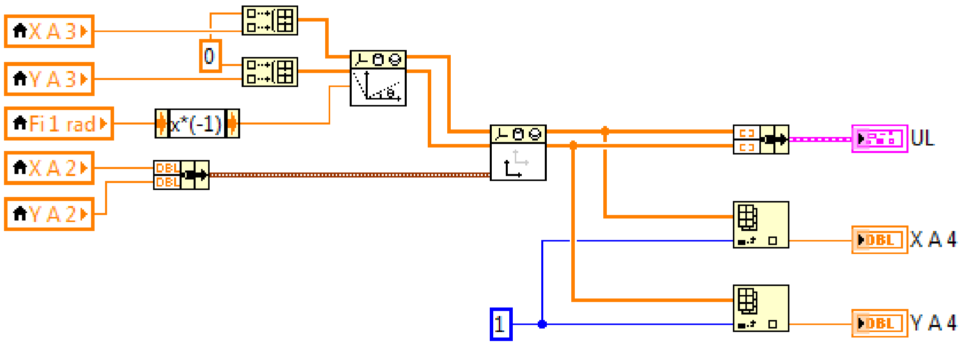

Fig. 5. Graphic of the code of the network throttle voltage vector calculation node

The developed CS takes into account the possible availability of an initial phase shift between the voltages of the connected transmission lines (Fig. 6) [17].

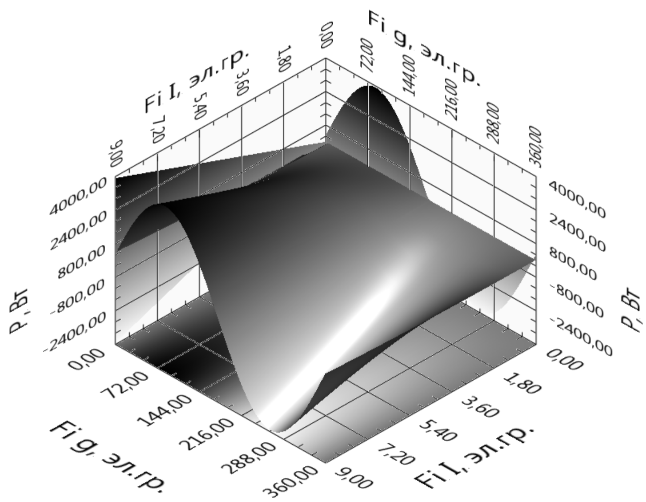

Fig. 6. Active power generated/consumed by the voltage inverter INV with leading voltage for line L2

Examination of the vector system's behavior with different parameters of transmission line voltages allowed the obtaining of dependence of the active power value generated/consumed by the voltage inverter INV on the set phase angle of the network throttle current (FiI) and the value of the phase shift between the transmission line voltages (Fig).

Analysis of the parameters of the surface formed with the geometric place corresponding to the amplitudes of the active power of the points allows the conclusion to be drawn that the consumption of active power is minimal when the initial phase shift angle is absent between the transmission line voltages. The maximum power consumed by the converter is used for establishing a reactive current in line L1 and is increased proportionally to the increase of the initial phase shift between the lines.

The results of the modeling of the converter's operation indicate different initial phase shifts between the voltages in the line connection nodes; the nature of the established current is not identical to the current nature consumed by the voltage inverter.

This phenomenon is explained by the fact that despite the set nature of transmission line current, the vector of additional e.m.f. can prompt the phase angle relative to the network throttle's current and, as a consequence, the interaction of e.m.f. introduced in the line and the established current follows its own course.

The nature of the phase shift between line voltages is important for determination for the active power component of the output converter regulating voltage on the network throttle. The lagging nature of the voltage of the line L2 increases consumed active power by the converter of the transmission line from 0 to 90 el. gr. The growth in active power generation by a converter to transmission line prevails in the range of 180–270 (Fig. 7).

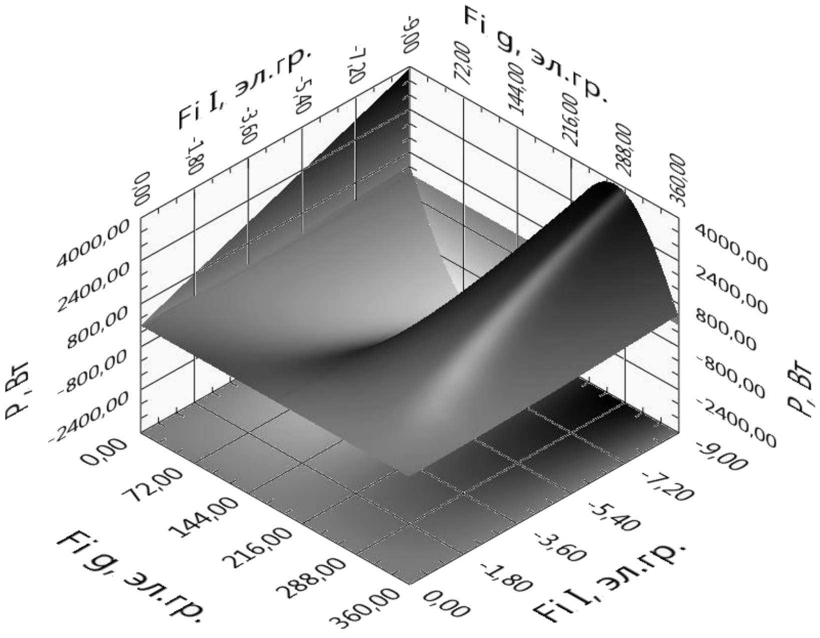

Fig. 7. Active power generated/consumed by the voltage inverter INV with lagging voltage for line L2

The leading nature of the voltage of line L2 has an inverse dependence on the consumption/generation of active power on the set current phase angle and phase shift between the line voltages.

The presented dependencies indicate the occurrence of additional power flows that do not have the direct effect of establishing the transmission line currents; however, they have the capacity to affect the primary power source of the voltage inverter, as well as the operation of the converter by means of disturbing the power balance in the power system. This aspect should be taken into account when establishing a current to ensure the stable operation of the voltage inverter, as well as conditions to be implemented that permit inverter operation in energy recuperation mode.

The method outlined here to regulate vector transmission line currents by means of control of the phase angle's voltage value on the network throttle by means of additional e.m.f. with the set parameters of amplitude and phase angle relative to voltage at the line connection points ensures the following:

- reduction in transmission line load by means of the re-distribution of power flows between lines;
- reverse directions of power flow from one transmission line to the other;
- modes of reactive power compensation.

It should be noted that the active currents of transmission lines generated by the device will be active–reactive in nature relative to the established voltage at the inverter output and will therefore affect the inverter power supply circuit's balance of power.

The initial phase shift angle between the voltages of the combined lines in the common load node should be taken into account at the stage of control algorithm development and commissioning operations without which the implicit power flows can appear in the voltage inverter circuit connected to the primary winding of the series transformer.

The occurrence of this effect disturbs the correct fulfillment of the control algorithm and causes unpredictable consumption or vice versa, as well as generation by converter of active power in the transmission line, which can result in a disturbance of the energy balance in the direct current link and, consequently, to the incorrect operation of the converter.

REFERENCE

1. *Kobets B.B., Volkova I.O., Okorokov V.R.* SMART GRID as a concept of innovative development of electric power industry abroad // Energoexpert, 2010. no. 2. Pp. 52–58 (In Russian).
2. *Zhang X., Rehtanz S., Pal B.* Flexible AC Transmission Systems: Modeling and control // Springer Nature, 2012. 552 p.
3. *Loskutov A.B.* Solving problems in transition of electrical industry to digital technologies // Smart electrical engineering, 2018. no. 1. Pp. 9–27 (In Russian).
4. *Chivenkov A.I., Vikhorev N.N., Trofimov I.M., Gedifa A.* Physical model of Smart Grid // Transactions of NNSTU n. a. R.E. Alekseev. 2016. no. 1(116). Pp. 83–89 (In Russian).
5. *Chivenkov A.I., Sevastyanov V.V.* Power modules of the integrated control system of electrical networks // Transactions of NNSTU n. a. R.E. Alekseev. 2013. no. 2(99). Pp. 196–204 (In Russian).
6. *Trofimov I.M., Zyrin D.V.* On the prospects for the regulation of traffic in coffee networks // Innovative technologies: theory, tools, practice. 2014. Vol. 2. Pp. 102–107 (In Russian).
7. *Vikhorev N.N., Aleshin D.A.* Perspective solutions for the development of adaptive automation devices of a new generation (energy router) // Proceedings of 20th International Scientific and Industrial Forum «Great Rivers 2018». In 3 Vol. Vol. 3, N. Novgorod: NNGASU, 2018. P. 77-82 (In Russian).
8. *Sosnina E.N., Chivenkov A.I., Shalukho A.V., Lipuzhin I.A.* Development of medium voltage power flow control device // Proceedings of the 2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Sarajevo, Bosnia and Herzegovina, 2018. P. 1–6.
9. *Grebenshchikov V.I., Chivenkov A.I., Sevastyanov V.V., Zakharov I.A.* Development of control systems for intelligent regulators of electrical energy quality parameters // Transactions of NNSTU n. a. R.E. Alekseev. 2014. no. 5 (107). Pp. 106–111 (In Russian).
10. *Kubarkov Yu.P., Golubeva K.A., Makarov Ya.V.* The use of materials of distributed generations to improve the voltage levels in the intellectual power grids // Proceedings of the IX open youth scientific and practical conferences «Dispatching and control in electric power industry», Kazan, Russia, 2015. 386 p (In Russian).
11. *Korol S.* Vector control of the active corrector of power factor // Naukovipratsi Donetsk national technical university. Series: electrical engineering and energy. 2013. no. 1 (14). Pp. 118–121 (In Russian).

12. *Obukhov S.G., Chaplygin E.E., Kondratiev D.E.* Pulse width modulation in three-phase voltage inverters // Electricity. 2008. no. 7. Pp. 23–31 (In Russian).
13. *Zinoviev G.S.* Fundamentals of power electronics, 2nd ed. Novosibirsk: NSTU, 2003. 664 p (In Russian).
14. *Hase Y.* Handbook of power system engineering with power electronics applications // 2nd ed. 771 p.
15. *Vikhorev N.N., Panfilov S.Yu., Panfilov I.S., Chivenkov A.I.* Power Management System with Fuel Cells and Buffer Storage // Proceedings of Scientific and Technical Conference Actual Problems of Electric Power Industry, N. Novgorod, Russia, 2014. P. 179–182 (In Russian).
16. *Loskutov A.B., Chivenkov A.I., Antropov A.P., Suyakov S.A.* Automated load management system in the construction of intelligent power networks // Industrial Energy. 2012. no. 5. Pp. 4–10 (In Russian).
17. *Bedretdinov R.Sh., Gedifa A., Chivenkov A.I.* On the issue of power flow regulator // NovaInfo.Ru. 2016. no. 51, vol. 1. Pp. 16–23 (In Russian).

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СПОСОБ РЕГУЛИРОВАНИЯ ТОКА ЛИНИИ ЭЛЕКТРОПЕРЕДАЧИ В УЗЛЕ НАГРУЗКИ*

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Аннотация. *Статья посвящена устройствам и способам автоматизированного регулирования потоков мощности в интеллектуальных электрических сетях. Приведено описание способа векторного регулирования тока линий электропередачи, электрически объединенных в общем узле нагрузки, посредством введения добавочной э.д.с. и применения сетевого дросселя с известными электрическими параметрами. Приведена векторная диаграмма напряжений и токов энергосистемы, поясняющая принципы формирования параметров тока сетевого дросселя, установленного в регулируемой линии электропередачи. Описан виртуальный инструмент, выполненный в среде графического программирования* LabVIEW *на базе платформы* CompactRIO*,*

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используемый как элемент системы управления преобразователем напряжения, реализующим управление электрическими потенциалами на сетевом дросселе. Описано влияние начального фазового сдвига между напряжениями соединяемых узлов линий электропередачи. Приведены результаты анализа системы векторов напряжений в регулируемой энергосистеме при измерении начального фазового сдвига между напряжениями линий электропередачи и формировании заданного характера тока сетевого дросселя; показано изменение величины, генерируемой/потребляемой инвертором напряжения активной мощности.

Ключевые слова: *векторное регулирование тока, инвертор напряжения, интеллектуальная система, микросеть, сетевой дроссель, система управления, LabVIEW.*