Technological Basis for Compromise of Interests at Voltage Regulation in Electric Grids

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***Abstract*-A solution is presented to the task of voltage regulation in distributing electric grids in the situation of the contrariety of interests between power consumers, grid companies and grid generation. A system of decentralized voltage regulation of multi-agent type is offered, providing compromise voltage in power grids with the use of universal rules of behavior by every regulator with obligatory control of the mode in the adjusting area of the grid.**

***Index Terms*--Power Systems Operations and Control, Electric Grids, Smart Grid System, Decentralized Voltage Mode Control, Demand Side Management, Power Quality.**

I. Introduction

The tendency of developing distribution power grids is transition from passive grids connecting power centers with load nods (Fig. 1 a) to grids with “active” power consumers and distributed generation, participating in mode regulation of grids for achieving their own goals [8]. Conditions for this transition are economic, ecological and technological factors, inducing consumers to rationalize power consumption, to participate in the production of power and regulation of voltage.

For passive grids the basis for voltage regulation is the method of counter load voltage control consisting in increase of voltage in power centers at the load growth and its decrease at power decrease, as well as the usage of means for local voltage regulation with centrally determined operating values.

It is possible to single out three conceptions of voltage regulating, used in existing electric grids.

1) Centralized regulation in power centers (PC) with constant operating values of local regulators. This type of regulation is used in distributing grids with low automatization.
2) Centralized regulation in power centers (PC) with adaptive operating values of local regulators, at which operating values of local regulators are changed according to a set time program or controlled load.
3) Centralized regulation in the real time mode with optimization of the mode along all the grid with complete controllability.

It should be noted that these conceptions are oriented at interests of grid companies, but not the owners of distributed generations and consumers having their own interests and means of voltage regulation.

II. Goals And Criteria Of Voltage Regulation In Electric Grids

Let us set goals and criteria of voltage regulation for all participants of the process: the consumer, the distributed generation, the grid company.

The consumer.

The presence of optimal and stable voltage on the consumer feeder bars. As a rule, the issue is about a nominal voltage or a voltage reduced by 5–10%. At that its value must correspond to Standard of quality of electric power, for example, Standard EN 50160, and be sufficient for providing normal functioning of electrical equipment.

$$\Delta U = |U_i - U_{i\,des}| \rightarrow min \qquad (1)$$

where :
ΔU – voltage deviation from the desired value,
U_i – voltage value in i-th mode,
$U_{i\,des}$ – desired voltage in i- th mode.

Such levels of voltage correspond to Standard of quality and provide an optimal mode of power consumption assisting to get minimal consumption of power capacity and maximum increase of service life of the equipment. At present, the consumer can solve this task both independently, using the patented innovative device of demand side management (DSM) [2, 3, 4, 5, 6, 7, 10] for supporting a desired voltage on feeder bars, and ordering a desired voltage at the local market to subjects capable to provide a desired voltage. It can be a grid company or a small generation.

The distributed generation.

- With the absence of commercial obligations on voltage regulation – the voltage capability on the bars with minimal power losses on the section up to commercial

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metering devices of supplied power is described according to the formula (2):

$$\Delta P(U) \to min, \quad (2)$$

where :

ΔP- power losses.

- With the presence of commercial obligations on voltage regulation depending on their character – supporting stable voltage in some nods of the adjacent area of the grid, providing a permissible power mode in the nods of the adjacent area, providing minimal losses in the network of the adjacent area are described by the formulas (3), (4), (5):

$$|U_i - U_{i\,des}| \to min, \quad (3)$$

or

$$\sqrt{\frac{\sum_{i=1}^{n}(U_i - U_{i\,(des)})^2}{n}} \to min, \quad (4)$$

or

$$\Delta P(U) \to min, \quad (5)$$

The grid company.

- The provision of a necessary voltage mode in all nods of the grid, quality voltage in load nods and maximum pass of power at minimal losses ΔP in grids is described by the formulas (6), (7):

.

$$\Delta P(U) \to min\,, \quad (6)$$

$$U_i \in D \quad (7)$$

where :

U_i – voltage in the i-th nod of the grid,

D – acceptable area of voltages in the nods of the grid.

For explanation, let us turn to Fig. 1, where in principle are presented distributing electric grids:

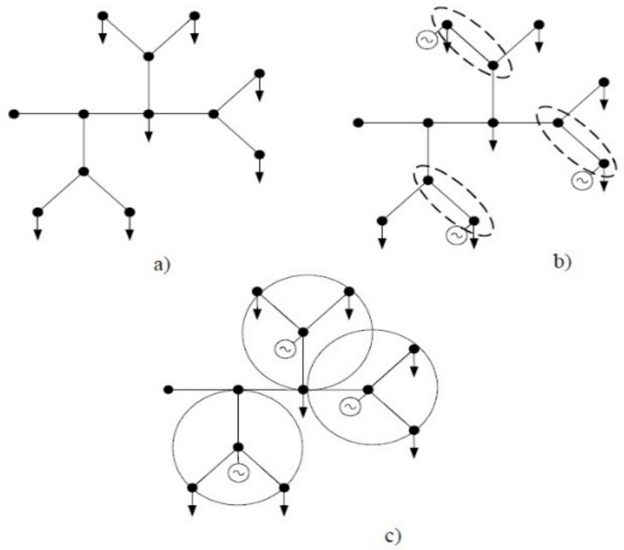

Fig. 1. Principle diagrams of passive and active distributing electric grids

a) – a passive grid, b) and c) – grids with distributed generation in which the subjects of the grid development and systems of voltage generation are different. In the case b) these are power consumers, in the case c) it is a grid company. The variant b) reflects the wish of consumers to use maximally the potential of the generation in their own purposes, and the variant c) corresponds to the purposes of the grid company when they allocate their own generation or regulated sources of reactive capacity.

Taking into account the contradiction of interests of the consumer voltage, the distributed generation, the electric grids, it is necessary to find a qualitatively new solution to the task of voltage regulation, providing their compromise. Such a decision is possible both with using special devices of demand side management, and by means of organizing compromise decentralized voltage regulation in electric grids.

III. Regulating Customers' Voltage With The Use Of Innovative Method And Device Of Demand Side Management

An innovative method [2] and device [3, 4, 5, 6, 7] of demand side management are presented which can be used to power electrical equipment of industrial company, lighting networks, communication systems, automation and remote control, residential and public buildings in order to control the quality of electricity optimization of consumption and conservation of electric power.

The innovative device of DSM has been developed and produced by the scientific industrial enterprise LLC "AVEC" (Novosibirsk, RF) under the trademark NORMEL™®© [9] and has been successfully introduced in hundreds of enterprises.

The device of DSM provides consumers with quality electric power in accordance with the Standard for quality of electric power. The functional diagram of the device is presented in Fig.2. The voltage is regulated automatically phase by phase by means of voltage regulation transformers (T_A, T_B, T_C). The winding of low voltage (LV) of these transformers is switched into the grid phase in series with the load.

The winding of high voltage (HV) is switched into regulation grid. According to the second law of Kirchhoff, the voltage on the load is equal to the vector sum of grid voltage and EMF, induced by the winding of high voltage in the winding of low voltage.

Three modes are realized:

1) voltage pull-down on loading,
2) voltage pull up on loading,
3) transit.

When the load voltage changes, the current and capacity in the load and in the grid change too enabling consumers to provide their interests, by regulating demand on power consumption.

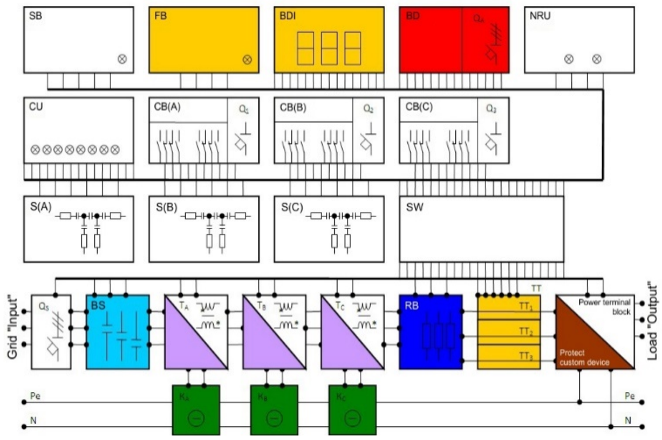

Fig. 2. Functional block-diagram of the device of DSM NORMEL™®©.

In Fig. 2:
NRU – noise reduction unit;
QS – incoming switch;
BS – block of power snubbers;
TA – transformer of phase «A»;
TB – transformer of phase «B»;
TC – transformer of phase «C»;
RB – resistant block;
TT – block of current transformers;
PCD - Protective Cutout Device up to 85 kVA or power terminal block "Load";
KA – cooler of phase "A";
KB – cooler of phase "B";
KC – cooler of phase "C";
SB – security block;
FB – feeding block;
NRU – noise reduction unit;
QS – incoming switch;
BS – block of power snubbers;
TA – transformer of phase «A»;
TB – transformer of phase «B»;
TC – transformer of phase «C»;
RB – resistant block;
TT – block of current transformers;
PCD - Protective
Cutout Device up to 85 kVA
or power terminal block "Load";
KA – cooler of phase "A";
KB – cooler of phase "B";
KC – cooler of phase "C";
SB – security block;
FB – feeding block.

The introduction of innovative technology of DSM in power grids solves the following problems: a) to save material and financial resources by 10–50%; b) to save electricity by 5 –25%; c) to provide operation of the equipment responsible for manufacturing science-intensive products, etc. [11, 12, 13, 14, 15, 16, 18, 19]. The time of recovery of outlay 1.5 Years.

IV. COMPROMISE DECENTRALIZED VOLTAGE REGULATION

In this paper the compromise voltage regulation of electric grids is realized on three technological foundations:

1) decentralization of regulation;
2) every local regulator's control of the mode of the area adjacent to the nod (fig.1 b, c), which provides necessary informativeness of the data [10];
3) the use of artificial intellect (on the ground of knowledge base and expert technologies) in regulators (agents of the systems of voltage regulation in networks), providing the completeness of the regulation process, adaptivity of regulators' behavior.

Voltages on remote ends adjoining to line nods, losses of capacity and pass of power in the adjacent area of the grid can be determined as a result of inferential measurements on local parameters for nods of generation connection on the basis of known characteristics.

The main principles of realizing decentralized voltage regulation with participation of distributed generation and consumers can be formulated in the following way:

- in normal modes of electric grids every subject has the right to pursue their own purposes of regulation, without preventing other subjects from achieving their goals;
- when there are violations of normal modes of electric grids the subjects' behavior complies with the purpose of preventing appearance of failures and of liquating arising failures;
- to achieve their goals, all subjects use their own means of voltage regulation and available local information about the mode of electric grids.

Technical realization of the regulation of the voltage in the grid assumes the use of PC algorithms of indirect measurements and artificial intellect (expert systems) in every nod of active behavior. The structure of the 'intellectual' regulator is shown in Fig.3.

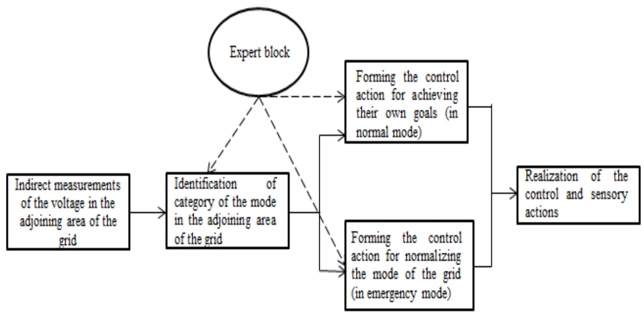

Fig.3 Regulation of voltage with control of the mode of the adjoining area according to the rules of multi–agent control.

V. MODELING VOLTAGE REGULATION WITH THE MODE OF CONTROL OVER THE ADJACENT AREA

Modeling a traditional system of voltage regulation does not present any particular problems, as it is this system that is realized in ordinary calculation complexes. Modeling multi-agent systems, including decentralized ones, with the use of mode control of adjacent area and expert blocks in subsystems of decision making, has not been realized in industrial programs yet. That is why an experimental program of mode calculations with smart local regulators was developed on the basis of creating external procedures for ordinary programs of modes calculations [10,17]. The program finds an established compromise voltage mode in the electric grid at corrected operating values of local regulators according to the underlying rules of decentralized regulation. For this, the following procedures are carried out in succession in every active nod:

1) singling out the region of electric grids adjacent to the nod with the mode controlled according to local parameters;
2) classification of the mode of the network (normal, abnormal) and introduction of controlled parameters (such as the number of active nods, voltage mode in the adjacent area of every active nod, the voltage in nods with invalid parameters, etc.) in the record;
3) correction of operating values of the regulators in the active nod in accordance with specified goals of regulation, namely:
   - maintenance of stable desired voltage on the bars of some consumers,
   - provision of admissible voltage mode in the adjacent area of the electric grid,
   - minimization of losses in the adjacent area of the electric grid.

At that, a necessary condition for every regulator is admissibility of voltage mode in all nods of the adjacent area of the electric grid.

The result of the calculation is the mode of the electric grid with operating values on regulators' voltage, as well as figures characterizing accessibility of regulation goals.

VI. Comparison Of Efficiency Of Different Conceptions Of Voltage Regulation

With multi-aim voltage regulation in electric grids by various subjects there arises some uncertainty in evaluating its efficiency, as the task becomes multi-objective and it is required to evaluate the quality of the compromise voltage mode.

In the conditions of multimode it is offered to evaluate the quality of the compromise mode by means of comparing the degrees of achieving goals of regulation in the conditions of multimode by means of different methods. At that multimode is created by setting daily graphs of load and generation. .

As an index of achieving the goals of regulation it is offered to use:

- deviations of half-value of voltages in load nods from desired values;
- root-mean-square deviation of voltages in nods from desired values;
- maximum deviations of voltages in nods from desired values;
- values of pass or losses of active capacity in the grid.

The evaluation of the quality of compromise by means of comparing degrees of achieving individual goals of subjects is realized according to the following algorithm.

1) For each conception of voltage regulation, planned modes of power consumption in grid nods and generation of active capacity by generators, they carry out the calculation of power modes with modeling the corresponding regulators.
2) For each subject they determine the coefficient of achieving goals at different conceptions of voltage regulation.

The coefficient of goal achievement for every subject is determined by the formula:

$$K_{cд} = \frac{\sum_{i=1}^{k} t_i}{T}, \quad (8)$$

where

$\sum_{i=1}^{k} t_i$ – duration of modes, in which the goal of a subject is achieved (hours),

k – the number of modes in which the goal of a subject is achieved,

T – the general duration of analyzed modes (hour).

3) General indexes of satisfaction with voltage mode are calculated by all the subjects. Thus, to evaluate the degree of satisfaction with voltage mode by consumers there is used a number of load nods (generation) of the grid, in which the coefficient of goal achievement is higher than the set value (for example, 0,5).
4) Conclusions are made on the basis of results obtained.

VII. Example of Calculation of Modes at Different Methods of Voltage Regulation and Comparison of Their Efficiency

In order to evaluate the efficiency of decentralized voltage regulation when the generation renders commercial services on voltage regulation to the grid company, a research was carried out in the fragment of the scheme of high voltage distributing grid with a small generation of *Surgut power system* (RF). The grid contains three objects of the small generation, transmissing and distributing grids with the voltage 110, 35 and 6 kV. While modeling the load, their statistic characteristics concerning voltage were taken into account.

The evaluation of the efficiency of voltage regulation was carried out by means of three different methods:

1) *CR TCUL* – Centralized regulation only by means of (the situation was modeled when the distributed generation (DG) is not controlled by a grid company and supports nominal voltage on its bars;
2) *CR TCUL + DR* – centralized regulation by means of devices of regulating transformers on load TCUL and DR – distributed generation (a global optimization was modeled with complete observability and controllability of the grid);
3) *DR* – decentralized regulation according to the criterion of minimum losses of capacity in the grid (DG – distributed generation renders services on reduction of losses to the grid company GC).

Modeling was realized with the help of a created program according to the criterion of minimum losses of active capacity in the grid in the adjacent areas of the grid.

The comparison of the methods of voltage regulation was realized on the basis of results of modeling typical modes of power grids with due consideration of different methods of voltage regulation at set load graphs.

Different methods of regulation were compared in respect to the quantity of summary pass and losses of power along the grid (Table 1).

TABLE I
LOSSES OF POWER IN CONTROLLED AREAS AND IN ELECTRIC GRIDS ON THE WHOLE FOR DIFFERENT METHODS OF VOLTAGE REGULATION

Area adjacent tothe nod with DG	Day losses of power, MWt*h		
	Regulation method		
	CR TCUL	CR TCUL+DR	DR
1	22,188	21,154	21,276
2	15,848	13,989	15,162
3	4,538	4,504	4,399
All electric grid	122,685	107,726	111,716

The optimal voltage mode found with the help of the developed program with decentralized regulation is close to the result of global optimization, but does not require global observability and controllability of the grid. Besides, the pass of power in the grid is increased in the interests of the network company.

VIII. CONCLUSION

Methods of decentralized voltage regulation in distributing electric grids are offered, that allow to provide a compromise mode of voltage meeting the interests of different subjects of the grid. Rules and algorythms are developed to realize smart decentralized voltage regulation with the control of the adjacent area of electric grids on the basis of indirect measurements for different regulation criteria.

A special program is developed for modeling the decentralized voltage regulation with the control of the adjacent area of electric grids.

A procedure for evaluating the quality of compromise voltage modes is offered that is based on comparing satisfaction factor of subjects of the grid in achieving their individual goals.

The fulfilled calculation confirms the efficiency of the offered methods of decentralized voltage regulation and their ability to provide compromise voltage regulation in the interests of all the subjects participating in the process : the electric grid company, consumers, the distributed generation.

REFERENCES

Dissertations:

[1] Klavsuts I.L., "Methods of demand side management in the power system," Ph.D. dissertation, Dept. Management Systems and Energy Economics, Novosibirsk State Technical University, 1999.

Patents:

[2] Feigin L.Z , Levinson S.V., Klavsuts D.A. et al "Method and Apparatus for Regulating Voltage", U.S. Patent № 7 816 894 B2, filing date 06.20.2007 date of publication - October 19.2010.

[3] Feigin L. Z. , Levinson S.V., Klavsuts I. L. et al "AC voltage regulator with elements of protection and backup", RU patent № 2377630 C1 Russian Federation from 16.09.2008

[4] Feigin L.Z., Levinson S.V., Klavsuts I.L. "Alternating voltage stabilizer with protection elements" The international application for the invention № PCT/RU2009/000441 (PCT) of 16.09.2008.

[5] Feigin L.Z., "The device of voltage control of electricity-generating equipment" RU patent № 120499 Russian Federation from 23.09.2011

[6] Feigin L.Z., Feigin I.L., Klavsuts A.B., Klavsuts I.L. "The device (utility model) of modes control of the work of asynchronous motor" The application for the invention № 2014116596/07(026157) от 25.04.2014.

[7] Feigin L.Z., Feigin I.L., Klavsuts A.B., Klavsuts I.L. "The device (utility model) of modes control of the work of asynchronous motor" The international application for the invention № PCT/RU2014/000669 of 09.09.2014.

[8] Fishov A.G., Denisov V.V., Kobets B.B., The method of voltage control of the node of electric grid, Patent of SU № 1372465, valid from 8.07.1993

[9] Certificate on the trademark № 43 6079, trademark owner LLC "AVEC"/ Russian Federation from 7.05.2010

Papers:

[10] Fishov A.G. Smart electric grid – revolution in relations of subjects and mode regulation of electric energy/Collection of reports of the 3-d international scientific-technical conference. Yekaterinburg October, 22-26, 2012. V.1. P. 91-97.

[11] Klavsuts D.A., Klavsuts I.L., Levinzon S.V. "Innovative method of demand side management" / 46-th International Universities' Power Engineering Conference - UPEC2011, hosted by South Westphalia University of applied Sciences, Soest, Germany \ Section- Innovation and Future Power System\\ 5th - 8th September 2011.

[12] Klavsuts D.A., Klavsuts I.L., Levinzon S.V. "New Method for Regulating Voltage an Ac Current" / 46-th International Universities' Power Engineering Conference - UPEC2011, hosted by South Westphalia University of applied Sciences, Soest, Germany \ Section-Section- Power Conversion\\ 5th - 8th September 2011.

[13] Klavsuts I.L., Levinzon S.V., Klavsuts D.A. "Integration Innovative Method Of Demand Side Management In Smart Grid" 47th International Universities' Power Engineering Conference – UPEC 2012, hosted by Brunel University Institute of Power Systems in the School of Engineering and Design at Brunel University, London, UK \\ 4th - 7th September 2012.

[14] Klavsuts D.A., Klavsuts I.L., Rusin G.L. "Aspects Of Evaluating The Efficiency Of Introducing Innovative Method And Technology Demand Side Management In Smart Grid System" \ 48 th International Universities' Power Engineering Conference – UPEC 2013, hosted by Dublin Institute of Technology, Ireland \\ Section- Smart Drids \\ 2th - 5th September 2013.

[15] Klavsuts I. L., Klavsuts D. L., Rusin G. L., Mezhov I. S / Perfecting business processes in electricity grids by the use of innovative technology of demand side management in the framework of the general conception of smart grids /. // 49 International Universities power engineering conference (UPEC), Romania, Cluj-Napoca, 2–5 Sept. 2014. – IEEE, 2014. – 4 p. – ISBN 978-1-4799-6556-4.

[16] Klavsuts D. A., I. L. Klavsuts, T. V. Avdeenko / Providing the quality of electric power by means of regulating customers' voltage/ / // 49 International Universities power engineering conference (UPEC), Romania, Cluj-Napoca, 2–5 Sept. 2014. – IEEE, 2014. – 4 p. – ISBN: 978-1-4799-6556-4. - (UPEC).

[17] Fishov A. G., Klavsuts D. A., Klavsuts I. L. / Multi-Agent Regulation of Voltage in Smart Grid System with the Use of Distributed Generation and Customers [Electronic resource] // Electrical Engineering, Energy, Mechanical Engineering – EEM 2014, pp - 761-767 - Mode of access: http://www.scientific.net/AMM.698.761.

[18] Klavsuts D.A., Klavsuts I.L. Development of systems of integrated regulation of energy saving in industrial enterprises./"Scientific and technical gazette of S.-PSPU" Series "Economic sciences", №5, Saint-Petersburg- 2010. P. 78-82.

[19] Khayrullina M. V. Innovative territorial clusters as instruments of Russian regions development in global economy [Electronic resource] / // Procedia Economics and Finance. - 2014. - Vol. 16. - P. 88-94. - Mode of

access:http:// http://www.sciencedirect.com/science/journal/22125671/16/supp/C.
Title from screen. - DOI:10.1016 / S2212-5671(14)00778-3.