Decentralized Smart Multi-Agent Voltage Regulation in Electric Grids. Ideology and Modeling.

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***Abstract*—The paper presents the principles of constructing Decentralized Multi-Agent System of compromising regulation of voltage in electric grids with the voltage of 0,4 – 110 kV by distributed means of compensation of reactive capacity, the possibilities of its modeling and the results of research of its operating capability and efficiency on a concrete example, including the one with the use of innovative patented devices of Demand Side Management – the Normalizer of AC voltage.**

Keywords—Demand Side Management, Technological Innovation, the Normalizer of AC Voltage, Power Quality, Electric Grids, Smart Grid System, Distributed Generation, Voltage Control, Energy Efficiency, Decentralized Multi-Agent Systems.

I. Introduction

At present the independent (active) behavior of consumers of electric energy and distributed generation, contributing into the increase of the efficiency of functioning the energy system on the whole, is directly connected with creating numerous areas of local mode regulation of the work of the electric grid with distributed regulation. The basis of their formation for voltage regulation is the locality of balances of reactive power. The cause lies in the fact that it is impossible to transfer it over large distances due to emerging excessive losses of voltage and active power. At the same time, there appears necessity of a qualitatively new solution of voltage regulation in electric grids, which takes into account, among other things, the difference in goals and means of management for different subjects.

In a number of works created in this direction [15, 16] they have offered to use hierarchical multi-agent systems (MAS) with a central agent, breakdown of which makes the whole power supply system unworkable. It makes urgent the development of decentralized multi-agent systems (DMAS) without any coordinating level.

The key idea of this paper is in the construction and research of one-level DMAS of compromising voltage regulation in active electric grids, in which every agent has sufficient knowledge of mode parameters and the ability to coordinate his actions with neighboring agents in the zone of his mode impact. At the same time every intellectual regulator, included into DMAS, uses exclusively local mode parameters, is a bearer of interests of the subjects of all the process of energy supply (network company, small generation, consumer), and the voltage mode is determined as a compromise of their interests [13, 17, 18, 19]. At that the consumers, that have no means of influence on the general mode of electric grid, are able to solve the problem of supporting a desired voltage with the help of innovative-patented devices of Demand Side Management – Normalizers of AC voltage, which gives them qualities inherent with regulators of electric grid modes [3, 4, 5, 6, 7, 8, 10, 11, 12, 14].

II. Building a Decentralized Multi-Agent System

A. Terminology of DMAS for the following description

Agent – an intellectual voltage regulator, working in the node of electric grid in the interests of one of the subjects of small generation of the process, realized collectively and following the rules, common for all the agents [19].

Controlled area – the zone adjacent to the agent of the electric grid area with controlled voltage mode.

Base agent – the agent in whose controlled area threshold increase/decrease of voltage happened, initiating the actions of DMAS.

Adjacent agent – the agent with whose node there is a direct electric connection.

Participant – the agent participating in the collective process of voltage regulation.

Notification – the agent's message to a neighboring agent about a state class of his control zone and the character of planned actions.

Request – the agent's message to a neighboring agent containing the request for help.

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Permission – the message sent by an agent in response to a request, containing permission or prohibition of actions in response to the request, confirmation or refusal to give help.

B. *The principles of building DMAS*

- The equality of agents as part of DMAS, which contributes to non-discrimination compromise on the voltage mode of electric grid;
- The locality of mode control (the agent has at his disposal mode parameters only in the controlled area. which limits are determined by the possibilities of indirect measurements of voltage in branch lines of electric grids);
- Minimum of information exchange between agents (for data transfer low-cost, but low-speed channels are used to transfer data along the lines of electricity transmission);
- The locality of information exchange (agents exchange messages only with the agents directly connected with lines of electricity transmission).

C. *The basic principles of behavior of DMAS agents*

The right of the agent of the subject to follow the goals of the subject in normal modes of electric grid, without preventing other DMAS subjects from achieving their goals. For this, every agent efficiently uses his own means of voltage regulation, available local information about the mode of the grid, coordinates his actions with adjacent agents and, if necessary, gives and gets mutual help.

Subordination of goals of all agents for preventing the development and elimination of all emerged violations of normal mode of electric supply.

III. THE RULES OF AGENTS' ACTIONS IN THE DECENTRALIZED MULTY-AGENT SYSTEM

The decision of DMAS agents on the change of balance of reactive power in the controlled zone, transformation coefficients is based on a universal classification of state classes of electric grid on voltage: (1) normal optimal; (2) normal; (3) admissibly increased; (4) admissibly reduced; (5) urgently increased; (6) urgently reduced; (7) bilateral violations (with increased and reduced voltages).

A. *Rules of making decisions on the correction of settings of means of compensating reactive power by DMAS agents*

If the state class of electric grid on voltage is (1), and the goal of regulation is to reduce losses in the area of electric grid, a probe change of setting in any direction is made and the change of losses or power transfer in the adjacent area of electric grid are determined [25].

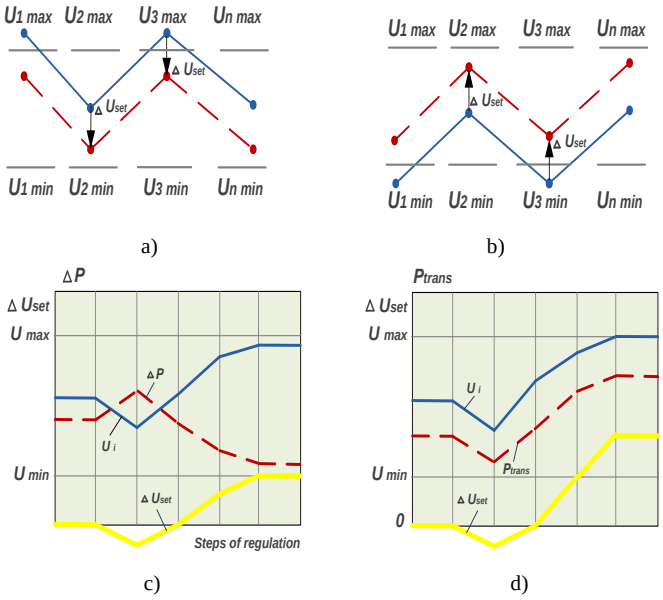
If, at that, decrease or increase of power transfer in the adjacent area of electric grid occurs, then they continue to change the setting in the adopted direction until the achievement of zero increment of losses or power transfer or maximum or minimum admissible voltages in controlled nodes in the adjacent area of electric grid.

If at the probe change of the setting there occurred the increase of losses or the decrease of power transfer in the adjacent area of electric grid, then they change the direction of the setting and continue to change the setting in the new direction until the achievement of zero increment of losses or power transfer or maximum or minimum admissible voltages in controlled nodes in the adjacent area of electric grid (Fig. 1 c, d).

If the state class of electric grid on voltage is (3) or (5), then the setting of the regulation of the source of reactive power is reduced (Fig.1 a).

If the state class of electric grid on voltage is (4) or (6), then the setting of the regulation of the source of reactive power is increased (Fig.1 b).

If the state class of electric grid on voltage is (7), then the setting of the regulation of the source of reactive power is left unchanged, but they request for the help of adjacent agents for normalizing the voltage.



Notes:
ΔUset – the setting of the regulator;
Ptrans – the change in the size of transferred electric power;
ΔUi – factual voltage value;
ΔP – losses of active power.

Fig. 1. Situational adjustment of the setting of voltage control in controlled nodes of the adjacent area of electric grid.

If at the adjustment of the settings in state classes (3) - (6) the losses of power decrease or transfer of power increases, then the adjustment of settings is continued in the same direction until the achievement of maximum or minimum admissible voltages in any of controlled nodes or till the disappearance of increments of losses or power transfer in the controlled area of electric grid [26].

B. *The rules of coordinating the interaction of adjacent DMAS agents*

The coordination of the interraction of adjacent (neighboring) DMAS agents is realized with the goals of

coordinating their actions while normalizing the voltage mode of electric grid (the introduction of the mode of the controlled grid zone into the admissible area) and the optimization of voltage mode of the electrci grid. For the coordination of their actions the agents exchange, as needed, messages with notifications, requests or permissions.

The agent planning to take an action notifies neighboring agents about its aim or character.

At the absence of his own possibility to normalize the voltage mode in his area the agent requests for the help of neighboring agents.

The agent, receiving the notification about the planned action of the neighboring agent, prohibits it if he has no possibility to compensate negative consequences from the actions of the neighboring agent in the controlled area.

The agent fulfills the actions after receiving the permission for their fulfillment from neighboring agents and acts till the achievement of his aims or till the reception of prohibition to continue them from neighboring agents.

The agent notifies neighboring agents about the completion of the actions.

C. The exchange of messages between adjacent DMAS agents

For the coordination of the interaction, DMAS agents use the following messages, transferred by means of a certain code:

1.“*The mode is normal, I am idle, ready to help”.*

2.“The mode is admissibly increased, losing voltage, prohibit the increase of voltage by adjacent agents”.

If there is no possibility to reduce the voltage on his own, then: “*Request to help reduce voltage”.*

3.If the mode is admissibly reduced, then:”Increasing voltage, prohibit the decrease of voltage by adjacent agents”.

If the resource of regulation is exhausted, then “Request to help *increase voltage”.*

4.“The mode is urgently increased, reducing urgent voltage, prohibit the increase of voltage by adjacent agents”.

If there is no possibility to reduce the voltage on their own, then: *“Request to help reduce voltage urgently”.*

5.“The mode is urgently reduied, increasing voltage, prohibit the decrease of voltage by adjacent agents”.

If the resource of regulation is exhausted, then *“Request to help increase voltage urgently”.*

IV. The Algorithm of Actions of Agents of the Decentralized Multi-Agent System with Regard to the Interaction with Neighboring Agents

If the action of neighboring agents of the decentralized multi-agent system significantly influences the mode of the zone of electric grid controlled by them, then each of the agents coordinates his actions with neighboring agents. In accordance with the unified classification of state classes of electric grid on voltage, presented above (Part III), a DMAS agent acts according to the following algorithm:

1. Identifies the state class in their controlled area.
2. Checks and analyzes messages from neighboring agents.
3. Determines necessary actions.

In normal mode (1), (2):

- allows actions on notifying neighboring agents;
- in response to requests of neighboring agents gives help to normalize voltages of adjacent areas of the grid;
- if there are no requests about the normalization of voltages in adjacent areas of the grid, the agent, with notification and permission of neighboring agents, realizes the optimization of voltage modes in his controlled area.

In the mode of admissible deviations (3), (4):

- prohibits neighboring agents to realize actions, which deteriorate the voltage mode in the controlled area of the grid;
- permits neighboring agents to realize actions, which improve the voltage mode in the controlled area of the grid;
- determines, coordinates with neighboring agents and, after receiving the permission, realizes his own actions on normalizing the voltage mode in the controlled area of the grid;

In the mode of admissible deviations (5), (6):

- prohibits neighboring agents to realize actions, which deteriorate the voltage mode in the controlled area of the grid;
- requests for help of neighboring agents in normalizing voltages in the controlled area of the grid;
- determines and realizes his own actions on normalizing the voltage mode in the controlled area of the grid.

In the mode of bi-lateral violations (7):

- prohibits neighboring agents to realize actions, which deteriorate the voltage mode in the controlled area of the grid;
- Requests for help of neighboring agents in normalizing voltages in the controlled area of the grid.

V. Modeling Modes of Electric Grids with Multi-Agent System Votage Regulation and Research of its Efficiency on the Example of Distributed Electric Grid with Small Hydroelectric Power Station of Kazakhstan

Modeling a traditional system of voltage regulation in electric grids, in which act regulators with constant settings, determined in a centralized way for all the variety of modes, does not present special problems, as it is this system that is realized in ordinary computing systems.

At present, there are no programs modeling modes in electric grids with DMAS mode regulation, which does not allow to analyze the efficiency of such regulation and use this technology in practice, that is why the authors developed an experimental computer program (in the programming language VBScript in soft environment of PCC RastrWin) for calculating the modes with smart local regulators by creating external procedures for ordinary programs of mode calculations. The program finds an established compromise voltage mode in the electric grid while adjusting settings of local regulators according to set rules of centralized regulation.

The research of the efficiency of the decentralized multi-agent voltage regulation and the check of working capacity of the developed modeling program have been carried out on the example of distributed electric grid with small Hydroelectric power station (HEPS) of Zhambyl region of Kazakhstan. The grids have long HVTL with voltage of 35 kV and distributed small generation (Fig. 2).

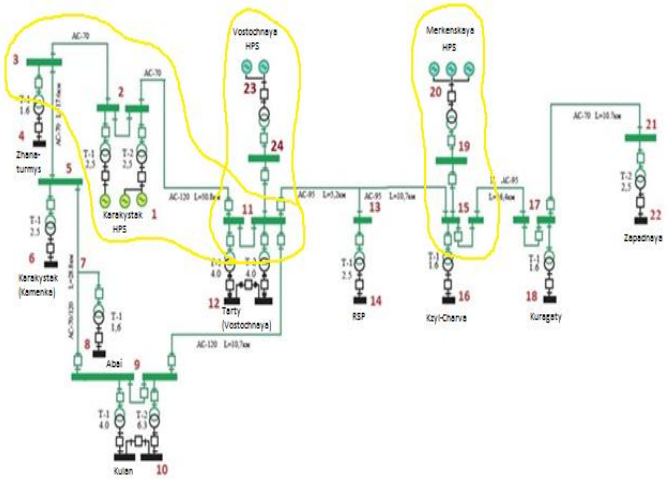


Fig. 2. A fragment of distributed electric grid with the voltage of 35 kV with three DMAS agents - small Hydroelectric power station of Zhambyl region of Kazakhstan

The deployment of small generation in distant parts of the distributed electric grid has a number of advantages:

- it increases the reliability of energy supply to consumers (the level of diversification of electricity supply);

- it reduces the losses of active power and cross-flows of reactive power;

- it supports the stability of voltages in nodes owing to possibilities of theses generators to generate reactive power.

Every agent (L_j) controls the area of electric grid, adjacent to him (A_i).

Typical processes of voltage regulation in electric grid (Fig.2) with regard to DMAS agents' while introducing the mode in the admissible area and optimizing the mode in relation to capacity are presented in Fig. 3 and Fig. 4.

One can see that agents 1 and 3, regulating voltage in their controlled zones, violate admissible limits of Agent 2, get prohibition from him to increase voltage. After Agent 2 cancels the prohibition, Agents 1 and 3 continue to regulate voltage. The process is completed after introducing voltage mode of electric grid to the admissible area.

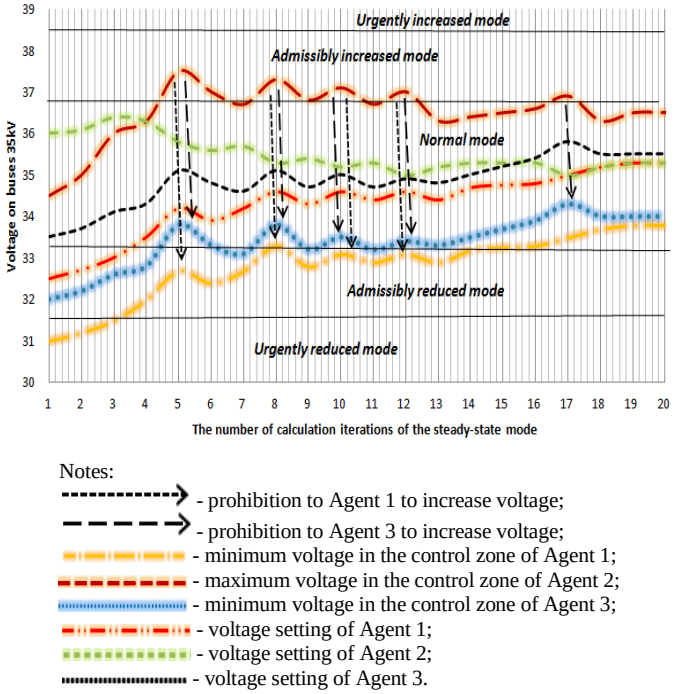


Fig. 3. The process of introducing a voltage mode with regard to interaction of DMAS agents.

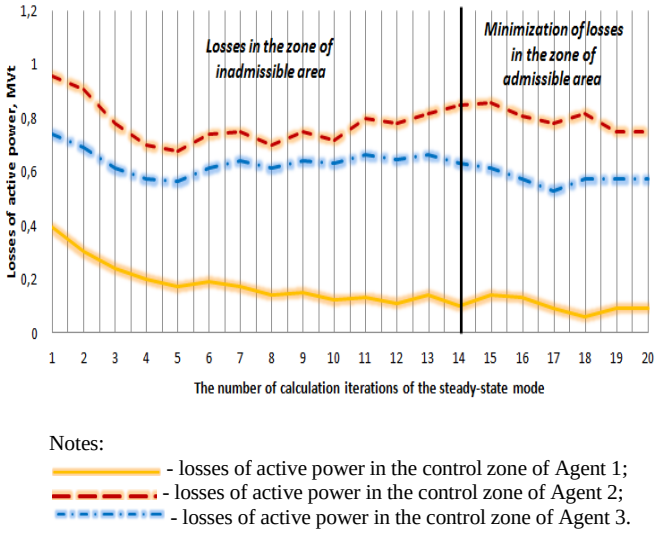


Fig. 4. The process of voltrage mode regulation with the optimization of losses in control zones of DMAS agents

After the normalization of the mode the goal of regulators became the minimization of losses. Fig. 4 presents the process of coordinated optimization of losses in controlled zones with

regard to interaction of agents on preventing the voltage outcome from the admissible zone.

VI. The Sysytem of Supporting Standartized Parameters of Electric Grids on Consumers' Buses with the Voltage of 0,4 kV on the Basis of the Technology of Voltage Normalization

In papers [20-32] the results of realized research are described, as well as many-year experience of practical use of the patented method and devices of Demand Side Management – normalizers of AC voltage, developed and produced under the trademark NORMEL™®© of scientific industrial company LLC "AVEC" (Novosibirsk, RF) [3, 4, 5, 6, 7, 8, 10, 11, 12, 14].

The use of the technology of voltage normalization allows to get the voltage of 0,4 kV on buses, optimal for consumers irrespective of the mode of supply net.

Technical decisions, on which the development of the normalizers of AC voltage was based, as well as the used system of settings of the regulation of phase voltages levels, are designed to achieve the goal of supporting the voltage levels at inputs of switched consumers within the limits permitted by normative documents, regulating the main electrical parameters, for example [1].

The existing today systems for stabilizing voltage of 0,4kV in electric grids are not used on a large scale due to their high costs, accounted for by their complicated construction, which, at its turn, results in insufficient reliability. The costs of the stabilization systems is affected by their excessive functionality: exceedingly wide range of regulation, precision level of input voltages, the presence of additional nodes designed for providing sinusoidality of electrical parameters of AC voltage grids.

In spite of the fact that the sphere of use and the switch points (integration) of stabilizers and normalizers fully coincide, their functional and the aims of usage differ significantly.

Stabilizers are designed for supporting output voltages at a set level with input voltages being within the limits of their working range.

The normalizer, getting its input voltage within the framework of its working range, regulates input voltage within the limits of the corridor of deviations of phase voltages, (admitted by Standard [1]) and allows to support voltage on consumers' buses in the zone of desired reduced voltage, which leads to the economic effect of the use of the Normalizer, caused by the decrease in the consumption of electric power, switched to the normalizer of the load.

Differing from well-known devices for regulating AC three-phase voltage, the normalizer realizes the function of regulating voltage without the commutation of power supply circuits, that is it does not contain kinematic nodes. The normalizer does not contain power semi-conductor elements in its construction either and is not a device, introducing violations into the sinusoidality of the curve of electric power.

The realized research and practical experience show that it is advisable to consider the normalizer of AC voltage as a device designed for voltage regulation with the effect of reduction of excessive active power, consumed by the load. The joint practical use of normalizers with a commonly known system of compensation of reactive power on the basis of compensator devices, revealed their complementarity and the synergy of the obtained economic effect.

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Conclusion

The principles of building a decentralized multi-agent system of regulating voltage mode in electric grids with a multitude of distributed controlled compensators of reactive power and voltage normalizers of distributed small generation are offered.

For modeling and research of DMAS of voltage regulation in electric grids, the algorithm in the software environment of PCC RastrWin has been developed and realized.

The working capacity of DMAS and the developed program have been checked on the example of the existing electric grid. The results of the calculations correspond to expectations both in the part of possibility and efficiency of decentralized voltage regulation and in the part of modeling similar systems by means of modification of existing calculating complexes.

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