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OPTIMAL CONTROL OVER THE DISTRIBUTE ELECTRIC ENERGY SOURCES WITH ASYNCHRONOUS GENERATORS BY *SMART GRID*

The paper, in accordance with the conception of Smart Grid, considers some questions of formation of intellectual electric nets, the solution of which will allow to create the prerequisites for efficient use of dispersed sources of electric energy.

Key words: *dispersed sources of electric energy, wind-electric power station, Smart Grid, asynchronous generators.*

Introduction

Modern tendencies to decentralization of electric power supply, caused by an increase in costs of traditional fuel resources, result in increase in quota of dispersed production of electric energy due to the dispersed sources of electric energy (DSEE) and lead to the complication in planning the modes of electrical power systems (EPS) and their operating control. Apart form that, the combination of the above processes with the reformation of the power engineering economy – introduction of bilateral agreements – makes it practically impossible to organize the efficient EPS functioning without the improvement of their informational infrastructure with gradual transition to the concept of the intellectual electric nets *Smart Grid* [1].

Modern realizations of the *Smart Grid* elements in different countries [2, 3] allow to state that technologically such systems create prerequisites for efficient use of DSEE for the solution of local (ensuring maximum income from their operation) as well as system-wide (increase in functioning quality of distribution electric nets) tasks. According with the Smart Grid [2] concept, all the participants and the organizers of electric energy exchange process in EPS may be divided between the spheres of influence, or, so- called domains (Fig. 1).

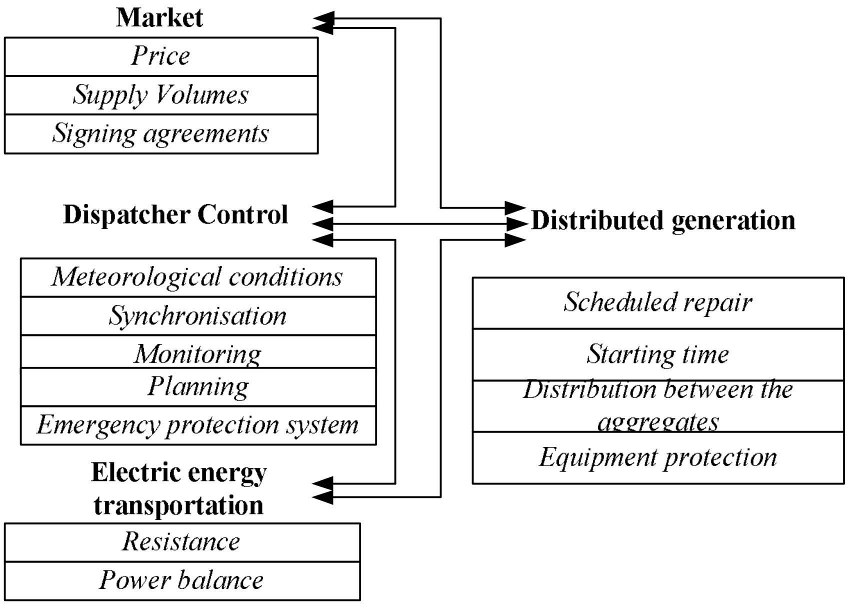

Fig. 1. Main function of some domains in Smart Grid, related to the generation of electric energy due to the dispersed sources

Main function of domains, related to the operation of the renewable energy source in the distribution net, are presented in fig.1. Domain “Distributed generation” unites the electric power station, including DSEE of different types, which supply energy to the distributive nets. Its main function is to improve the efficiency in electric energy production. Peculiar difficulties arise during the optimization of functioning of wind farms and solar power plants, since their modes are determined by stochastic influence of the environment and it is almost impossible to store the initial energy (as, for instance, in case with small hydroelectric power stations). The described domain relates by the information flows to the controlling domains, organization of electric energy market functioning as well as the domain of electric energy transportation. The informational relation to the latter is the most important one since the transport domain together with the other domains performs information generation and processing, protection of the equipment, functioning optimization etc.

Information relations on the level of power system dispatching allow to consider the operating peculiarities of different electric stations, using the renewable energy sources, especially wind farms and solar power plants, where the process of electric energy production has some peculiarities of technical and organizational character. The information relations with the domain "Market" allow to co-ordinate tasks of operative optimization of EES with the demanded volumes of electric energy supply under the conditions of bilateral agreements, electric energy market situation, price correction for the electric energy sully and other system services.

Optimal control over the distributed energy sources

Optimization of DSEE functioning is made by planned succession of controlling influences, received by solution of the corresponding optimization tasks with the integral quality criterion the specific time interval. Typical task of ensuring the efficient use of distribution sources, which is aimed at maximum income from the realization of the produced electric energy [4], may be presented as follows. The set aggregate of *n* controlled DSEE, for instance, small hydroelectric power stations, and *m* conditionally controlled wind farms and solar power plant, the mathematic expectation of the total active capacity of which makes up:

$$\mathrm{M}_{\mathrm{VAR}}(\mathrm{t}) = MBEУ\{\mathrm{P}(\mathrm{t})\} + \mathrm{M}_{CEC}\{\mathrm{P}(\mathrm{t})\}. \quad (1)$$

Capacity of small hydroelectric power stations are accepted as control variables, since they are the most stable and are not subject to environmental influence. The losses from the power flows in conditionally controlled DSEE and small hydroelectric power stations in the distribution net are functions from generation capacities and must be considered in the target function. The configuration of small hydroelectric power stations equipment, which is switched on within 24 hors and its energy characteristics are constant. It is necessary to find such modes of small hydroelectric power stations (SHES) $P_i(t)$ on time interval [t_0; t_k], which would ensure the maximum income from the realization of electric energy DSEE on the electric energy market:

$$\int_{t_0}^{t_k} \text{ц}(t)\left[\sum_{i=1}^{n} P_i(t) + M_{VAR}(t) - k_{\text{ц}}(t)\cdot\Delta P_{\text{РДЕ}}(t)\right]dt \to \max, \quad (2)$$

where $k_{\text{ц}}(t)$ – weighting coefficient, determined by the correlation of the release tariff for DSEE ц(t) and costs of the capacity losses for this distribution net ц_0; $\Delta P_{РДЕ}(t)$ – constituent of capacity losses in the distributive electric nets, stipulated for by DSEE functioning; $P_i(t)$ − active capacities of generation of small hydroelectric power stations.

$$\varphi(t) = \sum_{i=1}^{n} P_i(t) + \Delta P_{\text{ЦЕ}}(t) - P_{н\Sigma}(t) - \Delta P_{\Sigma}(t),$$

where $\Delta P_{\text{ЦЕ}}(t)$ − capacities due to centralized electric power supply; $P_{н\Sigma}(t)$ − total load of the set aggregate of consumers; $\Delta P_{\Sigma}(t)$ − overall loss of capacities in the electric nets.

The solution of the task is considered in [4]. As the solution, using the principle of maximum of integral functions of Pontrjagin, there had been received the condition of optimal functioning of DSEE as correlation:

$$z_{\text{EP}}^{*}(t)=\frac{\lambda_1 q_1^{*}(t)+q_1^{\text{ш}}}{1-\sigma_1^{*}(t)}=\frac{\lambda_2 q_2^{*}(t)+q_2^{\text{ш}}}{1-\sigma_2^{*}(t)}=\ldots=\frac{\lambda_n q_n^{*}(t)+q_n^{\text{ш}}}{1-\sigma_n^{*}(t)}, \tag{3}$$

where $z_{\text{EP}}^{*}=z_{\text{EP}}+z'_{\text{EP}}$, $\text{q}_{\text{i}}^{*}=\text{q}_{\text{i}}+\text{q}'_{\text{i}}$, a $\sigma_{\text{i}}^{*}=\sigma_{\text{i}}+\sigma'_{\text{i}}$ on condition that

$$\begin{cases} z_{\text{EP}}=-\text{ц}(t);\; z'_{\text{EP}}=\dfrac{d\text{ц}(t)}{dt}, \\ q_i=\dfrac{\partial Q_i}{\partial P_i};\; q'_i=-\dfrac{d}{dt}\dfrac{\partial Q_i}{\partial P_i};\; q_i^{\text{ш}}=\dfrac{\partial \text{Ш}_i^{P}}{\partial P_i}+\dfrac{\partial \text{Ш}_i^{\text{H}}}{\partial P_i};\; \sigma_i=k_{\text{ц}}\dfrac{\partial \Delta P_{\text{РДЕ}}}{\partial P_i};\; \sigma'_i=-k_{\text{ц}}\dfrac{d}{dt}\dfrac{\partial \Delta P_{\text{РДЕ}}}{\partial P_i}, \end{cases} \tag{4}$$

where Q_i – current water losses on the i-th small hydroelectric power stations; Ш_i^{P}, Ш_i^{H} – penalty functions, introduced into the target function to consider the restrictions of the kind of inequality, correspondingly on capacity of the i-th DSEE($P_i^{\min}\le P_i(t)\le P_i^{\max}$) and on the pressure between the pools ($H_i^{\min}\le H_i(t)\le H_i^{\max}$) in case, when the i-th DSEE is a small hydroelectric power stations.

Considering the stochastic character of the external action of the environment, as well as the fact that the parameters of the generation of some dispersed sources, in particular of wind farms and solar power plants, are presented in (1) and (2) by mathematic expectations, the determination of the tatter require the current and predictive (up to four 24 hours) meteorological parameters. The values of the latter are ensured by domains “Electric energy transportation” and “Dispatcher control”. The results of meteorological parameters prediction are used for the evaluation of the perspective electric energy consumption, necessary for the consideration of the restrictions on the electric energy balance, as well as the determination of losses constituent and its sensitivity to the change of P_i in (3) and (4). Proceeding from this, the concept of *Smart Grid* stipulates for the development of the generalized mechanism for prediction of the weather condition for planning the consumption and limit volumes of electric energy production.

Evaluation oft he capacity losses, stipulated for by the functioning of DSEE

Decentralization of electric power supply with the signing the bilateral agreements between the representatives of the DSEE owners and electric energy consumers (or state enterprise “Electric energy market”) constrain the functioning of domains “Electric energy transportation” and “Dispatcher control”.

As it was stated above, the main factor of the DSEE operation efficiency is the economic effect from the realization of the produced electric energy. Depending on the operating conditions of such stations (agreement conditions for the connection to the nets of the mediator as well as bilateral agreements) the criteria of optimal control over the modes of DSEE (2) may consider the losses of electric energy for its transportation as the stable rate in money or natural expression, or as the analytical calculations with the consideration of the operation mode and topology of electric nets (EN). The latter requires choosing losses from the aggregate balance losses of electric energy, which are ensured by the information subsystem of the domain “Electric energy transportation” stipulated for by the functioning of separate DSEE or groups of them $\Delta P_{РДЕ}(t)$, often as the mathematical expectation $\text{M}_{\Delta P_{РДЕ}}(t)$.

The latter is possible under condition of using methods for distribution of capacity losses, reduced in [5]. In practice there is a number of methods, among which it is necessary to emphasize the method for the determination of complex matrix of factors of redistribution of capacity losses [5]:

$$\Delta\mathbf{P}_{\mathbf{в}}=\text{Re}\left(\dot{\mathbf{T}}_{\text{k}}\dot{\mathbf{S}}+\dot{\mathbf{T}}_{\text{зр}}\right), \tag{5}$$

where $\dot{\mathbf{T}}_{\mathrm{k}}$ – matrix of factors of capacity losses redistribution in the electric nets brunches depending on capacities in their hubs with the consideration of transformation factors of coupling transformer; $\dot{\mathbf{T}}_{\text{зр}}$ – column vector of capacity losses in brunches of the schema from electromotive force of non-balanced transformation factors; $\dot{\mathbf{S}}$ – column vector of loading (generation) in hubs of the equivalent circuits.

Dimension $\dot{\mathbf{T}}_{\mathrm{k}}$ is stipulated by the number of independent hubs, without the basic one, and a number of brunches in the EM circuit:

$$\dot{\mathbf{T}}_{\mathrm{ki}} = (\dot{\mathbf{U}}_{\mathrm{t}}\mathbf{M}_{\Sigma\mathrm{ki}})\widehat{\mathbf{C}}_{\mathrm{ki}}\dot{\mathbf{U}}_{\text{д}}^{-1};$$
$$\dot{\mathrm{T}}_{\text{зpi}} = (\dot{\mathbf{U}}_{\mathrm{t}}\mathbf{M}_{\Sigma\mathrm{ki}})\widehat{\mathbf{D}}_{\text{бi}}\widehat{\mathbf{U}}_{\text{б}}, \tag{6}$$

where $\dot{\mathbf{T}}_{\mathrm{ki}}$ – row vector of factors matrix of capacity losses redistribution for the *i*-th branch of the circuit on the capacity in its hubs considering the complex factors of transformation; $\dot{\mathrm{T}}_{\text{зpi}}$ – losses in the *i*-$^{\mathrm{th}}$ branch from the electromotive force of non-balanced transformation factors of coupling transformer; $\dot{\mathbf{U}}_{\mathrm{t}}$ – transposed vector of voltage in hubs; $\mathbf{M}_{\Sigma\mathrm{k}}$ – matrix of coupling considering transformation factors in an explicit form; $\dot{\mathbf{U}}_{\text{д}}$ – diagonal matrix of voltage in hubs; $\widehat{\mathbf{C}}_{\mathrm{k}}$ – matrix of current distribution considering the transformer coupling; $\widehat{\mathbf{D}}_{\text{б}}$ – matrix of conductivity, which forms the formative circulating currents from non-balanced transformation factors in closed circuit of EPS; $\widehat{\mathbf{U}}_{\text{б}}$ – column vector of voltage in balancing hubs.

Depending on the electric distance to the consumer, with which there is an agreement for electric energy supply, configurations of EN, consumption schedules of other consumers and aggregate consumption, the losses of electric energy differ. This must be considered in the target function (2) or in tariff for transportation, and, in the end, in the electric energy price. Proceeding from this, changing by means of the domain “Dispatcher control” the ways of electric energy flow (considering the conditions of the agreement for its supply), loading of separate sections etc/? allows to correct the final cost of electric energy for consumer. Thus, it allows to get additional income due to the efficient cooperation between the electric energy market and electric energy supply companies.

Influence of the distributive energy sources on losses of electric energy in EN

The asynchronous generators (AG) are known to use for the transformation of mechanical energy into the electric one in separate dispersed energy sources (small hydroelectric power stations, wind power station, cogeneration plants etc.). The AG, with number of advantages during the operation are the consumers of reactive capacity. This influences the efficiency of transportation of electric energy of such stations, and, consequently, must be considered in the tasks of optimization of DSEE with AG. The non linear dependence of reactive consumption from the generation of active capacity P_i may lead to the disproportion in the increase of relative losses of electric energy in modes with low efficiency release of the station.

On the example of the schema fragment «Crimea electric power station» (Fig. 2) it is shows that depending on the circuit parameters of EM and capacity of the generation, the dispersed sources of electric energy influence differently the capacity losses in electric system. And the reactive consumption of AG is a significant factor in the task of ensuring the efficiency of DSEE operation.

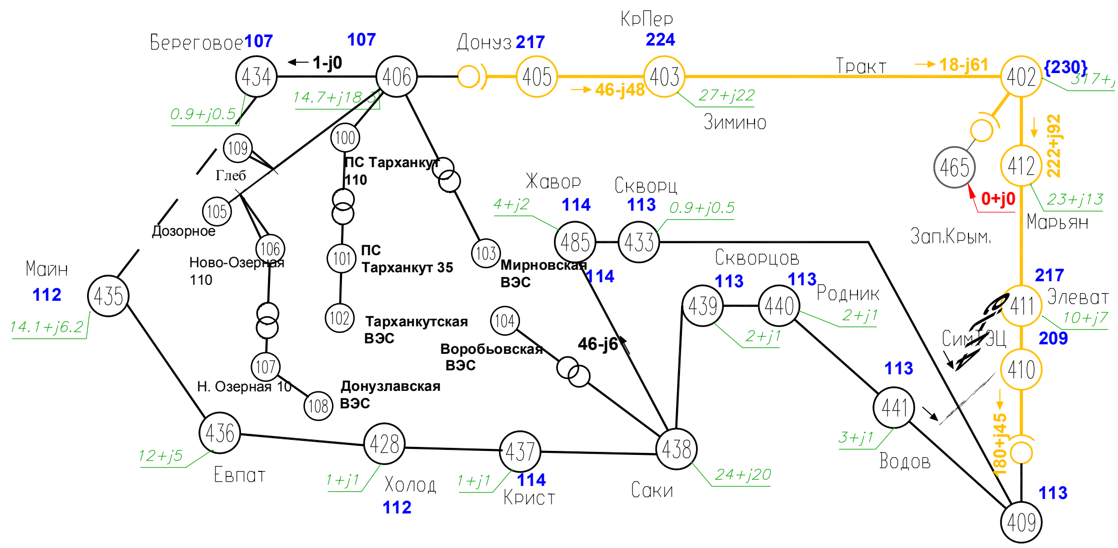

Fig. 2. Schema fragment «Crimea electric power station»

Four wind farms with the asynchronous generators are connected to the EM under research: Donuylavska, Tarkhankut, Mirnovska and Vorobievska. Fragment EM contains 32 hubs, 35 branches and 7 transformer couplings. Line 435-434 with voltage of 110 kilovolt is an open-circuit one. For the evaluation of the capacity losses, stipulated for by DSEE functioning, there had been used the equation (5). Simulation of modes of the under research EM was made by "Graph-Scanner". There had been considered two cases:

− reactive consumption of AG in wind-turbine electric plant was not compensated by the capacitor device ;

− reactive consumption of AG was completely compensated in wind-turbine electric plant.

The results of determination of losses, stipulated for by the functioning of some wind-turbine electric plant, are reduced in table 1 and 2.

Total capacity loss in power system ΔP, determined on the base of distribution factors $\dot{\mathbf{T}}_k$, coincides with the calculation results of the steady-state mode of this electric net by the "Graph-Scanner" software, which testifies the adequacy of the method (5).

With no compensation of reactive consumption of AG they make up: ΔP = 14,5 megawatt, and with full compensation by the capacitor device with automatic regulators − ΔP=13,3 megawatt. Comparison of the calculating results (table 1, 2) testify to the fact that practically all wind-turbine electric plants ensure the positive influence on operation efficiency of power system, reducing capacity losses.

For all wind-turbine electric plants the compensation of reactive consumption results in additional reduction in constituent losses. Due to this the total losses of active capacity in power system from the transportation of capacity of the distributed sources of electric energy without the compensation of reactive consumption of AG decrease by 0,124 megawatt and with compensation - by 0,651 megawatt.

Table 1

Distribution of capacity losses in the AG operation mode with the consumption of reactive capacity

№ узла	Hub estimated power		Matrix coefficient of capacity losses distribution	Losses of active capacity from the hub, megawatt
	$P_г$, МВт	$Q_н$, МВАр		
108	10,9	8,18	-0.138+0.227j	0,347
104	2,3	1,73	-0.061-0.363j	-0.559
103	16,7	12,52	-0.12+0.136j	-0.306
102	13,8	10,35	-0.123+0.151j	-0.133

Table 2

Distribution of capacity losses in the AG operation mode with the compensation of reactive capacity

№ узла	Hub estimated power		Matrix coefficient of capacity losses distribution	Losses of active capacity from the hub, megawatt
	$P_г$, МВт	$Q_н$, МВАр		
108	10,9	0	-0.009+0.151j	-0.103
104	2,3	0	-0.055-0.326j	0.069
103	16,7	0	-0.032+0.103j	-0.542
102	13,8	0	-0.028+0.112j	-0.387

Conclusions

Production of electric energy due to the renewable energy sources, its transportation and distribution under the conditions of generation decentralization are connected with the necessity of coordination of interests of separate participants of electric energy exchange. This complex task cannot be solved without the development of information infrastructure and intellectualization of control systems on the base of Smart Grid. Electric energy losses during its transportation from DSEE to the power system of the energy market, or to the single consumer upon an agreement for its supply may act as the means of influence on functioning of such stations. Consequently, it is possible to ensure the participation of DSEE in the solution of the complex task of improvement the functioning efficiency of power system on mutually beneficial bases.

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