Functionning optimization of various types of renewable sources of electric energy in electric networks

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Abstract **– the paper considers the conditions of optimality functioning of renewable sources of energy (RSE) in electric networks on the example of small hydroelectric stations and the chains of such stations in the aggregate with wind and solar energy installations, controllability of which is limited by the influence of non-stable weather conditions.**

Keywords – renewable sources of electric energy, electric networks, optimal control optimality conditions

I. Introduction

For modern electric networks of electric energy systems (EES) characteristic feature is growth of loads, ageing of equipment, and more rigid requirements, regarding the reliability of energy supply and quality of energy. To provide necessary quality of electric energy and reliable supply it becomes necessary to reconstruct energy supply systems as well as to construct new over-head transmission lines (TL) and develop decentralized generation on the basis of alternative sources of energy (steam-gas installations (SGI) gas-turbine installations (GTI) and cogeneration installations (CGI) and renewable sources of energy (RSE), particularly solar electric stations (SES), wind electric stations (WES) and small hydropower stations (SHES).

Development of distributed generation (Fig. 1) is urgent for all countries. In the countries of EU, for instance, the possibility to increase the share of renewable sources of energy up to 20% in 2020 is considered.

Much attention is paid to hydroelectric stations, particularly to SHES. It is planned to put into operation about 17 000 small hydropower stations of 14 GW installed capacity by 2012 and to provide annual generation up to 55 TW·h. Such approach has a number of advantages, namely, the possibility to provide the required quality of electric energy and reliability of energy supply as a result of smaller volumes of main equipment modernization, prolongation of the term of electric networks reconstruction and additional possibilities to attract investors to solve problems aimed at increasing of electric networks efficiency. Besides, new possibilities of increasing technical economic indices of electric networks at the expense of correction of connection schemes and parameters of RSE appear.

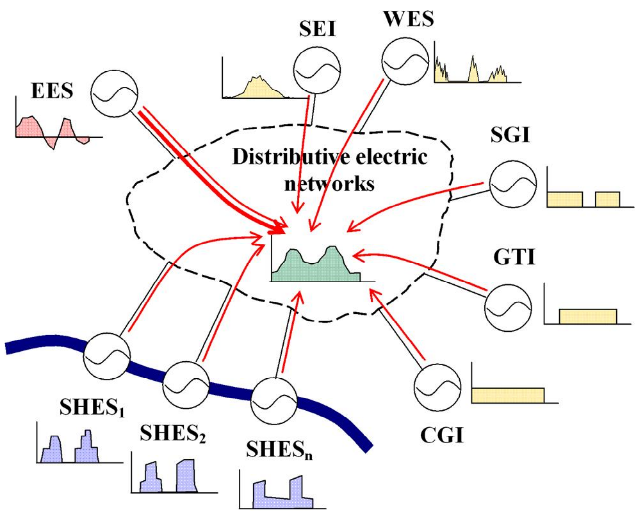

Figure 1. Electric networks with renewable sources of energy

As a result of transition from centralized energy supply to combined supply, new problems emerge, one of them being optimal control of RSE within local electric systems (LES), in which distributive electric systems are gradually transformed with the development of RSE [1-3]. The aim is to achieve maximum technical economic effect as a result of implementation of RSE and, to increase the capacities of new alternative and renewable sources of energy. This effect can be achieved by means of matching in time the optimization of the process of generation, transporting and consumption of energy. Usage of modern information-communication technologies SMART Grid provides information service of centralized energy supply and energy consumers with RSE.

The given paper considers problem dealing with organization of decentralized control of RSE in local energy systems, the paper presents mathematical models of optimality conditions and methods of optimal control of RSE, using as the example small hydropower stations and their chains as controlled sources in the aggregate with wind electric stations, solar installations, controllability of which is considerably limited by the dependence of the generation on non-stable weather conditions.

II. Characteristics of Distributed Sources of Electric Energy as the Object of Control

Distributed sources of electric energy are divided, according to the degree of influence of random processes of natural environment and primary sources of power into [2]:

− renewable sources with variable generation – use renewable resources, but generation is variable in time (WES, SES);

− renewable sources with non-variable generation – use renewable resources, and, generation is constant during certain period of time (SHES, etc.);

− non-renewable sources with non-variable generation – use organic fuel but provide controllability of generation process (CGI, SGI, GTI).

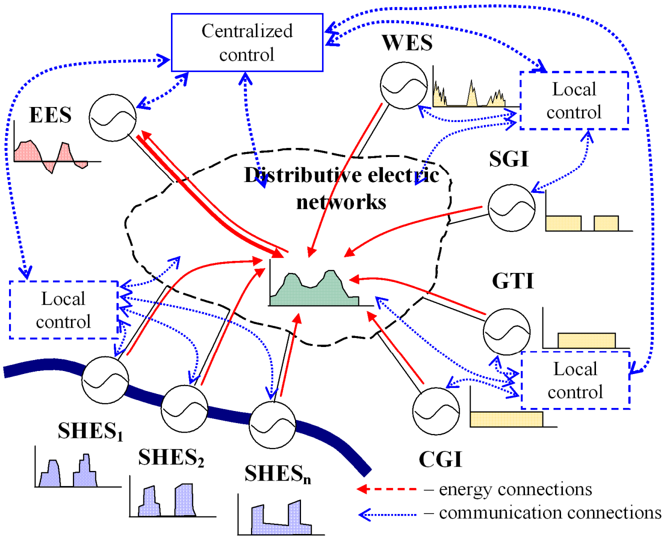

Figure 2. Energy and communication connections of renewable sources of energy in SMART Grid

Support of optimality of generation, distribution and consumption processes, taking into account characteristic features of RSE in real time, requires, besides powerful communication facilities, decentralized (dispersed) control system, involvement of corresponding approaches, regarding formation of control impacts and control laws of separate sources of energy, taking into account specific features of their controllability and observability.

Decentralization of certain control functions (Fig. 2) as a result of application of local control systems, mainly automatic ones, requires the provision of conditions of stability, adequacy and adaptability of energy objects control both in standard situations, in order to optimize functioning, and in non-standard situations, in order to liquidate accidents and minimize their consequences.

To perform tasks of operative and automatic control of RSE normal modes in local electric systems it is possible and expedient to use adaptive control system of regulating devices. The efficiency of adaptive approach increases as a result of division of RSE modes control function – centralized formation of control laws according to complete mathematical models of electric system and RSE and decentralized realization of these laws in local control systems and regulation of separate RSE and their groups using the information of local character.

In these case the synthesis of control laws using limited information, is required, these laws maximally represent the principles of centralized control. The realization of the given control concept enables to unload the centralized control level from computational operations, connected with determination of control impacts of separate RSE, and decreases the capacity of communication facilities, needed for centralized control.

III. Tasks of RSE Functioning Optimization in Electric Networks

For formation of optimality conditions of RSE functioning possible tasks, inherent to operation of such sources in electric networks have been analyzed. Based on the results of analysis, the following list of functioning optimization task of local electric systems with RSE has been determined.

For optimization of RSE functioning in normal modes of electric systems the problems of planning organization and on-line control of operation mode of such stations in order to obtain maximum profit from their operation become very important. Hence, the most urgent, taking into account the specific features of profitability provision, is the task of optimization of daily modes (on time intervals) of controlled RSE $P_i\ (t)$, $i=1,2...n$, taking into account modes of variable sources to provide maximum incomes from selling their electric energy on conditions of multistage tariff of energy market and technical limitations on the side of certain RSE.

$$\int_{t_0}^{t_k} tariff(t)\sum_{i=1}^{n} P_i(t)dt \to \max . \qquad (1)$$

2. In case of control of decentralized sources of energy in states, connected with special situations in EES, it is expedient to pass to solution of the problem, dealing with optimization of RSE modes, in order to decrease the dependence of local electric system with aggregate loud $P_{load}(t)$ on centralized energy supply, i.e. minimization of local system load on main centre of supply P_{main}.

$$\begin{cases} \int_{t_0}^{t_k} tariff(t) P_{main}(t)dt \to \min; \\ P_{main}(t) + \sum_{i=1}^{n} P_i(t) - P_{load}(t) = 0. \end{cases} \qquad (2)$$

3. To provide the resistance of local electric system in the periods of maximum (minimum) load or limited carrying capacity of centralized system of energy supply, when variation of local generation . parameters may lead to violation of limitation on EES modes, optimization of RSE modes is urgent in order to minimize deviations from the preset schedule

of aggregate generation $P_{RSE}(t)$ in case of preset limitations on primary energy resources and RSE characteristics:

$$\int_{t_0}^{t_k} \frac{1}{2}\left(P_{RSE}(t) - \sum_{i=1}^{n} P_i(t) \right)^2 dt = \min . \quad (3)$$

Forecasting information, regarding meteoparameters, upplied by corresponding subsystem Smart Grid and allows rather adequately to represent RSE states of variable type on the period of up to four days must be taken into account. As a result, variable and non-stable sources of energy of WES and SES type in efficiency functions and limitations of optimal control tasks can be presented by mathematical expectation of temporal dependence of generation $M_{\text{WES}}\{P(t)\}$, $M_{\text{SES}}\{P(t)\}$, $t\in [t_0; t_k]$.

IV. Conditions of RSE modes optimality in local electric systems

Proceeding from already mentioned tasks of optimal control of RSE modes, formation of common criterion and optimality conditions for their solution is complicated. Hence, functioning of such sources in local energy system (LES) must be subordinated to certain control lows, depending on the situation. For the realization of local control over renewable sources of energy (Fig. 2) conditions of optimally and control laws, formed on their basic, must be formed, proceeding from common methodology. The efficient way for the solution of the problem, dealing with formation of optimal control laws is application of calculus of variations in combination with the methods of similarity theory [4].

The task of optimal control (1) can be presented in the following manner. The totality of n controlled RSE (on the example of SHES) and m variable sources – WES and SES are set, mathematic expectation of total active power is

$$M_{VAR}(t) = M_{WES}\{P(t)\} + M_{SES}\{P(t)\}. \quad (4)$$

Powers of SHES are taken as control variables, since they are the most stable, regarding the influence of the environment. Losses due to transfers of power of variable RSE and SHES in distributive network are functions from generation powers and must be taken into account in efficiency function.

The composition of operating equipment of SHES during the day and its energy characteristics is stable. It is necessary to find such modes of SHES $P_i(t)$ in time interval $[t_0; t_k]$, which would provide maximum profit from selling RSE electric energy at energy market:

$$\int_{t_0}^{t_k} tariff(t)\left[\sum_{i=1}^{n} P_i(t) + M_{VAR}(t) - k_p(t)\cdot \Delta P_{RSE}(t) \right] dt \to \max , \quad (5)$$

where $k_t(t)$ – weight coefficient, determined by the ratio of selling tariff for RSE $tariff(t)$ and power losses cost for the given distributive network $tariff_0$; $\Delta P_{RSE}(t)$ is the component of power losses in distributive electric networks, conditioned by RSE operation.

Daily discharged at each SHES as well as balance of discharges in the chain $W_i = W_{i-1} + dW$ are set as limitations, dW value is determined by stochastic processes of water arrival at the section of the river between $i{-}1^{th}$ and i^{th} SHES. Taking into account limitations-inequalities regarding the capacity of controlled RSE $P_i^{\min} \le P_i(t) \le P_i^{\max}$ and by pressure $H_i^{\min} \le H_i(t) \le H_i^{\max}$ determined by the conditions of operation in water distribution systems is obligatory. Values $P_i(t_0)$ and $P_i(t_k)$ are considered to be known values. Solution of similar problem is considered in [4]. As the solution, using the principle of maximal integral functions of Pontriagin conditions of RSE optimality functioning are obtained in the form of relations:

$$z^*_{\text{main}}(t) = \frac{\lambda_1 q_1^*(t) + q_1^{\text{PF}}}{1-\sigma_1^*(t)} = \frac{\lambda_2 q_2^*(t) + q_2^{\text{PF}}}{1-\sigma_2^*(t)} = ... = \frac{\lambda_n q_n^*(t) + q_n^{\text{PF}}}{1-\sigma_n^*(t)} ,(6)$$

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

$$\begin{cases} z_{main} = -tariff(t);\ z'_{main} = \dfrac{d\, tariff(t)}{dt}, \\ q_i = \dfrac{\partial Q_i}{\partial P_i};\ q'_i = -\dfrac{d}{dt}\dfrac{\partial Q_i}{\partial P_i};\ q_i^{PF} = \dfrac{\partial PF_i^P}{\partial P_i} + \dfrac{\partial PF_i^H}{\partial P_i}; \\ \sigma_i = k_t \dfrac{\partial \Delta P_{RSE}}{\partial P_i};\ \sigma'_i = -k_t \dfrac{d}{dt}\dfrac{\partial \Delta P_{RSE}}{\partial P_i}; \end{cases} \quad (7)$$

Q_i – is water discharge for i^{th} SHES; PF_i^P, PF_i^{H} – are penalty functions, introduced to efficiency function for account of limitations, such as, in equalities by the capacity of i^{th} RSE and by the pressure between pools, correspondingly (in case, if i^{th} RSE is small hydropower station).

Carrying out optimal control of RSE according to conditions of optimality (6) we provide obtaining maximum profit from selling electric energy from RSE, and we reduce losses in electric networks of LES. If should be noted, that the accuracy of definition of mathematical expectation of variable sources of energy $M_{VAR}(t)$, influencing only the components of relative increments of losses σ_i^* is not critical for problem solution.

Solution of the problem of RSE functioning optimization (2), where the aim is to minimize the dependence of LES on the influence of centralized energy supply, may be performed in the following manner. LES with n controlled RSE (on the example of SHES) and consumers with total power $P_{load}(t)$ are set. We may neglect losses caused by power transfers of RSE in distributive network, since they are defined as a part of the preset useful supply. The composition of daily operating equipment of SHES is stable. We are to determine such daily modes of SHES $P_i(t)$ which would provide minimal expenditures for buying electric energy at energy market

$$\int_{t_0}^{t_k} tariff(t) P_{main}(t) dt \to \min , \quad (8)$$

on condition of the balance of active powers $\varphi(t)=P_{load}(t)-\left[P_{main}(t)+\sum_{i=1}^{n}P_i(t)+M_{VAR}(t)\right]=0$ and preset discharge at each SHES as well as balance of discharge in the chain of small hydropower station.

Limitation – inequalities by the power of RSE and by SHES pressure are taken into account. Representation of the problem (8) as the problem of calculus of variations and its solution, applying the method of Pontriagin integral functions minimum allows to obtain necessary conditions of optimal distribution of active loading between RSE in analytical form:

$$\begin{aligned} z^*_{main}(t) &= \lambda_1 q_1^*(t)+q_1^{PF}=\lambda_2 q_2^*(t)+q_2^{PF}=\dots \\ &=\lambda_n q_n^*(t)+q_n^{PF}=\lambda(t) \end{aligned}, \qquad (9)$$

where $z^*_{main}=z_{main}+z'_{main}$, a $q_i^*=q_i+q_i'$, on condition that

$$\begin{cases} z_{main}=tariff(t);\ z'_{main}=\dfrac{d\,tariff(t)}{dt}, \\ q_i=\dfrac{\partial Q_i}{\partial P_i};\ q_i'=-\dfrac{d}{dt}\dfrac{\partial Q_i}{\partial P_i};\ q_i^{PF}=\dfrac{\partial PF_i^P}{\partial P_i}+\dfrac{\partial PF_i^H}{\partial P_i}. \end{cases} \qquad (10)$$

Problem of RSE functioning optimization (3), which consists in minimization of deviations between real $\sum_{i=1}^{n}P_i(t)$ and set $P_{RSE}(t)$ schedules of total generation by the set limitations on the primary energy resources and RSE characteristics is solved in the same way as the above-mentioned problems (8). Conditions of RSE functioning optimality have the same form:

$$\begin{aligned} z^*_{RSE}(t) &= \lambda_1 q_1^*(t)+q_1^{PF}=\lambda_2 q_2^*(t)+q_2^{PF}=\dots \\ &=\lambda_n q_n^*(t)+q_n^{PF}=\lambda(t) \end{aligned}, \qquad (11)$$

where $z^*_{RSE}=z_{RSE}+z'_{RSE}$, a $q_i^*=q_i+q_i'$, on condition that

$$\begin{cases} z_{RSE}=P_{RSE}(t)-\sum_{j=1}^{n}P_j(t);\ z'_{RSE}=\dfrac{dP_{RSE}}{dt}-\sum_{j=1}^{n}\dfrac{dP_j}{dt}, \\ q_i=\dfrac{\partial Q_i}{\partial P_i};\ q_i'=-\dfrac{d}{dt}\dfrac{\partial Q_i}{\partial P_i};\ q_i^{PF}=\dfrac{\partial PF_i^P}{\partial P_i}+\dfrac{\partial PF_i^H}{\partial P_i}. \end{cases} \qquad (12)$$

Comparison of the obtained conditions of optimality (6),(9) and (11) shows that they are similar by their structure. The difference is that in problems (3) and (8) set up there is no power losses factor in distributive networks of LES. Physical content of Lagrangian multipliers λ_i for the cases (6), (9) − is profitable efficiency of water consumption for separate SHES. That is λ_i which is determined by iteration method, so that to provide the realization of the set discharge W_i shows how the cost of electric energy, supplied by the group of RSE will grow, on condition of water supply increase at i^{th} SHES by 1 m^3/sec. For optimality conditions (11) λ_i shows the non-balance portion between real and necessary generation schedules of RSE, which is covered by water supply of 1 m^3/sec at i^{th} SHES.

As it is seen from the above-mentioned, the solution of the problem of optimal control of the aggregate of RSE in various operation situations must be subordinated of common optimality conditions. For adaptation of RSE optimal control laws of to the conditions of local energy systems operation it is necessary to correct the parameters of RSE models, and independent parameters of λ_i.

V. Automation of RSE Modes Optimal Control in Local Electric Systems

To realize the above mentioned tasks the necessary condition is to provide the possibility of centralized control over the object in real time. But the above-mentioned condition cannot be completely realized as a result of spatial branching of objects and lack of reliable communication channels between them and dispatching centre. Proceeding from this fact, automatic control system (ACS) with the preset list of functions (Fig. 3) can be built as centralized system of on-line control with decentralized function of real time as a result of application of local adaptive systems of automatic control (SAC).

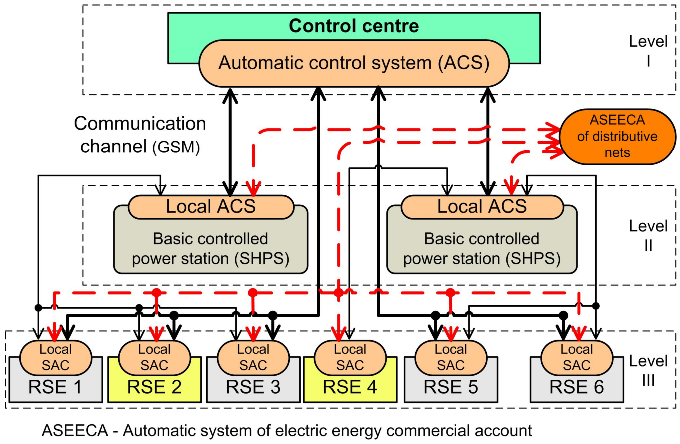

Figure 3. Structural diagram of ACS HPS

Taking into account the structure and material complexity of the given control system, as well as requirements, regarding minimization of capital and operating costs, ACS is built on the basis of the results of detailed technical economic analysis. As a result of such analysis, the concept of automation of small hydroelectric stations have been developed. Main principles of such concept is:

− The sequence of development and implementation of ACS is substantiated, this sequence envisages the priority of problems realization;

− Realization of three-level hierarchical structure with allocation of two levels of control of objects which perform the control of the lower level, and “basic” objects. Such structure reduces capital costs, needed for hardware and software realization of ACS;

− Complete independence of the objects of control of all the levels in normal (planned) modes of their operation allows to provide controllability of the objects and realization of the set functions during certain period of time even in case of failure of communication channels with higher hierarchical level.

Development and implementation of ACS by the group of small hydropower plants envisages a number of completed stages, each of which is responsible for realization of certain range of problems.

At the first stage problems of automation of commercial account of electric energy is performed as necessary condition of hydropower station functioning at energy market, hardware and software for collection and transfer of data, regarding semi-hour schedules of electric energy supply and formation of reporting documents in accordance with acting standards. Additional tasks to be realized at the given stage are testing of the chosen intelligent meters, hardware platform and communication channels, training of the staff for operation with new equipment.

At the next stage of ACS realization the aim is to automate the process of energy generation and to provide independent operation of hydroelectric station in normal (planned) operation modes. Problems of remote switching of hydropower station, automatic control of operation and protection of main equipment are solved; the solution of these problems will allow to reduce the number of staff.

The volume of information support considerably increases, since to perform the preset remote operation mode and carry out necessary decisions regarding operation control it is necessary:

− Control the level of the water in upper pool and stop the units if minimum level is reached;

− Control operation mode of generators, using measuring devices of control panel and correct correspondingly turbines capacity;

− Control parameters of mechanical part bearings of generators, turbines, transmissions) stop the units in case of reaching limiting values of vibration and temperature;

− Registration emergency and reemergence presence of the staff and strangers on the territory of hydropower station (including videorecording) and inform higher hierarchical level (dispatching centre) and operation staff.

Solution of the problems of information support of hydropower station mode monitoring requires expansion of hardware-software part of local control systems (Fig. 4) – installation of sensors (S) of mechanic and electric parameters, as well as actuators (A), connected with information network of the lower level, PLC – controllers for organization of real-time problems performance and data exchange between subsystems, etc.

The third stage of development and realization of ACS SHPS starts with allocation (by territorial principle, installed capacity, quality and qualification of the staff) of basic hydroelectric stations. At these stations additional equipment for organization of local automatic control system is installed to realize the control over such stations and stations of the lower level connected with them. PLC-controllers of such objects are united in local network Ethernet that provides the possibility of data exchange between them and the server of local ACS. The server is equipped with the software that enables to accumulate and analyze retrospective data of the local SAC and SAC of the group of HES, improve the efficiency of water resources usage, forecast emergency states and liquidate failures with minimum losses.

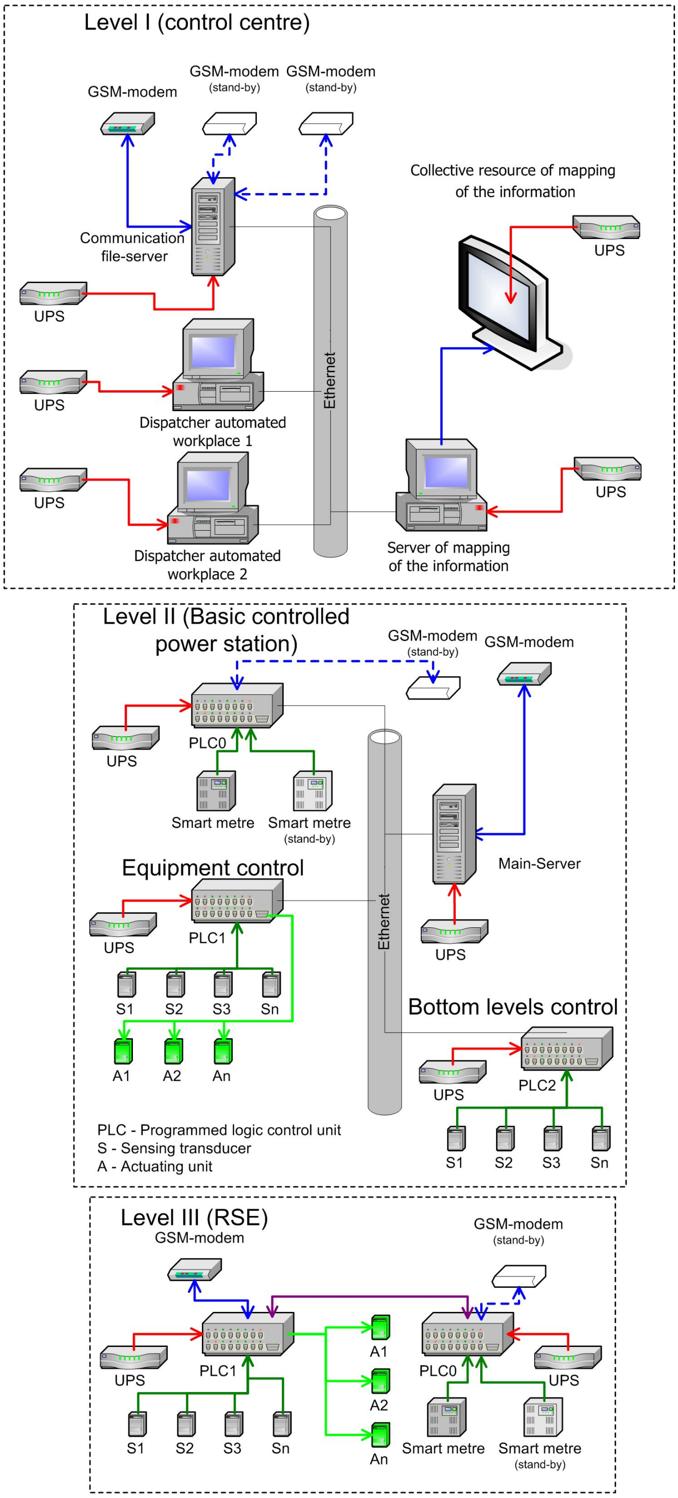

Figure 4. Structural diagram of ACS HPS hardware realization

Thus, local ACS of basic HES are intended for independent computer-based control of HES operation modes in accordance with the changes of environment parameters, on-line analysis of operation modes of their equipment and transmission of information to dispatching centre and attendant staff of corresponding HES regarding possible emergencies, analysis of trends of main parameters (electric, mechanic), their registration and organization of information exchange between the objects of control and dispatching centre.

It is obvious that realization of the described ACS by small HES requires, besides hardware realization, the development of corresponding mathematic and programming software, which for separate HES (especially for HES of the second level) requires capital investments and time. But expenses are reimbursed as a result of better controllability and maneuverability of HES, reduction of the staff, improvement of operation reliability and efficiency of usage of water potential, as well as fulfillment of the schedule of power generation in LES with such non stable sources of energy as WES and SES.

CONCLUSIONS

1. Possible variants of usage of renewable sources of energy in distributive electric networks is considered, the conditions of their mutual optimal functioning are substantiated. It is shown that application of Smart Grid systems enables to solve problems of RSE modes optimization in distributive electric networks in a complex manner, on the basis of the suggested optimality conditions.

2. As a result of flexible feedbacks using communication networks it is possible to control operation modes of separate electric installations of consumers in order to adapt consumption modes to non stable generation of RSE. To realize this approach adaptive system of automatic control in real-time is proposed, the system allows to carry out the control over technological processes of generation and consumption of electric energy in conditions of incomplete and non-reliable current information relatively the characteristics of the objects of control and impacts of external environment, which is characteristic feature for decentralized sources of energy.

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