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An approach to coordination of power generating units*

by

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Abstract: The importance of the problem of power generating facility identification is justified against the background of interconnection of the European and Russian power grids. Intelligent control techniques for power generation facilities are presented. A methodology for estimating the dynamics of participation of the power grid generating facilities in the overall primary frequency regulation in contingency situations is developed based on frequency and generating capacity time series. Process identification algorithms, based on virtual model design using process data archives and knowledge bases, are discussed. Associative search methods are used for identification algorithm development.

Keywords: generating facility identification, knowledge base, associative search models, soft sensors.

1. Introduction

Power generation is a key factor of European Community's economic growth and the welfare of its citizens. Nowadays, the European energy supply system faces a number of structural, geopolitical, social, and ecological challenges, related to supply safety, depletion of oil and natural gas resources, volatility of oil prices (with direct negative effect on transportation), and the need to reduce greenhouse gas emissions and thus mitigate the environmental impact (Ayuev, 2007).

New ways should be found to transform the existing power systems into more viable form, less dependent on fuel import. Energy conservation, based on its more efficient utilization is a must. Therefore, the program aimed at tighter association of Russian and Western European power grids, approved by the business community and politicians, looks rather promising. This approval

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forms the background for establishing the world's greatest power union with total installed power exceeding 860 GW and covering 12 time zones.

For Western European power companies this means new opportunities to meet the increasing energy demand under constraints on the construction of new generating facilities and network infrastructure. For country-regionplaceRussia, migration to synchronized work with European power systems means integration with European markets and new opportunities for national power businesses. The significance of country-regionplaceRussia in the power unification process is determined by abundant natural resources, developed power infrastructure and historically formed connections with adjacent countries.

Nowadays, technical cooperation of Eastern and Western synchronous zones is regulated by special international agreements.

The countries participating in the new power union can benefit from:

- aid in emergency situations
- new opportunities for power trade
- improved reliability of final customer supply
- optimum utilization of generating facilities and primary energy resources, due to idle capacity reduction, time shift of peak loads in different time zones, etc.

The development of technical requirements for reliable dynamic behavior of the united energy system has been carried out by working teams including more than 80 experts from 17 countries in five directions:

- investigation of steady-state operation modes
- investigation of transients and low frequency oscillations
- power grid control
- development of organizational procedures and forms of interaction for system operators
- preparation of legal forms and documents.

The marketing component should be a key factor of interaction (Kraftnat, 2000; Rzewuski et al., 1999; Sheble and Fahd, 1994; Anderson and Fouad, 2003).

To improve power production and marketing efficiency, power companies should undertake the development of information-analytical systems according to the accepted performance indicators; these systems should support decision-making. Such system can either be stand-alone or integrated with the process monitoring systems of the united energy system.

The information systems would allow the company to acquire, store, process, display, analyze and document information in real time, based on the data collected from power measuring, supervisory control, and energy accounting systems.

The primary requirements embodied in compound control performance criteria either for power units, or for their combinations, should be operation reliability along with benefit maximization.

An information-analytical system will make recommendations to real-time control, based on the estimates of power object current state and prediction, in particular - of possible emergencies.

2. Power monitoring and accounting systems

Operation mode (state) planning is seriously affected by the market through such aspects as larger amount of information to be processed, tighter time schedules, and the need for more sophisticated computation algorithms (Voropai and Handscin, 2001).

Modern concepts of power systems development presume the application and enhancement of supervisory control systems, enabling grid control integration at operations and business levels (Kozhevnikov, 2008), combined with power monitoring and accounting system. The latter allows a power grid to perform purposeful regulation of power consumption, thus reducing the shortfall in the grid and meeting tighter end-user requirements.

Based on the consolidated diverse information, the following functions are performed:

- Monitoring of all process variables
- Development of various analytical reports subject to power unit specificity (dead band, etc.)
- Operation mode analysis and planning for power systems of any complexity and voltage ranges
- Reliability calculations on regular basis for reducing the risk of cascaded emergencies
- Generating facility state predictions based on adaptive models
- Integration of solution to control problems for various cells and levels of power facilities and units within a certain power company
- Real-time operation of commercial power accounting systems
- Loss evaluation
- Prediction and optimization of annual, seasonal, and daily balances
- Adaptive prediction of maximum benefits for a specified time interval
- Optimization of fuel consumption and generating facilities, reduction of electric power transmission costs
- Coordination of development planning of company power generation facilities and plants
- Coordination of day-to-day operation of power grids and plants, in particular:
    - optimal power distribution
    - optimal power units startup
    - optimal maintenance planning
    - compliance with common reliability criteria
    - automatic frequency control.

Automated systems, comprising such functions as power facility state planning, power flow control, emergency control, etc., have been developed to improve system operators' team-work and the efficiency of national power companies (Kraftnat, 2000).

Modern power grids are geographically distributed multi-variable hierarchical objects with variable structure, complex dynamics of power facility states under external and internal disturbances of both systematic and random nature (Zakharov and Ulyanov, 1995).

The complexity of the state control problem causes the need for its decomposition into several simpler tasks interrelated at different levels (Gonzalez, 2003). These include:

- long-term generation scheduling
- medium-term generation scheduling
- short-term scheduling and control done by operations staff
- on-line automatic control in design and emergency modes.

To implement these functions, the systems should allow for predicting operation state based on current power output and idle capacity. State optimization across the whole grid, involving all market participants, enables fuel saving, better utilization of generating facilities and reduction of power transmission costs.

3. Optimization of power plant operation based on its identified model

An identified model allows for obtaining a dynamic estimate of power plant state. On-line power plant control based on a model adjustable in real time makes it possible to:

- optimize reactive power losses
- optimize equipment configuration
- control voltage to avoid its reduction or oscillation, thus ensuring higher efficiency of various electrical machines and devices
- control harmonic composition and imbalance of currents and voltages, take timely actions to remove quality deterioration sources, thus increasing equipment lifetime and power supply reliability
- optimize maintenance costs
- diagnose equipment condition, prevent contingencies.

The model is developed with various factors in view, such as: optimization of capital investments in generating facilities and power networks, maintenance planning, optimal selection of power facility configuration, rational load distribution, frequency control, and minimization of power generation and transmission costs against the desirable level of power supply reliability (Oppel and Aronson, 1999).

All facilities of a power grid are required to use all available resources for overcoming an emergency situation and post emergency states. Simultaneous state planning is based on bilateral and multilateral contracts and agreements between the participants of the generation and transmission market. Total frequency is maintained within admissible range by each power grid, controlling its agreed power flow balance with frequency correction. All facilities of any power grid should have agreed power reserve for emergency aid and frequency control.

4. Application of intelligent techniques in power facility identification

The above listed tasks, in their turn, require solving a number of process control problems for power industry with the focus on development of:

- high-order model reduction algorithms for automatic frequency and power control
- multi-level state observers for power systems
- pre-emergency state detection and electric equipment diagnosis algorithms based on state estimation and parametric identification techniques.

State estimation models for power facilities are widely used nowadays in medium- and short-term scheduling and on-line control. Moreover, state estimation is often a function of automatic systems, such as dispatcher's adviser, centralized anti-wreck system, etc.

On-line information is delivered by remote measurements (Prikhno, 2004) coming to the state estimator from on-line information systems (OIS). Historical data are supplied from OIS history modules.

Process knowledge is widely used by modern state control systems. Depending on model types employed, intelligent logical control systems and intelligent controllers can be distinguished. The former use logical, e.g., automaton-type models, while the latter employ the models of classical control theory.

In recent years, neural network (NN) models have been often used for load prediction. Most of their developers report on typically higher accuracy of NN-based load prediction compared to statistical models.

Chukreev et al. (2000) present an expert system design technique for medium- and short-term supervisory control using NN technology. An estimate of regional power system limiting states is presented and a solution to the problem of efficiency monitoring and on-line correction of power system state parameters using expert knowledge is given. Prikhno (2004), Ou and Singh (2003), Novicky (2008), Zhu Chengjun et al. (2006), and Pereira (1989) present approaches to state planning as a problem of power facility selection w.r.t. maximum reliability criterion. The problem is important, because today operations engineer from a central control station has no precise tool for quick selection of the most reliable state among a vast variety of possible states.

For state modeling under random impacts on a complex system, Ou and Singh (2003) propose to apply synthetic sampling (placeMonte Carlo method) considered to be most reliable in such circumstances. A number of tests sufficient for obtaining a reliable result are performed where the values of probabilistic characteristics are chosen from probability distributions in each test.

As a grid reliability factor, Prikhno (2004) selected the mean of load or power shortage in various grid nodes or over the whole grid:

$$W = \sum p_i \Delta P_i,$$

where p_i is the probability of failure, ΔP_i is total cut-off load and/or generation power for i-th node.

As a reliability criterion, Pereira (1989) uses the lost load, i.e., the power need that was not satisfied due to the lack of idle generation capacity and network throughput multiplied by the time interval when the lack of local power took place. Zhu Chengjun et al. (2006) present a solution to a hydroelectric plant state optimization problem based on a two-level Markov model for day-ahead electricity prices forecast and water inflow data. Mo, Gjelsvik and Grundt (2001) discuss a stochastic dynamic model for joint hedging and generation planning of a hydropower system. Gjelsvik (1992) presented a two-level model and introduced an approach called stochastic dual dynamic programming that can be used with multi-reservoir system. A model, presented by Kang Chongqing et al. (2006), is based on stochastic dynamic programming techniques and expert knowledge.

5. Soft sensor design

In this and further sections, we present a soft sensor, meant to describe the dynamic behavior of power grid generation facilities participation in the overall primary frequency regulation in emergency situations. The soft sensor, based on generating capacity data and frequency time series, was developed by the authors for the Control Center of Russia's Unified Energy System (RAO UES).

The establishment of power plant participation and the estimation of the degree of its contribution to the overall primary frequency regulation (OPFR) are performed at the frequencies exceeding 0.2 Hz. When the grid is operated in design mode (with frequency deviations less than 0.2 Hz), control is purely qualitative and informative.

At the same time, due to the qualitative assessment of generating facilities participation in the OPFR at abrupt frequency excursions in the grid in the range of 0.05. . . 0.2 Hz, the systematic (more than 50% cases over a year) lack of participation in the primary regulation of the generating facilities from a number of heat power plants was detected due to the shortage of the requisite power adjustments to compensate for the frequency deviations.

Along with the establishment of the fact of specific generating facility participation (or nonparticipation) in the OPFR, the technology of RAO UES Control

Center's historical data processing enables the evaluation of the degree of plant participation in the regulation.

In order to rank the generating facility participation in the OPFR, identification models and algorithms describing power grid dynamics were developed. When building an identification model, essential non-linearity of the object under investigation was allowed for. Therefore, it was considered rational to use associative search models in the soft sensor design.

The identification algorithms show the generation facilities ranked w.r.t. the probabilities of violation of the OPFR participation requirements for the generating facilities. The indicators of specific generating facility influence on the OPFR were evaluated, which contributed to the quality improvement of the secondary frequency regulation.

6. Associative search models in soft sensor design

Soft sensors can be used to support process operator decision-making. They enable on-line power plant state prediction. Recommended control actions are presented to operators directly from process schematics or through an independent interface. Identification algorithms underlying modern soft sensors are based on expert knowledge. Soft sensors employ both decision-maker's expert knowledge and process knowledge bases. In the second case, the operator is offered either a recommended control action or the values of process variables obtained by means of process monitoring.

The experts differ from the novices in the structure and mode of thought, in particular - the decision-making strategy (Larichev, 2001). If a person is not an expert, he/she often employs so-called backward reasoning, where information on current process status is used for enumerating decision versions and searching for the arguments to draw a conclusion. On the contrary, an expert does not need to analyze current information as he/she uses forward reasoning where the control action development strategy is shaped on a subconscious level and is thus not verbalized. Therefore, in the context of the computational view of thought (Patel, 1997), system efficiency is substantially determined by the expert's level of proficiency and the available a priori information. In the framework of such approach, cognitive psychology defines *knowledge* (Hunt, 1989) as a specific set of elements – symbols that are stored in an individual's memory, processed during the reasoning and determining his/her behavior. The symbols, in their turn, can be determined by the structure and nature of interneuron bonds (Newell and Simon, 1972).

Data processing in an intelligent system is reduced to knowledge recovery (associative fuzzy search) from its fragment (Gavrilov, 2002). Here, knowledge can be interpreted as an associative relation between *images*. The associative search process can go on either as a process of image recovery by partially specified symptoms (or knowledge fragment recovery under incomplete information; this process is the one that is most often represented in various associative memory models), or as a process of searching other images, associatively related with the one under recovery and tied to other instants of time (these images have the meaning of the cause or the effect of the given one).

7. A nonlinear dynamic prediction algorithm and its modification

To identify complex nonlinear dynamic objects, like continuous and batch processes, one can offer an identification algorithm with continuous real-time self-tuning based on *virtual model* design. The algorithm enabled product quality improvement in advisory mode by statistical treatment of process and laboratory data.

At every time step, a new virtual model is developed. To build a model for a specific time step, a temporary "ad hoc" database of past and current process data is created. After the forecast calculation, based on object current state, this database is deleted.

The linear dynamical prediction model looks as follows:

$$y_N = \sum_{i=1}^{m} a_i y_{N-i} + \sum_{j=0}^{n} \sum_{s=1}^{S} b_{js} x_{N-j,s}, \tag{1}$$

where y_N is the object output forecast at the N-th step, x_N is the input vector, m is the output memory depth, n is the input memory depth, S is the input vector length.

The original dynamic algorithm consists in the design of an approximating hyper surface of input vector space and the related one-dimensional outputs at every time step. To build a virtual model for a specific time step, the points close in a sense to the current input vector are selected. The criterion of point selection is described below. The hyper surface dimension is selected heuristically. The output value at the next step is further calculated using the classical (non-recurrent) least squares technique.

It should be noted that the algorithm *does not* build a *single* approximating model for a real process, it rather builds a new model for each time step. Still, it is an effective identification algorithm because the parameter estimates are the best in terms of mean-square error at every time step. Here, each point of the global nonlinear regression surface is obtained as the result of "local" linear models application.

The algorithm has proved its high forecast precision over a wide range of chemical and petrochemical processes. Still, a number of issues required additional investigation, in particular, the technique of designing the approximating hyper surface and evaluation of its dimension.

The criterion of input vector selection from the archive for building a virtual model at the current time step subject to the current object state was as follows. At the first step, a point (an S-dimensional input vector, where S is the number of the most informative process variables) was selected, for which the absolute value of the difference between the first component of this vector and the first component of the current input vector, respectively, was minimal in the whole archive of input vectors:

$$d^1_{N,N-j} = \left|x^1_{Ns} - x^1_{N-j,s}\right| = \min_{p=0,..j..,N} \left|x^1_{Ns} - x^1_{N-p,s}\right|,$$

The absolute values of the differences of the first components were further ranked in decreasing order, and a point in the input space was selected, for which the absolute value of the difference of second components was minimal,

$$d^2_{N,N-j} = \left|x^2_{Ns} - x^2_{N-j,s}\right| = \min_{p=0,..j..,N} \left|x^2_{Ns} - x^2_{N-p,s}\right|, \quad \text{etc.}$$

The scheme was applied for selecting R points, $R \geq S$, without any guarantee that the resulting system of linear algebraic equation would have a solution.

To overcome the problem and to improve the convergence rate, the following approach can be applied.

We introduce the quantity:

$$d_{N,N-j} = \sum_{s=1}^{S} \left|x_{Ns} - x_{N-j,s}\right|, \ \forall j = 1, ..., n \tag{2}$$

that defines a distance between the points of the S-dimensional input space (the norm in $\Re^s$), where x_{Ns} are the input vector components at the N-th time step.

By virtue of triangle inequality, we have:

$$d_{N,N-j} \leq \sum_{s=1}^{S} \left|x_{Ns}\right| + \sum_{s=1}^{S} \left|x_{N-j,s}\right|, \ \forall j = 1, ..., n. \tag{3}$$

Denote for the current input vector x_N

$$\sum_{s=1}^{S} \left|x_{Ns}\right| = d_N.$$

To build an approximating hyper surface for x_N, we select such vectors x_{N-j}, $j = 1, ..., n$ from the input data archive that for a given $d_N^{\max}$, the following condition holds:

$$d_{N,N-j} \leq d_N + \sum_{s=1}^{S} \left|x_{N-j,s}\right| \leq D_N, \tag{4}$$

$$D_N \geq d_N^{\max} = \max_j \sum_{s=1}^{S} \left|x_{Ns}\right|.$$

If the number of inputs in the selected region is not sufficient to apply the least squares technique, i.e. the corresponding system of equations is unsolvable, then the chosen point selection criterion can be slackened by increasing the threshold D_N.

The procedure proposed for building the approximating surface ensures higher speed compared to Bakhtadze et al. (2007), because the values $d_{N-k} = \sum_{s=1}^{S} \left| x_{(N-k),s} \right|$, $k = 1, ...N-1$ for all time steps prior to N can be once determined and ranked at the learning phase, while the sequence is supplemented with a new member at each new input entry.

8. Interpretation of the virtual models algorithm as an associative search procedure

The problem of the convergence rate of virtual models algorithm is important for process variables prediction and often becomes paramount. To solve the problem, we use the approach based on applying an associative thinking model for prediction.

To build an associative search procedure, consider, for example, the following approach.

Let the sets of process variable values (which are the components of input vectors) and the values of the system output vectors at earlier time steps form altogether *a set of symptoms*:

$$K = \{x_{t,s}, y_t\}, \quad t = 1, \ldots, N, \quad s = 1, \ldots, S. \tag{5}$$

The total number of symptoms equals

$$N^{sym} = N(S+1). \tag{6}$$

The number of input vectors used to build the approximating hyper surfaces (including the current vector) and the corresponding outputs will be further called *the set of symptom values combinations* over the set K:

$$P = \{\bar{x}_N, \bar{x}_{N-j}, y_{N-j}\}, \quad 0 \le j \le N, \tag{7}$$
$$\bar{x}_N = (x_{N1}, ..., x_{NS}),$$

describing the specific images that the intelligent system deals with during its operation.

Denote the image initiating the associative search as P and the corresponding resulting image of the associative search as R. In process of associative recalling, the images described by symptoms are used. A pair of images (P, R) will be further called *association* A or $A(P, R)$. The set of all associations on the set of images forms the *memory* of the *knowledge base* of the intelligent system.

The associative search with the value TRUE is called successful, while the one having value FALSE is called unsuccessful. Each association $A(P, R)$ generally conforms to a set of successful associative searches $\Omega = \{\Xi_i(P_i^a, R_i^a), T^a)\}$, where $P_i^a \subseteq P$ and $R_i^a \subseteq R$. The associative search (P^a, R^a, T^a), using a single association contained in the intelligent system memory is called *elementary associative search*.

Formation of this set depends on the features of the specific realization of the associative memory (namely, the juxtaposition of the initial image P_i^a of the associative search and the image P).

We consider the current input vector x_N as an initial image P^a of the associative search. The approximating hyper surface built with the help of the algorithm described in Section 7 is the final image R^a of the associative search. The algorithm recovers R^a from P^a (i.e., implements the associative search process) and can be described by the predicate $\Xi(P^a, R^a, T^a)$, where T^a is the associative search time.

For the algorithm (2)-(4), the predicate $\Xi(P^a, R^a, T^a)$ is a sentential function predicating of the verity or the falsity of the current input vector membership in the input space region:

$$d_N \leq d_{N,N-j} \leq d_N + D_N. \tag{8}$$

9. Associative search models for power object dynamics

Based on RAO UES Control Center's telemetry data on behavior of generating facilities, the associative search models were built for estimating the key parameters of power unit frequency responses (Fig. 1).

The calculations of the index of thermal and hydroelectric plants participation in power imbalance elimination and the analysis of the generated power and frequency trends show that higher values of the calculated index correspond to a generating plant more active participation in the OPFR. The cases where the generating capacity increased at frequency increase above 50 Hz, or decreased at frequency decrease below 50 Hz, were detected automatically as the cases of complete nonparticipation of the plant in the OFPR.

After some malfunction in the grid, a specific power unit (Fig.1) has been decreasing its capacity for 20 seconds, then returned to its previous capacity in 60 seconds. Thereafter, it started increasing the capacity, thus responding to the frequency drop in the grid.

Further research should be focused on investigating the dynamic performance of power generating facilities for deeper analysis of contingencies and performance gaps detection, both for generating facilities and the grid as a whole.

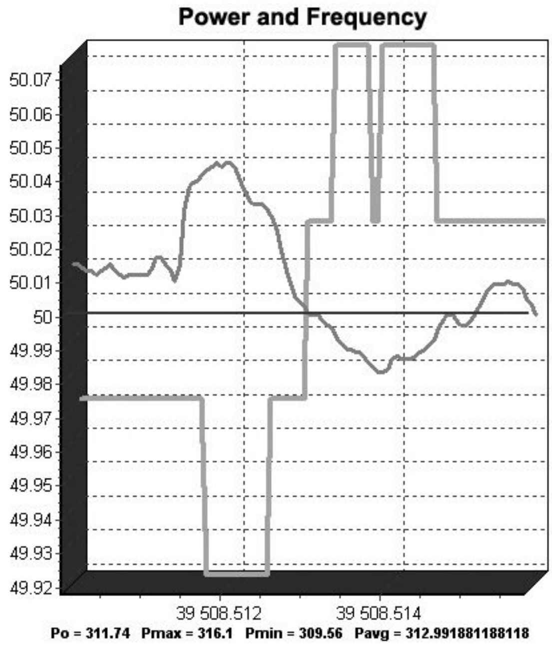

Figure 1. The dynamics of a power unit

References

ANDERSON, P.M. and FOUAD, A.A. (2003) *Power System Control and Stability.* Wiley-IEEE Press.

AYUEV, B. (2007) In the same rhythm with Europe (in Russian). *Mirovaya Energetika* **6**, 25-28.

BAKHTADZE, N., LOTOTSKY, V., MAXIMOV, E. and PAVLOV, B. (2007) Associative Search Models in Industrial Systems. *IFAC International Workshops Intelligent Assembly and Disassembly (IAD'07) & Intelligent Manufacturing Systems (IMS'07).* 1, 120-126.

CHUKREEV, YU.YA., KHOKHLOV, M.V. and ALLA, E.A. (2000) Supervisory control of regional power grid states using artificial neuron network technology (in Russian). *Elektrichestvo* **4**, 2-10.

GAVRILOV, A.V. (2002) The Model of Associative Memory of Intelligent System. In: *Proc. 6th Russian-Korean International Symposium on Science and Technology.* CityplaceNovosibirsk. 1, 174-177.

GJELSVIK, T., RTTING, A. and RYNSTRAND, J. (1992) Long-term scheduling of hydro-thermal power systems. In: *Proc. 2nd Int. Conf. Hydropower*, 539-546.

GONZALEZ, C., JUAN, J., MIRA, J., PRIETO, F.J. and SANCHEZ, M.J. (2003) Long-term generation scheduling in systems with large hydro resources in a deregulated electric power market. *Power Engineering Society General Meeting*, IEEE, 1, 323-326.

HUNT, E. (1989) Cognitive Science: Definition, Status and Questions. *Annual Review of Psychology*, 40.

KANG, CH., GUO, L., BAI, L., XU, R., HE, J., XU, K. (2006) Joint analysis of power system reliability and market price considering the uncertainties of load forecasts. In: *International Conference on Power System Technology.* MK4-02 C0614.

KOZHEVNIKOV, D.A. (2008) System operator's infrastructural role increases (in Russian). *Promyshlenny Yezhenedel'nik*, 8, 236-239.

KRAFTNAT, S. (2000) The system operator's role and challenges in an open market environment. Power Engineering Society IEEE Winter Meeting **2** (1), 822-830, 2000.

LARICHEV, O.I., ASANOV, A., NARYZHNY, Y. and STRAHOV, S. (2001) ESTHER. Expert System for the Diagnostics of Acute Drug Poisonings. *Proc. 21st SGES International Conference on Knowledge Based Systems and Applied Artificial Intelligence.* Springer, Cambridge, 159-168.

MO, B., GJELSVIK, A. and GRUNDT, A. (2001) An integrated risk management of hydro power scheduling and contract management. *IEEE Trans. Power Systems* **16**, 216-221.

MURTY, P.S.R. (2005) *Operation & Control in Power Systems.* BS Publication.

NEWELL, A. and SIMON, H.A. (1972) *Human Problem Solving.* Prentice Hall, Englewood Cliffs, NJ.

NOVITSKY, D.A. (2008) Power system state planning for reliability provision (in Russian). *Proceedings of the Press Conference in Power Ministry of Russian Federation.*

OPPEL, L.J. and ARONSON, D. (1999) Information technology. Its increased importance in the power industry after deregulation. *Power Engineering Society Summer Meeting*, IEEE. **2** (1), 1196-1199.

OU, Y. and SINGH, C. (2003) Calculation of risk and statistical indices associated with available transfer capacity. *IEEE Proceedings. Generation, Transmission & Distribution*, 150 (2).

PATEL, V.L. and RAMONI, M.F. (1997) Cognitive Models of Directional Inference in Expert Medical Reasoning. In: P. Feltovich, K. Ford and R. Hofman, eds., *Expertise in Context: Human and Machine.* AAAI Press, Menlo Park, CA.

PEREIRA, M. (1989) Optimal stochastic operations scheduling of large hydroelectric systems. *Int. J. Electr. Power Energy Syst.* **11**, 161-169.

PIRAS, A. (1996) A multiresponse structural connectionist model for short term electrical load forecasting. EPFL, Lausanne.

PRIKHNO, V.L. (2004) Hierarchical principles of steady state models development based on telemetry information (in Russian). Transactions of the Institute of Electrodynamics of Ukrainian National Academy of Sciences. Kiev, 147-148.

RZEWUSKI, M. ET AL. (1999) Economic load dispatch problem solving using global optimization algorithms (in Polish). *Nat. Conf. on Evolutionary Computation and Global Optimization*, Potok Zoty, Poland, 275-282.

SHEBLE, G.B. and FAHD, G.N. (1994) Unit Commitment literature synopsis. *IEEE Trans. on Power Systems* **9** (1), 128-135.

STOFT, S. (2002) Power System Economics. IEEE Press.

TAKAGI, T. and SUGENO, M. (1985) Fuzzy identification of systems and its applications to modeling and control. *IEEE Trans. Systems Man Cybernetics* **26** (1), 116-132.

VOROPAI, N.I. and HANDSCIN, E.J. (2001) Liberalization and modernization of power systems. *IEEE Power Engineering Review* **21** (1), 16-19.

ZAKHAROV, V.N. and ULYANOV, S.V. (1995) Fuzzy models of intelligent industrial controllers and control systems. II. Evolution and principles of design. *Journal of Computer and Systems Sciences International* **33** (2), 102-106.

ZHU, CH., JIANZHONG, Z., JUNJIE, Y. and WEI, W. (2006) Optimal scheduling of hydropower plant with uncertainty energy price risks. International Conference on Power System Technology. MK1-07 C1345.