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REVIEWS - LETTERS - REPORTS

ROLE OF OPERATORS DURING POWER SYSTEM BLACKOUTS

Ivan Petružela *

Electric power system is a vertically integrated system where energy generation, transmission, distribution and consumption are tied together. Those are juridically different subjects whose operation must respect physical and technical conditions of the transmission, parallel cooperation of plants and unstorability of the electric energy. Implementing of the liberalization on the electric energy market created another economical condition, which influence operating of the power systems.

Mental models used by operators are very important for operating. If a mental model does not respect all current influences and restrictions, the system is transferred into an area of higher error rate. As example is used higher occurrence of emergency conditions of electric power systems in economically advanced countries.

K e y w o r d s: power system, island mode, blackout, operator, mental model

1 PROCESS CONTROL

A control system allows the personnel purposefully influence the operated object so that it is possible to reach the desired state of the process. The system is expected to fulfill certain tasks either fully or partially as a part of a task shared with another system or personnel. The operating personnel performs optimizations of the operation and makes it possible to respect economical, technical, physical and other demands imposed on the behavior of the process.

Most of the systems in the energy industry are dynamic systems, which change their controlled variables to minimize the variation of required values, Fig. 1.

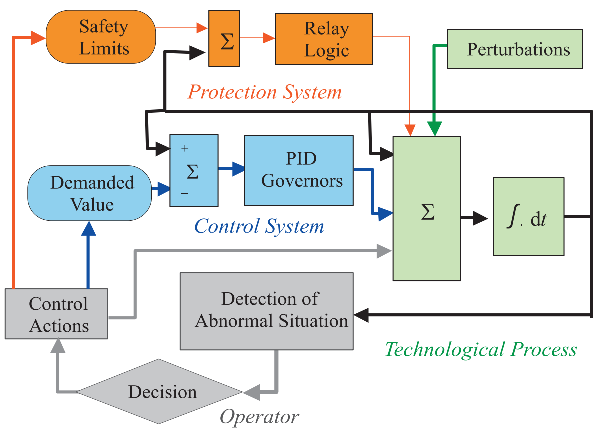

Fig. 1. The role of the operator in the control of the process

1.1 Model of Operating the Processes

Majority of the systems in the energy industry are composed of the process (TP), protections, control system and operator activity. The operation is influenced by numerous error effects. Failures and errors can originate out of the system or even in the system itself. That is why a human - operator - plays an irreplaceable role in the control of complex systems.

The operator must watch the state of the process and, in case of deviation from the desired value; he must perform the adequate intervention. If the operator can not keep the system in its allowed working area, the safety systems shut down the process.

Dynamic properties of the operated object can be described by means of differential equations, whose solution is the state vector x. The state variables are the smallest possible subset of system variables that can define the state of the system at any time.

The control system must keep the state quantities on the required values (set points) w. In dynamic processes of control the operating system changes the state of the process system through the action quantities u so that design conditions are to be achieved. The mathematical notation of it is a set of following differential equations

$$\dot{\mathbf{x}}(t) = \boldsymbol{F}_{TP}\left\{\mathbf{x}(t), \boldsymbol{G}_{RS}\left[\mathbf{x}(t), \mathbf{w}(t)\right], \mathbf{v}(t), t\right\} \qquad (1)$$

where $\dot{\mathbf{x}}$ — is derivation of the state vector (TP state change), $\mathbf{x}(t)$ — is state variables vector (TP state), $\boldsymbol{u}(t)$ — is action variables vector (OS state), $\boldsymbol{F}_{TP}$ — is function matrix (TP description), $\mathbf{v}(t)$ — is error variables vector (TP perturbations), $\boldsymbol{G}_{RS}$ — is function matrix (control system description), $\boldsymbol{w}(t)$ — is desired values vector (required state of TP).

The deficiency of this procedure is the fact that the formalized notation mentioned above is not possible in complex processes and that not all state variables are measurable and do not have to be the output quantities of the system. That is why we choose a set of measurable quantities, vector $\boldsymbol{r}$, which are controlled to trace the desired values as closely as possible. Vector of the desired values of the regulated quantities is represented as $\boldsymbol{w}_z$.

* Czech Technical University, CVUT, Department of Electrical Power Engineeering, Technická 2166 27 Prague 6, Czech Republic; Ivan.Petruzela@ds-s.com

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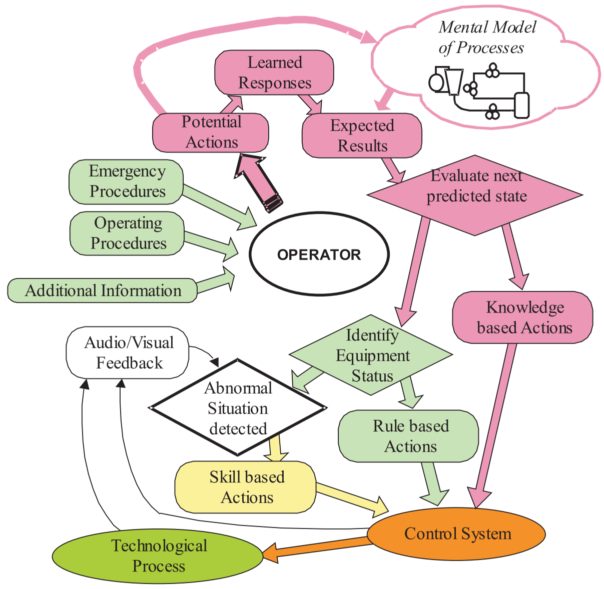

Fig. 2. Role of Mental model at the operator control activity

In the process of the control, the real value of controlled quantities is measured by sensors and is compared to the desired value. According to found deviations (control error) individual governor intervene in the process in a manner to minimize the error or to respect the demands of the project. The set of equations mentioned above (1) is simplified to

$$\boldsymbol{r}(t) = \boldsymbol{F}\left\{G\left[\mathbf{w}_z(t) - \mathbf{r}(t),\right], \mathbf{v}(t), t\right\} \qquad (2)$$

These equations are currently available on many systems and create a basis of models and simulators of the process systems. Power plant simulators allow the operator to learn perfectly the behavior of systems, which means feedback of the control actions or perturbations.

2 HUMAN AND PROCESS SYSTEM INTERACTION

In the control of complex process systems, the presence of human - operator is necessary. Figure 2 shows a way of control a power plant by a human operator. The operators in the control room (CR) can use the following equipment to fulfill their tasks:

- *Audiovisual feedback* — information about the current operational state of the process, about the values of important controlled quantities, about the state of each component and partial systems, about the state of functions and systems providing safety
- *Set of controllers* — which can intervene into the development of the production process and control or revise its running in various operational or failure states.

Non-linear behavior of systems in energy sector makes their operation and optimization difficult. That is why it is important to understand the thought process of operators. From the operator point of view, the process of operating a unit can be divided into three categories [1], which come up to three types of cognitive levels of human behavior:

- *Skill based activities* — these are frequently practiced exercises, which are executed as more or less subconscious routines controlled by fixed rules. Simple failures are solved this way when an operator detects an abnormal situation through the information system. Its timely detection initializes automatic operation and leads to a renewal of the rated state of the power plant.
- *Rule based activities* — when a more complex situation occurs, the operators must identify the real state of the process - either by validation of input information or by watching the results of control interventions, which aim to renew the normal state of the power plant. When performing less-known tasks, the operator helps himself with remembered or written rules.
- *Activities based on knowledge* — when the situation is too complicated and the state of the process isn't clear from the monitoring systems, *eg* thanks to multiple failure including sensor drop-out, the operators must evaluate the current state of the whole power plant, predict probable development of the state of the power plant and determine the procedure to reach the safe state. These are the situations when common models and rules cannot be used directly. This complex of activities comes up to knowledge-based operation.

In all cases, it is very important to estimate all impact of potential operating activities. Each operator uses his own mental model for that. Everybody builds it during the time with his/her own experience, training, interaction with other operators and knowledge of the operating procedures.

Quality of personal mental model and ability to use it makes the difference between good and bad operator.

3 ELECTRIC POWER SYSTEM BLACKOUTS

In advanced countries, the electric power system blackouts occur more and more often. That justifies the fact that the operation of systems was moved to the area covered by safety systems. As stated above, operating is a result of activity of control systems and operator. We can't presume that the same deficiencies happen in different control systems. These electric power systems have another common factor - gradual liberalization of the electricity market. This phenomenon changes the legislative scope and even the method of operation of the energy industry.

Liberalization of the electricity market is the counterpart of unified operating, which is needed for stable operation of concurrently working power plants. Free electricity market magnifies the customer pressure on the producer and holds down the influence of natural monopoles, which results from the technical conditions of electricity production. Under the market conditions, contradictory interests of profit maximization (cost minimization) struggle

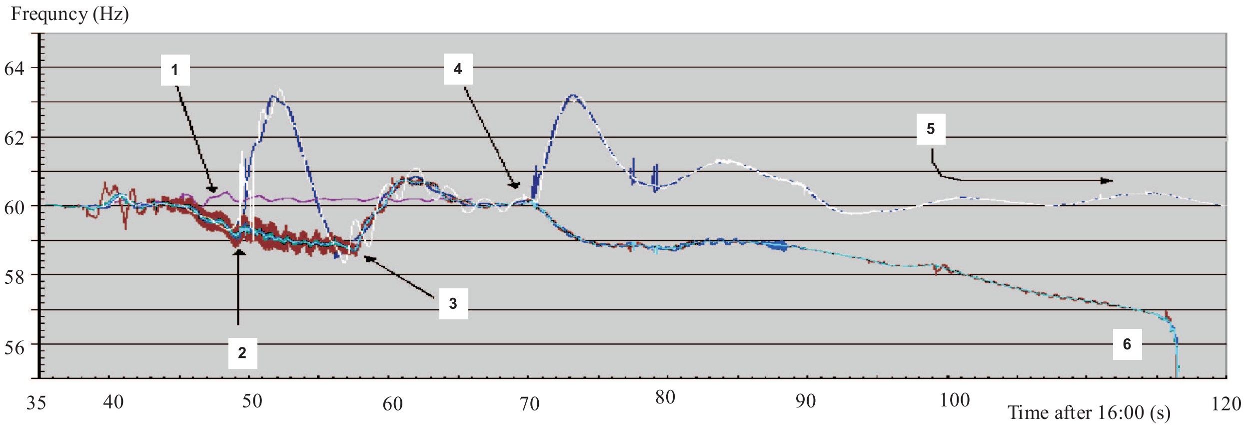

Fig. 3. Frequency behavior during the Blackout in Northeast America (2003): (1) — Northwest Ontario stays with Manitoba, (2) — Beck and St Lawrence Separate from Interior Ontario System, (3) — Beck reconnects to Interior Ontario System, (4) — Beck Re-separates from to Interior Ontario System, (5) — Frequency of Island power system New York stabilization, (6) — Frequency collapse Island power system Ontario

against the demands on high reliability. Trading creates a variable price tie between producer and consumer.

New price tie imposes new requirements on the power system technical structure. These can be contradictory although they have a common action component - the amount of produced electric energy. Direct result of this conflict is the occurrence of failure states

A suddenly high or unbalanced consumption of energy might disrupt the continuous distribution of energy in the network and cause a blackout in one area or even blackout in the whole network.

Analyses of major blackouts show that the first cause rises in the transmission system and spreads in a cascade manner until an isolated area comes up (this state is defined as the island operation of power system). Power plants are operated with non-rated parameters; especially the frequency might significantly differ from the rated values. If a main power plant trip in this situation, total frequency collapse turns up [2], Fig. 3.

3.1 What is the Cause of Often Blackouts?

To reduce blackouts, formerly relatively separate power systems were connected so they could quickly regain the missing power when needed. That is how the interconnected lines came up. As time passed, these were used not only in case of a failure, but also for trading exchange of electricity.

The last decades are characterized by implementing of market mechanisms in the energy sector. Politicians hold down the influence of power monopoles and create a competitive environment aiming to achieve a lower price for the consumers. The production moves to places with lower costs and because the consumption cannot move, the transports escalate. The utilization of interconnecting transmission lines for trading exchanges begins to dominate. Moreover, each system is due to competition operated with as low costs as possible, which leads to reserve lowering.

Operation rules did not take into account increased market liberalization. They do not respect the fact that the operation of power system is influenced by processes in neighbor systems more than ever. Thus, controlling mechanisms stayed in the frame of individual monopoles and stayed behind the dynamics of trading power exchanges, which act as a failure.

3.2 Imperfections in Operator Activity before Island Operation Inception, USA 2003

It became apparent that both rule and knowledge base did not react sufficiently on the changes caused by the legislation. Operators weren't able to change their inveterate mental models to correspond with the changed legislative conditions. The system operator in USA didn't recognize the rise of an emergency situation from the information of power plants.

In the operator communication records [3], it's possible to see insufficient knowledge of the system behavior, restriction disrespect of operator on other levels *etc.* Even two and a half hour before the collapse the operators of power plants reported to the power system dispatchers that the automatic operating moved the work point of the power plant very close to the limit of maximum reactive power. Although it was necessary to solve the question of voltage improvement, the system operator continued to follow the inveterate schemes. The situation did not seem to them too different from the usual situation of covering the daily maximum load.

Simply said, the situation was any time evaluated insufficiently, important signs were neglected and operation procedures were used inadequately. They failed to appreciate the fact that system cohesion in terms of market liberalization continues to increase and operators on all levels should be continuously prepared to face emergency states. Cohesion and unity of operation procedures on various levels (generations, transmission and distribution) was not validated. Thus the personnel committed faults in activities depending both on rules and knowledge.

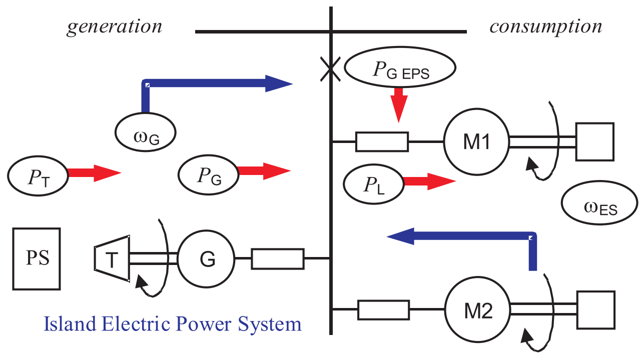

Fig. 4. Power balance at the occurrence of a deficit island system

4 PURPOSE OF THE POWER SYSTEM CODE

The main control tool in terms of liberalization is the Power System Code [4]. It determines both technical conditions of operation in power system for all the producers and distributors and assuring technical conditions of generation and consumption by buying ancillary services from selected producers.

The Code presumes continuous evaluation of how producers meet the quality terms. Rating is performed with certificate tests and failure analysis. Thorough analysis is important for feedback validation of operation rules and operator preparation for emergency conditions.

The Code defines so-called Island Operation which must minimize the impacts of emergency situations in ES. Terms of the Code had to be met by most of the Czech and Slovak power plants in the 90s before joining UCTE. Basic measure was implementation of island operation mode in most power plants. Island operation was a new operation mode, which consists of the necessity to control the ES frequency in a less stable power system.

Although the Code does not define a scheme of governor, it used term Island Operation Controller (ROP). ROP contains, in addition to a proportional speed governor, restrictive control from steam pressure and primary source and opening of bypass stations to the condenser. On some power plants, this controller is a relatively complicated autonomous system. That is why the most of operation personnel perceive the island controller as a black box. Such a solution is not standard. UCTE thoroughly uses the term speed governor.

5 MODEL OF STABILITY ASSURING FOR ISLAND POWER SYSTEM

Operation in an island power system is not a common situation. The rules for these cases cannot be concrete and contain a list of possible scenarios (surplus or deficit island, etc.). If we add the complexity of automation, it is almost impossible for operators to create a mental model to help them in such situations. Nevertheless, it is very important for all operators concerned to share the same simply model. Then their cooperation can be fast and effective, because main necessary information (frequency variation, power variation) are shared in parallel. From the transients of basic controlled quantities, they can identify the basic state of the whole power system and estimate its progress without the need to check all the information with power system operator via telephone.

If generation power PG ES is missing after the occurrence of island system, the operation of the system transfers to a new working point so the production power equals the load power. The frequency is increased and the drop-out of production is covered by:

In the island mode, the system begins to behave differently. The loss of synchronism and the variations of power project mainly into the frequency variations. Power balance is determining, Fig.4.

- increase of plant power through proportional speed governor
- decrease of consumption through the operation on lowered frequency
- releasing the energy of rotating mass by lowering the speed.

6 CONCLUSION

In economic advanced countries, the power system blackouts occur more and more often. That justifies the fact that the operation of electric power systems was moved to the area of more frequent error occurrence.

Operation rules generally did not respond to the implementation of market mechanisms and stayed behind the dynamics of trading exchanges, which act as failures. Lesson learned from blackouts should improve operators mental model and ability to use it during major failures in power system.

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Ivan Petružela graduated from the Faculty of Electrical Engineering, Czech Technical University in Prague (CVUT). Formerly Assistant Professor at the department of Electrical Power Engineering (1989-90). Since 1990 he is with EGÚ Praha a.s., as a research worker in informatics and control systems. His field of interest are dynamic models of controlled plants, control of power distribution in active zone of VVER 1000 blocks, information systems for support of nuclear power plant operators. He was engaged in the design of Nuclear Power plant in Dukovany - primary regulation, island regime.