The Occurrence Reasons and Countermeasures to Power System Blackouts

Michael Uspensky[*1], Sergey. Smirnov[2]

The Institute for Social, Economical and Energy Problems of the North, the Komi Science Center, the Ural Division of the Russian Academy of Sciences; "SO – CDO for UES", JSC, Komi Branch
Syktyvkar, Russia
[*1]uspensky@energy.komisc.ru; [2]smirnov@komirdu.so-ups.ru

***Abstract*-Approaches to cascade failure modeling and their consequences are considered; requirements to controlled separation of power systems for the major emergency prevention with possible blackout are presented; existing approaches to its realization are shown. The power system restoration method after a major emergency with the separation, based on assembly sequence search of its scheme taking into account generation start-up for time is offered.**

Keywords-Power Systems, Cascade Failures, Blackouts, Controlled Separation, Power System Restoration

1. INTRODUCTION

The modern power system of Russia covers huge territory from town Chita to the Kaliningrad region, from the North Caucasus to Kola peninsula, includes a number of the power associations in parallel working on interconnection lines, consists of many thousand power stations, transmission lines and transformers, and is connected with power systems of neighboring countries. They cannot work smoothly for a long time due to the aging of the equipment, the influence of natural environment and the mistaken duty personnel. Nevertheless, thousands of large power system disturbances are annually eliminated by relay protection and automatics devices, which are almost imperceptible for the consumer. But under certain conditions, there can be uncontrollable disturbance, so-called cascade failure with blackout. The special emergency control automatically counteract cascade failures, carrying out switching-off of less responsible consumers, and forming power system islanding into the separate isolated subsystems [1]. However, serious blackouts with catastrophic consequences for consumers and for the power system are still possible.

2. UNAVOIDABILITY OF POWER SYSTEM BLACKOUT

Unfortunately, it is impossible to completely avoid cascade failures in such a difficult structure as power system [2]. In the mid-nineties, the USA offered two models of such failure emergence on the basis of two general system theories. One, an optimization model, championed by Caltech's Doyle, presumes that power engineers make conscious and rational choices to focus resources on preventing smaller and more common disturbances on the lines; large blackouts occur because the grid is not forcefully engineered to prevent them. The second, competing explanation, hatched by a team connected with the Oak Ridge National Laboratory in Tennessee, views blackouts as a surprisingly constructive force in an unconscious feedback loop that operates over years or decades. Blackouts encourage investments in strongly overloaded power systems, periodically counterbalancing pressure on returning maximization of investments and power delivery at the lowest cost. If either the realised optimization, or an uncontrollable feedback results in the disturbance of power systems, large blackouts are natural aspects of their work [3].

The some researchers mark shortcomings of wide liberalization on the power supply market as one of reasons for failure occurrence. Power delivery industry liberalization growth has led to an essential increase in inter-regional (international) deliveries where often the reliability assessment of system functioning is not carried out properly [4]. The traditional decentralized operational control way by the existing dispatching centers, with each of them only caring about the management of the area and a small information exchange in real time, leads to inadequate and slow reaction to large disturbances. Here a new way of the coordinated operational dispatching is necessary for system reliability maintenance. This new mode demands to overcome some organizational, psychological, legal and technical problems [5].

Irrespective of sights at a blackout, the electrical engineers believe that risks system disturbance can be lowered essentially. With disturbance imposing on power system, at first the mode does not pass out a zone of irreversible consequences; relay protection, emergency automation and also the operating staff provide fast enough mode restoration with the minimum losses of power deliveries to consumers. However, there is such disturbance (trigger) event at which the mode passes through the specified border [6, 7]. A number of researchers sort out the reasons of considered major accidents on the inevitable and what can be avoided. Firstly, there are casual events: an airplane crash on a line, blow of the building crane, the natural phenomena, etc. The second include, for example, wrong actions relay protection, the personnel on duty, flashovers due to a contact with trees. The reasons of the second group are more often in failure development. For Automatic problem, measures should be taken for a non-admission of trigger disturbance by means of balance operations of change with active and reactive powers by management of loadings and generation. In essence, it is the last stage of automatic protection work. As a rule, it resolves at functioning modes of power system equipment, close to the limit [8].

3. POWER SYSTEM ISLANDING AND APPROACHES TO ITS DECISION

Power system islanding refers to emergency measures with switching actions and is implemented during transient. As far as the first time power system islanding in the USSR was applied to the Volga Hydroelectric Station when it merged two interconnections, there was a need to transfer power between them. The experience of power system islanding application was highly successful when failures and overloads of power station intersystem transmission lines occurred because placement of section breakers roughly corresponded to the balance of power [9]. However, reliable generator division requires complicated and costly power stations circuit schemes to prevent further development of islanding. There are three types of islanding in terms of purpose: for prevention of violation of stability (preventive), for termination of asynchronous mode (out-of-step protection), prevention of power station own needs loss at an unallowable decrease of frequency in power system during accident (automatic frequency divider) [10]. The second and third types of islanding are widely implemented by local devices in practice. But with coordinated impact on defined breakers taking into account the additional conditions, preventive islanding can lead to significant systemic effect. Other names of such islanding are controlled as separation, partitioning, operated division etc. Modeling of large blackout, occurred on August 14, 2003 in the USA and Canada, showed that timely implemented power system islanding could rapidly limit the development of accident, decrease active power flows in the overloaded cross-sections, improve voltage levels and angle characteristics of generators in formed islands [11]. These benefits provide a good basis for further rapid restoration of power system and minimization of damage from accident. Unlike uncontrolled islanding, which is executed by stand-alone automatics installed on power system objects, controlled islanding is division coordinated by a number of featured mode and aimed at detection of trigger event. Controlled islanding involves three subtasks: when to initiate, for which cross-sections and in which sequence. The success of controlled islanding depends on the correct definition of where and when to divide. Below are the requirements for their solutions, as well as existing approaches to them.

3.1. Determining the islanding start time (when). The most effective islanding is almost right (of a second) after the occurrence of the trigger event [7]. The more time it delays, the greater development of accident will get and more power will be lost as a consequence. Definition of the islanding moment in real time is a rather difficult task because of unpredictability and diversity of possible disturbances in large power system. Actively developing methods of dynamic security assessment can be used to solve this problem [12]. The traditional approach to this evaluation is to conduct cyclical simulation of transient by solving differential equations. A large set of possible contingencies and power system model parameters significantly increase the time of receipt of assessment and it is unacceptable for controlled islanding purposes. Systems based on artificial intelligence and data mining have the following advantages over the traditional: speed of estimate (of a second), educability, detection of previously unknown characteristics and relationships in the system. In deciding islanding in real time, parameters, which can lead to a collapse of power system transient, can be used as a threshold (e.g. voltage phase angles). The resulting modeling database may be supplemented by information about large accidents that occurred in power system before and can be used to train decision trees or artificial neural networks. Using these tools of artificial intelligence with synchronized p*hasor measurement* units (PMU), automatic decisions can be made to start controlled islanding in real time.

3.2. Searching of islanding cut (where and how). Always there are many variants of islanding (cutsets) in a large power system. Choosing an optimal cutest among them is quite complex, multifactorial. Generally, the cutset is a set of some power lines. Therefore, for power system with $\boldsymbol{n}$ power lines, theoretical number of possible variants is 2^n. However, as the search result should ensure some constraints, the number of valid options is significantly reduced. These constraints include:

Dynamic stability. Clearly, all generators within an island must be synchronized. The response of power system generators to large disturbances is different and depends on their dynamic characteristics and structural features of the system. There are several approaches to determination of generators based on parameters of previous steady state which will show similar oscillations when a large disturbance happen [13]. Such generators can be coherent and grouped, but connection between the groups will be weak. Thus for dynamic stability of formed islands, generators from one coherent group should be included in one island. It is also necessary to consider that simultaneous tripping of transmitting significant power lines leads to transients due to an abrupt redistribution of power flows.

Ensuring acceptable frequency and voltage levels. In each island, the main operational parameters (frequency and voltage) must be within acceptable limits, which require to minimize the imbalance of active and reactive power between generation and consumption. Otherwise, the collapse of islands into smaller parts and their following blackouts can continue. To account this requirement during the search, the optimal cut graph of power system is typically used. Vertices are the nodes, edges – lines and transformers. In some approaches, the weight of the edges of the graph correspond to the absolute value and direction of active power [11], while others uses a graph, where the weight of a vertex is the difference between generation and consumption of active power at node [14]. In [15], edges have two values of the weights – values of active and reactive power flows, which is distinguished from others, providing a solution of the reactive balance problem due to automatic reactive power compensation local devices. Using libraries that implement the multilevel graph partitioning methods, islanding of power system with 22000 nodes (even without graph reduction) is provided in less than a second [15]. However, for large graphs (more than 5000 nodes and branches), the number of islands is greater than the desired [11], which leads to the need for additional calculations on their merging. Using ordered binary decision diagrams (OBDD) [16], angle modulated particle swarm optimization (AMPSO) [17] also significantly speed up the searching of optimal cut in large power system. Entering correction factor determined to a large extent by results of expert assessments is a common drawback of these methods. Although there are a number of effective approaches to finding a cut with a minimal power flow (minimal cut) but choosing the best of them is an open question. As the comparison of several algorithms with respect to certain power system has not been known. It should be noted that almost all methods mentioned here for the search of minimal cut are proposed for implementation outside of the real-time, before the accident.

Prevention of equipment overload in post-accident modes. Possible current overload of equipment will cause tripping and the further development of the accident. Thus, it is necessary to assess the acceptability of post-accident mode at each island to test proposed scheme of islanding.

Minimizing of formed islands and operations numbers. Another criterion for choosing optimal cut is a number of formed islands. Reducing the number of islands simplifies both the controlled islanding process and power system restoration. In order to minimize lost power flows, preference should be given to islanding schemes with a less number of disconnected lines and switched breakers. The more breakers the process of islanding involves, the higher the probability of their work failure. Breaker failure during islanding is reserved in accordance with the general principles of redundancy of such events.

To find the optimal islanding cut by taking into account the above conditions is an optimization problem. The results of the solution, as noted above, are necessary during the first and the second occurrence of the accident. There exists a problem of finding an acceptable ratio of the calculation speed and its accuracy. In this regard, searching of islanding cut apparently should be carried out in real-time, and the greatest attention should be paid to the accuracy of the result. Wrong selection of islanding cut may reduce the effect of its conduct, and even the development of the accident.

Form of implementation. Transience of severe accident (often seconds) leaves no time for dispatcher to peer review of different variants. In addition, there is a chance for the person making wrong decision in a stressful situation. These all need to design an automatic scheme. In this regard, algorithm of power system islanding can be implemented under the centralized emergency control computer system placed in dispatching center. With sufficient availability of breakers, remote control physical devices of islanding are not required. Otherwise, such devices should be installed at predetermined locations. Then, to avoid blackout, some devices must be operated at the same time with the remaining block [1]. However, the commonly used out-of-step protection devices are not adapted to coordinate at the system level and development of specific local devices is required. Serious attention should be paid to the coordination of the controlled islanding system with local relay protection devices already installed in power system.

Speed. The rapid nature of the accident development imposes special requirements on the time of the control action. Speed of islanding implementation largely depends on the breakers and communication devices. Various performances of breakers are caused by their type and technical condition. In addition, to control islanding in real time, there is an urgent need to improve power system infrastructure (widespread use of PMU, broadband telecommunications).

4. POWER SYSTEM RESTORATION METHOD

The following stage – island joining in system – is carried out by dispatchers in the time deficiency conditions. The predetermined procedures of managements and instructions on power restoration are difficult and cannot capture all possible variant circles of failure development. In these conditions, computers act as advisers for dispatchers, and in further as automation of failure liquidation.

It is noted in [18], search of power system restoration sequence after large system collapse can be organized by means of a program complex for power supply restoration in distribution networks. It uses competitive search of the restoration scheme by two algorithms: on a basis of network count and of artificial neural networks (ANN) with selection of decisions by the condition calculation block (CCB). For the specified application, here in complex algorithm, a number of the conditions defined by requirements at the restart of power system are added as follows:▪ An estimation of generation capacity possibilities in system buses for the moment defined by their start characteristics at technical minimum maintenance of their loading and the account of their input time;

▪ The account of connected bus importance (priority), defined by its function (generation, loading), loading liability, network topology and its mode features;

▪ Mode conditions on switching overvoltage and synchronisation possibility of restored islands.

The order of generating unit input is defined by the following conditions. For visualization, we will take advantage of the generalised unit start-up parameters (Tab. I) and the simplified start-up characteristic (Fig. 1). The majority of units demands start-up external power – P_S, necessary for work of auxiliary mechanisms (pumps, latches etc., Tab. I). With an increase in own capacity – $P_{inc..}$ – a supply of these mechanisms is transferred on the generator of the started-up unit (auxiliary capacity – P_{AC}).

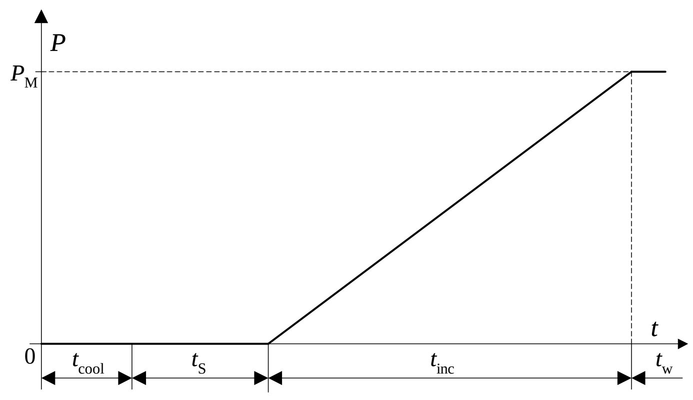


Fig. 1. Unit control characteristic example.

Unit start-up is carried out according to its control characteristics (Fig. 1) which defines the following parameters: P_M – the maximum working active power of the unit generator; $t_{cool.}$ – cooling time, time from the output moment of a thermal turbogenerator part from work, which concretises a control characteristic of the thermal unit (Tab. I); $t_{S.}$ –starting time, unit preparation for a capacity increase. Implementation steam generating unit time is put on the same meaning usually; $t_{inc.}$ – time of generator synchronisation with power system and power increase P_M; $t_{hc.}$ – hot condition time.

TABLE I. START-UP PARAMETERS OF ELECTRIC POWER GENERATION UNITS

Unit type	Start-up conditions	P_S, p.u.	t_S, h	$t_{inc.}$, h	P_M, MW
Diesel-generator	emergency starting	0	0.1	0.1	0.2 – 7
Turbo-gas unit (TGU)	emergency starting	0.003 P_M	0.3	0.3	2 – 150
Combined-cycle unit (CCU)	hot start-up , $t_{cool} \le 8$ h	0.04 P_M	2.0	0.5	30 – 300
	not cooled , 8 ч $\le t_{cool} \le 72$ h		3.0	0.5	
	cold start-up , $t_{cool} \ge 72$ h		4.0	0.7	
Hydro generator		0.01 P_M	0.1	0.1	3 – 300
Thermal station unit	hot start-up, $t_{cool} \le 8$ h	0.06 P_M	2.5	1.5	150 – 500
	not cooled, 8 h $\le t_{cool} \le 72$ h		5.5	3.0	
	cold start-up, $t_{cool} \ge 72$ h		7.0	5.0	
Nuclear station unit	hot start-up, $t_{cool} \le 24$ h	0.08 P_M	20.0	3.0	400 – 1000
	cold start-up, $t_{cool} \ge 140$h		72.0	5.0	

t_S – time of preparation and start-up unit, $t_{inc.}$ – time of load increase to rated power P_M, $P_п$ – necessary for start-up external power.

The control characteristic varies even for the same thermal unit, including, time of its cooling after an output from work, and it essentially influences on its time parameters. It is visible from Tab. I, depending on thermal unit cooling time after stopping work, the start-up mode can be divided into: hot ($t_{cool.} \le 8$ h), not cooled (8 h $\le t_{cool} \le$ 72 h) and cold start-up ($t_{cool.} \ge 72$ h). Similar characteristics exist for other thermal units: the turbo-gas unit (TGU), combined-cycle unit (CCU), thermal station, nuclear station etc. Here pertinently notice that, as a rule, atomic power station units do not participate in post-fault power system restoration.

With the account stated above, restoration process is reduced to the following steps (Fig. 2):

1. A control characteristic choice of units, which is brought into operation, depends on switching-off time, downtime duration (Tab. I) and a fuel kind. First of all, it is connected with thermal units of type: TGU, CCU, unit with the steam prime mover. There is priority estimation on their implementation.

2. A choice of an account step in time. It is convenient to accept that it's equal to the minimum starting time from the units chosen for start-up, but it is unessential. What matters is the time because anything essential does not occur in a starting mode. At its great value, incorrect transfer from a starting mode in a power increase mode of the unit is possible, and at its small – increase in time of unessential accounts.

3. Definition of the unit start-up moment in observance of conditions in time and on the capacity necessary for operation performance. In the absence of such characteristics for the concrete unit, they can be defined from Tab. I, which is constructed on the basis of the data [19].

4. On each account step, the available capacity P_{avl} is revealed in each restored generating bus by a technique [21]. Here as loading the necessary capacity for starting generating units acts, P_{avl} is the active power given out by generators minus the necessary capacity for start-up and work of units. The unit start sequence is defined, first, by smaller time of unit start-up and entering of a hot condition.

5. Repeat points 3 and 4 while the available capacity does not exceed the necessary capacity for start-up and work of the next units.

6. When system capacity is greater than the necessary capacity for start-up of all chosen units, the restoration method [20] uses for a consumer supply in addition to points 3 and 4.

Concerning a reactive power, the same operations with the active one are carried out, and at its known consumption, given values are substituted;, and at ungiven ones,

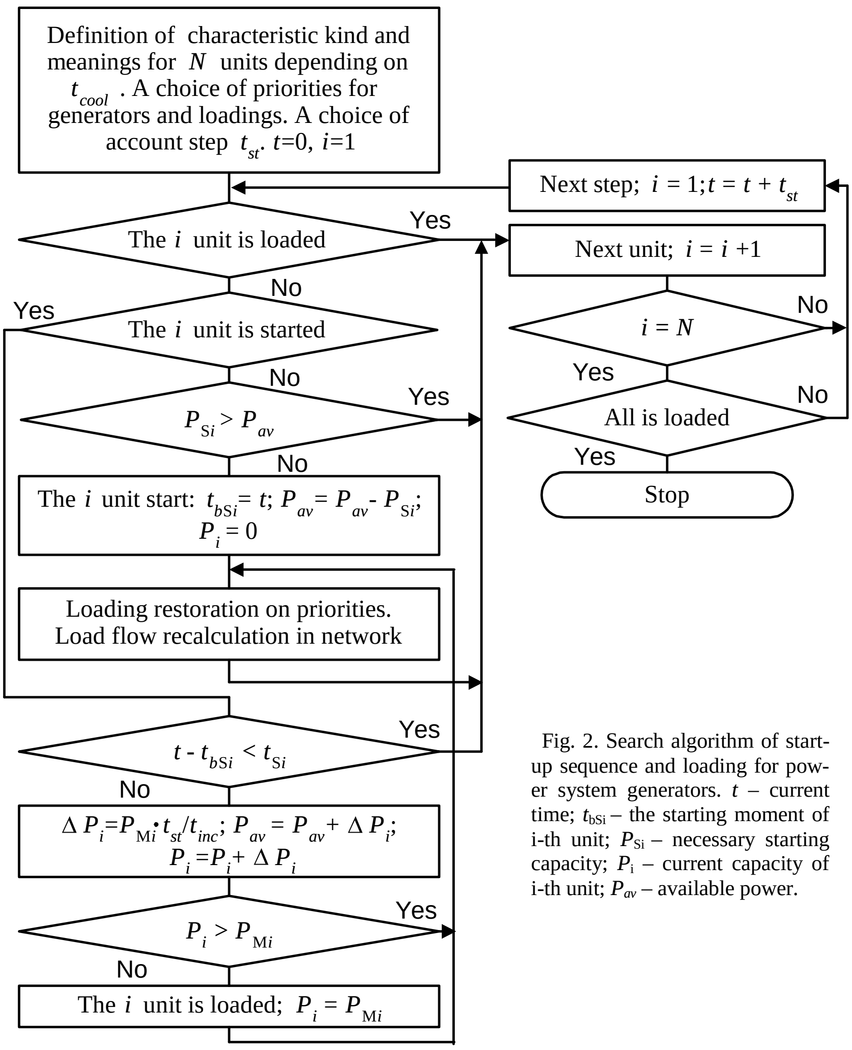


Fig. 2. Search algorithm of start-up sequence and loading for power system generators. t – current time; t_{bSi} – the starting moment of i-th unit; P_{Si} – necessary starting capacity; P_i – current capacity of i-th unit; P_{av} – available power.

it is estimated on *cos* φ = 0.85. It is necessary to note that units, which remained in work at failure occurrence and liquidation, are easily entered into the considered algorithm. t_S=0 and t_{cool}=0, and $t_{inc.}$ are defined to be in conformity with given out capacity.

Loading connection sequence search is carried out according to bus priorities. A bus with electric power source has the highest priority as it concerns auxiliary loading of generation bus. The received capacity taking into account the stipulated conditions in bus is distributed further between bus-consumers according to the bus priority base on its category and operation conditions, and the additional estimations stipulated. If there are consumers of different priorities at bus, it breaks on some virtual buses so that consumers of higher priority were provided first.

In a distributive network, scheme search occurs at the interaction of ANN, CCB and generalised error vector (GEV) blocks. ANN offers a scheme variant. CCB checks it on mode conditions and forms vector GEV at the negative answer, then corrects a scheme choice in ANN. Interaction of these blocks is stated in [20] in more detail. In system network unlike [20], the presence of different sources need their parallel work in the requirement of their teamwork mode check and at positive result – synchronisation of such system parts. Realisation of specified condition check is carried out in the GEV, that entering into a network restoration complex, as follows.

First, at the joining of two islands for the mode estimation period in model, the source signs of these islands are equal. Then the possibility of mode existence is checked in the condition of calculation block and at positive result, the joining dynamics of these islands is checked. If this stage answers in the affirmative, then the scheme is accepted and realised with synchronisation of these parts. Otherwise, other offered scheme variants are checked. The second difference in the restoration power net algorithm from a distribution net is that auxiliary for power station start with the highest priority is provided first. Scheme unacceptability and a direction of its change specify block GEV, using the information from CCB. It activates ANN self-training function of a solving complex, as the presence of zero in GEV means that current power system division into islands has not got training set, and search of the new decision is required.

As opposed to a method for a distribution net, here at GEV estimation three kinds of processed buses are considered. The first one – the load bus – is similar to a distribution net load bus; the second – the generating bus – should consider possibilities on delivery of an active and reactive power at the moment of its processing, which is similar to the bus in a distribution net, but takes into account the power developed in it at the moment of account; the third – synchronized bus – solves a joining problem of two neighboring buses, which are connected with different sources but not working in parallel. Its feature is the definition of joining necessity and possibility for parallel work of two islands. Taking into account these features, GEV block-diagram is shown as follows (Fig. 3).

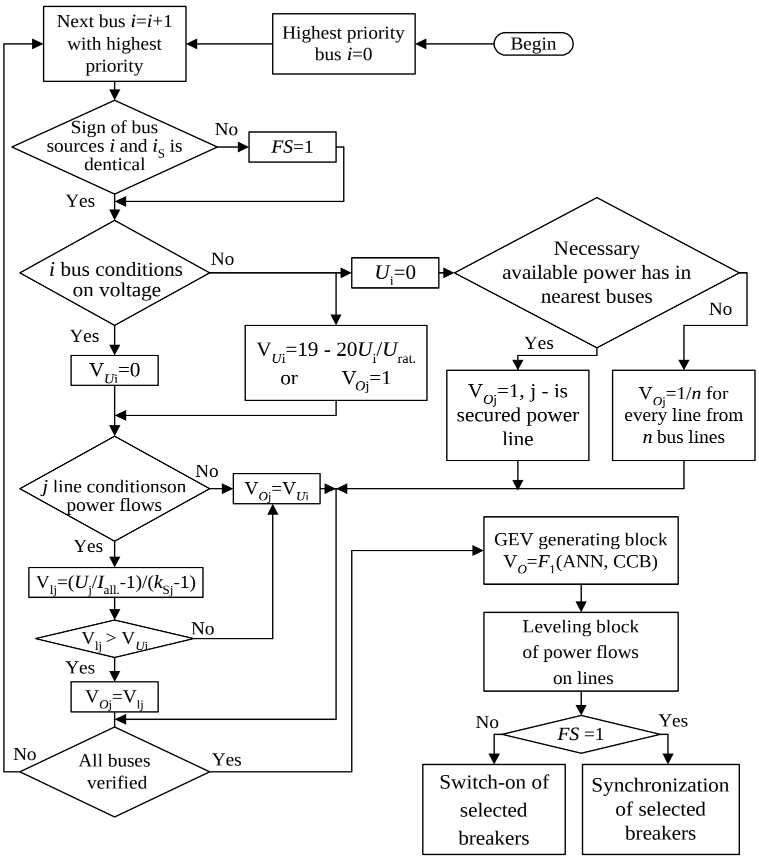


Fig. 3. GEV component formation block-diagram. *i* – bus number; *j* – number of feeding line for *i*-th bus; U_i and I_j – runing meanings of a bus voltage and a line current; $U_{rat.}$ and $I_{all.}$ – rated voltage and allowable line current; – admissible factor of an overload.

If simultaneously there are errors on bus voltage and on a line feeding current, then the greater one will be accepted. The line state error is defined from conditions according to the description [20].

At detection in the next bus, the GEV block temporarily levels these signs, thus establishing a synchronisation flag – ***FS***, and CCB block defines an joint mode admissibility a. At positive decision, GEV specifies communication between such buses as demanding synchronisation at power-on and unites signs of power system synchronizable parts. Otherwise in each part there is an own sign, the synchronisation flag is dumped, and restoration scheme search proceeds. Thus, ***FS*** specifies line, which joins with synchronisation of united system buses.

It can be noted that, algorithm-working conditions directly depend on state change, at the occurrence of additional power input or additional consumer in any of islands. Thus, it is possible to optimise not only a current state, but to consider prospect of the subsequent scheme change and to understand, what influences demand immediate implementation and which ones can be removed for later term, as expected input of power/loading can make influence undesirable.

5. SIMULATION RESULTS

The offered method of a power system restoration was verified on the test scheme (Fig. 4). A

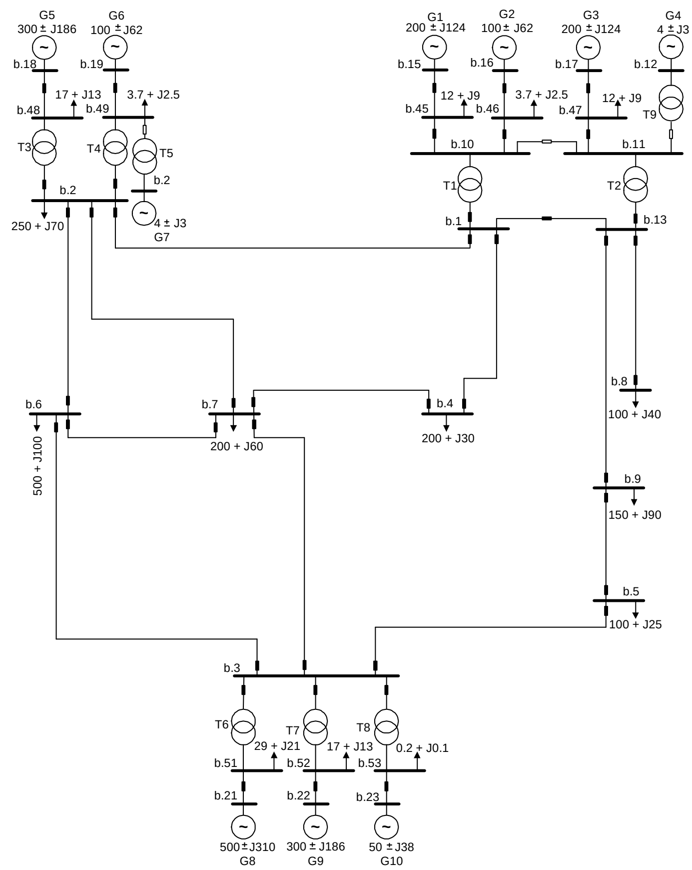


Fig. 4. Test power system model.

scheme specification is given in Tab. II. G4 and G5 generators are black start units; G10 is gas-turbine unit; G6 is steam-gas unit. Rest turbo generators are steam units. The grid is 220 kV. In load row, the last digit after "*p.*" is priority. Results of restoration sequence taking into account restrictions by a unit thermal part are reflected in Tab. III.

Generated capacity provides, first, generator auxiliary for buses with the highest priority, and are taken into account the connection possibilities defined by ANN scheme search block and CCB program, and generated value and allocation of capacity in the concrete time moment. The modeling step of a computer complex for power system restoration, according to a technique, is accepted in 6 minutes after diesel generator start-up time. The important problem is to reveal the synchronizing moment for the started generator with system. It is defined according to algorithm (Fig. 3).

The position "Loading maintenance ***n***-th bus" in a mode description cell (Tab. III) specifies change of this value at generated capacity change. At lack of such change, the ***n***-th bus is not mentioned. In the mode description column, the generated capacities, changed on a given step, are specified in brackets. The generator capacity growth is accepted linearly from time though this characteristic can be set at any necessary form on time.

The choice of the switching scheme on each step is carried out as follows. Generated power is the entrance data. On load priorities and a device switching condition, the ANN block offers scheme variants, and CCB program selects the scheme, admissible on mode conditions. The positive difference between available and consumed power defines some reserve at scheme restoration.

TABLE II. BASIC TEST POWER SYSTEM EQUIPMENT

Generators	G1–200 MW, G2–100 MW, G3–200 MW, G4–4 MW, G5–300 MW, G6–100 MW, G7–4 MW, G8–500 MW, G9–300 MW
Transformers	T1–400 MVA, T2–400 MVA, T3–400 MVA, T4–125 MVA, T5–4 MVA, T6–630 MVA, T7–400 MVA, T8–63 MVA, T9–4 MVA
Lines	1-2 – 250 km, 1-4 – 150 km, 2-6 – 50 km, 2-7 – 70 km, 3-5 – 145 km, 3-6 – 50 km, 3-7 – 300 km, 4-7 – 50 km, 5-9 – 40 km, 6-7 – 40 km, 8-13 – 70 km, 9-13 – 75 km
Loads	**2** – 20+j10-p.15, 230+j60-p.9; **4** – 30+j10-p.16, 170+j20-p.11; **5** – 100+j25-p.9; **6** – 30+j20-p.11, 470+j80-p.7; **7** – 30+j10-p.18, 170+j50-p.10; **8** – 100+j40-p.6; **9** – 40+j20-p.9, 110+j70-p.6;

It is obvious that in the restoration course the number of comprehensible intermediate schemes on this or that step can be big enough. The matter is that at certain initial conditions the load maintenance scheme is defined by variety of the changing entrance data, namely, generated power value and allocation on system at each concrete restoration step, a priority and loading sizes, status of the switching scheme and link loading, performance of conditions on bus voltages. That is why load maintenance at step-by-step restoration is not carried out strictly on priorities. The computer complex on each step offers some scheme taking into account the listed priorities of loadings and restrictions on a mode condition. If it does not pass on a mode (in CCB) on any step, there is a reduction of loadings to a high priority, and the rest of generated power is transferred to lower priority loadings. For the same reason, search of the comprehensible decision without using information technology is very complex.

Thus, for given power system scheme, the complete system restoration occurs on 65th step during 6 h. 30 min. and a generation complete recovery (taking into account a hot reserve) – on 68th step (6 h. 48 min).

5. CONCLUSIONS

At power system functioning, it is necessary to consider blackout possibility with the growing complexity of the system due to element ageing, external actions and human errors. Initiation to blackout is defined by one of consecutive indignations in power system, trigger event. Decrease in blackout risks is connected with the settlement of countermeasures by them, which, in turn, demands research technique development and failure course models. The operation islanding is concerned to the number of such measures and includes three subtasks: when, where and how to carry out power system islanding.

The operation islanding is a perspective method of power system protection from blackout caused by the major accidents. The resulted requirements for operation islanding allow the revelation of the problems to be solved at its carrying out, and the methods used in them. However, for its practical realization, further perfection in definition of time and a division place is necessary. There is a vital issue of maintenance for operation islanding in necessary volume of high-speed measurements and remote control means.

TABLE III. RESTORATION OPERATIONS AND THEIR SEQUENCE UNDER POWER SYSTEM TEST

Step	Time	The scheme	The mode description	Step	Time	The scheme	The mode description
0	00:00	All is discon-nected	Start-up DG-4000 in 12-th and 20-th bus-es.	41	04:06	+ (11-13-8); + (13-9-5); + (1-13); - (10-11)	Loading maintenance 60+j25 in.5-th bus, 30+j10 in 8-th bus. ($P_{G1,G3}$ on 39 MW; $P_{G5,G9}$ on 45 MW)
1	00:06	+ (12-11-10-46); + (20-49)	Energizing and start-up of auxiliary equipment (46-th and 49-th buses) and a thermal part of units in 16-th and 19-th buses.	42	04:12	+ (6-7)	Loading maintenance 60+j30 in 9-th bus. ($P_{G1,G3}$ on 53 MW; $P_{G5,G9}$ on 60 MW)
21	02:06		Start-up of unit electric part in 16-th and 19-th buses.	43	04:18		Loading maintenance 55+j35 in 2-th bus, 160+j90 in 6-th bus. ($P_{G1,G3}$ on 66 MW; $P_{G5,G9}$ on 75 MW)
22	02:12	+ (46-16); + (49-19)	16-th - 12-th and 20-th - 19-th buses are synchronized. ($P_{G2,G6}$ on 20 MW)	44	04:24		Start-up of unit electric part in 21-th bus. Loading maintenance 80+j50 in 2-th bus , 190+j100 in 6-th bus. ($P_{G1,G3}$ on 79 MW; $P_{G5,G9}$ on 90 MW)
23	02:18	+ (49-2-48); + (10-45); - (12-11); - (20-49); + (2-7-3-53); + (3-52)	Energizing and start-up of auxiliary equipment (45-th, 47-th, 48-th, 52-th and 53-th buses) and a thermal part of units in 15-th, 17-th, 19-th, 22-th and 23-th buses. Auxiliary switching (46-th and 49-th bus-es) on G1 and G6 generators. Switching-off DG-4000. ($P_{G2,G6}$ on 40 MW)	45	04:30	+ (21-51)	G8 connection with synchronisation in 21-th bus. Loading maintenance 100+j70 in 2-th bus, 240+j100 in 6-th bus. ($P_{G1,G3}$ on 92MW;$P_{G5,G9}$ on 105MW; P_{G8} = 20MW)
24	02:24	+ (1-4-7); + (3-51)	Energizing and start-up of auxiliary equipment (51-th bus) and a thermal part of units in 21-th bus. Buses 1 – 2 are syn-chronized. Loading maintenance 20+j10 in 7-th bus. ($P_{G2,G6}$ on 60 MW)	46	04:36		Loading maintenance 180+j70 in 2-th bus. ($P_{G1,G3}$ on 106MW;$P_{G5,G9}$ on 120MW;P_{G8} =40MW)
26	02:36	+ (2-6-3); + (53-23)	G10 connection with synchronisation in 23-th bus. Loading maintenance 70+j40 in 6-th bus and 40+j20 in 4-th bus. ($P_{G2,G6}$ on 100 MW; PG_{10} = 10 MW)	50	05:00		Loading maintenance 250+j70 in 2-th bus, 100+j30 in 4-th bus, 500+j100 in 6-th bus, 80+j30 in 7-th bus. ($P_{G1,G3}$on 187MW;$P_{G5,G9}$ on 210MW;P_{G8} =160MW)
27	02:42	+ (3-5)	Loading maintenance 40+j20 in 5-th bus. (P_{G10} = 50 MW)	51	05:06		($P_{G1,G3}$on 200MW;$P_{G5,G9}$ on 225MW; P_{G8}=180MW)
38	03:48		Start-up of unit electric part in 15-th, 17-th, 18-th and 22-th buses.	52	05:12		Loading maintenance 200+j60 in 7-th bus . ($P_{G5,G9}$ on 240 MW; P_{G8} = 200 MW)
39	03:54	+ (15-45); + (17-47); + (18-48); + (22-52)	Connection with synchronisation of G1, G3, G5 and G9 generators in 15-th, 17-th, 18-th and 22-th buses. Loading mainte-nance 25+j7 in 2-th bus, 90+j50 in 6-th bus. ($P_{G1,G3}$ on 13 MW; $P_{G5,G9}$ on 15 MW)	57	05:42		Loading maintenance 200+j30 in 4-th bus, 100+j25 in 5-th bus, 120+j60 in 9-th bus. (P_{G8} = 280 MW)
40	04:00	+ (1-2)	Loading maintenance 35+j15 in.2-th bus, 120+j70 in 6-th bus, 20+j10 in 7-th bus. ($P_{G1,G3}$ on 26 MW; $P_{G5,G9}$ on 30 MW)	68	06:48		Loading maintenance 100+j40 in 8-th bus, 150+j90 in 9-th bus. (P_{G8} = 500 MW)

Important component of counteraction to failure consequences helps the organization of power system restoration. It is shown that, for search of restoration scheme after failure, it is possible to use algorithms on a choice of the restoration scheme for distribution network and to add the algorithms, considering the power system restoration specificity. The data on generation unit start-up sequence and an available power are defined by generation restoration algorithm according to their control characteristics and a technical state at the starting moment. GEV block modification is connected with revealing and realisation of teamwork for two buses with different generation sources by their joining through synchronisation.

As a whole, modeling on test system has shown availability of the offered method at power system restoration after blackout.

REFERENCES

[1] M. M. Adibi, R. J. Kafka, S. Maram, L. M. Mili, "On Power System Controlled Separation", *IEEE Trans. on PS*, vol. 21, no. 4, pp.1894-1902, 2006.

[2] F.F. Rodjukov, "Correct Mathematical Model of the Synchronous Machine and Mathematical Model of the Big Power System", *Mathematics in high school*, no. 10, Internet magazine SpbGpU. Available: http://www.spbstu. ru/public/m_v/N .../ contents.html. Родюков Ф.Ф. Корректная математическая модель синхронной машины и математическая модель большой электроэнергетической системы. // Математика в ВУЗе, № 10. Интернет-журнал СПбГПУ. –. (In Russian).

[3] P. Fairley, "The Unruly Power Grid", *IEEE Spectrum*, pp. 22-27, August, 2004.

[4] J.W. Bialek, "Blackouts in the US/Canada and Continental Europe in 2003: is Liberalisation to Blame?", *IEEE PowerTech*, paper #698, Russia, June 2005.

[5] M. Ilič, "Technologies and Management Structures to Support Reliable and Efficient Operation over a Broad Range of Generation and Demand", *First Energy, Inc. website, November 2003*, (also *New Electricity Transmission Software (NETSS), Inc. WP03-01, December 2003*).

[6] P. Pourbeik, P.S. Kundur, C.W. Taylor, "The Anatomy of a Power Grid Blackout", *IEEE Power&Energy Magasin*, pp. 22-29, September/October 2006.

[7] N. I. Voropai, D. N. Efimov, "Analysis of Blackout Development Mechanisms in Electric Power Systems", IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, pp.1-7, 2008.

[8] "Cascade Failures in Power Systems, Their Prevention and Restoration of Working Capacity of Power Systems: Prevention of Large-scale Fan Switching-off of an Electrical Supply in Large Cities-Megacities", Available: ftp.so-cdu.ru/RZA/old_archiv/kaskad_avar.pdf.
Каскадные аварии в энергосистемах, их предотвращение и восстановление работоспособности энергосистем: Предотвращение крупномасштабного веерного отключения электроснабжения в крупных городах-мегаполисах. (In Russian).

[9] J. Barkans, D. Zalostiba, *Protection against Blackouts and Self-Restoration of Power Systems*. – Riga, Latvija RTU Publishing House. 2009.

[10] L.A. Koshcheev, *Emergency Control in Power Systems* – Leningrad, Energoatomizdat, 1990.
Кощеев Л. А. Автоматическое противоаварийное управление в электроэнергетических системах. – Л.: Энергоатомиздат, 1990. – 140 с. (In Russian).

[11] B. Yang, V. Vittal, G.T. Heydt, "Slow-coherency-based Controlled Islanding – a Demonstration of the Approach on the August 14, 2003 Blackout Scenario", *IEEE Trans. on PS*, vol. 21, no. 4, pp.1840-1847, 2006.

[12] G.P. Shumilova, N.E. Gotman, T.B. Starceva, "Border Estimation of Dynamic Reliability for Power System", *Komi Science Centre News of Russian SA*, *Ural Department*, no.1, pp.80-86, 2010.
Шумилова Г. П., Готман Н. Э., Старцева Т. Б. Оценивание границы динамической надежности электроэнергетической системы // Известия Коми научного центра УрО РАН. 2010, №1. – С.80-86. (In Russian).

[13] N.A. Abramenkova, N.I. Voropai, T.B. Zaslavskaja, *The Structural Analysis of Power Systems* (*in Modelling and Synthesis Problems*), – Novosibirsk, Nauka, 1990.
Абраменкова Н.А., Воропай Н.И., Заславская Т.Б. Структурный анализ электроэнергетических систем (в задачах моделирования и синтеза). – Новосибирск: Наука, 1990. – 224 с. (In Russian).

[14] K. Sun, K. Hur, P. Zhang, "A New Unified Scheme for Controlled Power System Separation Using Synchronized Phasor Measurements", *IEEE Trans. on PS*. [Early Access], 2011.

[15] J. Li, C. C. Liu, K. P. Schneider, "Controlled Partitioning of a Power Network Considering Real and Reactive Power Balance", *IEEE Trans. on Smart Grid*, vol. 1, no. 3, pp.261-269, 2010.

[16] K. Sun, D. Z. Zheng, Q. Lu, "A Simulation Study of OBDD-Based Proper Splitting Strategies for Power Systems Under Consideration of Transient Stability", *IEEE Trans. on PS*, vol. 20, no. 1, pp.389-399, 2005.

[17] L. Liu, W. Liu, D. A. Cartes, I. Y. Chung, "Slow Coherency and Angle Modulated Particle Swarm Optimization Based Islanding of Large-scale Power Systems", *Advanced Engineering Informatics*, vol. 23, no. 1, pp.45-56, 2009.

[18] M.I. Uspensky, I.V. Kyzrodev, *Power Supply Restoration in Distribution Networks: Methods and Decisions*, LAMBERT Academic Publishing GmbH&Co. KG, Saarbrücken, Germany, 2012.
Успенский М.И., Кызродев И.В. Восстановление электроснабжения в распределительных сетях: Методы и решения. (In Russian).

[19] "The Standard Time of Generating Unit Starting for 150-800 MW Thermal Power Stations from Various Thermal States". Available: http://www.normativ.su/catalog /46110.php.
Норматив продолжительности пуска энергоблоков мощностью 150-800 МВт тепловых электростанций из различных тепловых состояний. (In Russian).

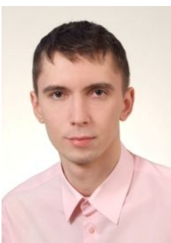
[20] M.I. Uspensky, I.V. Kyzrodev "Combined Method of a Distribution Network Reconfiguration for Power Supply Restoration", *Proceedings of the IEEE PowerTech*, St. Petersburg, Russia, 27-30 June, ref. 33, 2005.

[21] M.I. Uspensky, I.V. Kyzrodev, S.O. Smirnov, "Automation of Power Bus Restoration Sequence Search after a System Blackout", Methodical Questions of Research of Reliability of the Big Systems of Power. – St.-Pb., Russia: "Northern Star", pp. 260-264, 2010.
Успенский М.И., Кызродев В.И., Смирнов С.О. Автоматизация поиска последовательности восстановления узлов ЭЭС после системной аварии //Методические вопросы исследования надежности больших систем энергетики. – СПб.: «Северная звезда», 2010. – С. 260-264. (In Russian).

Michael Uspensky was born in Dushanbe, Tajikistan, on April 9, 1943. He received the M.S. and Ph. D degrees in Leningrad Polytechnic Institute, Leningrad (St.-Petersburg), Russia, in 1971 and 1985, respectively. He worked for the checkout management, Ural, and for the relay protection service of Altai's power plant.

At present, he is leading scientist, laboratory of power system reliability, the Institute for Social, Economical and Energy Problems of the North, the Komi Science Center, the Ural Division of the Russian Academy of Sciences, Syktyvkar, Russia. He is member IEEE since 1998 and the author more 100 scientific papers and several monographies, including, in English.

His research interests include operating control of power system objects.



Sergey Smirnov was born in Syktyvkar, Russia, on October 26, 1985. He received the M.S. degree in electrical engineering from Syktyvkar Forest Institute in 2008. At present he works for "SO – CDO for UES", JSC, Komi Branch, Syktyvkar, Russia.

His research interests include power system control and protection.