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DEVELOPMENT OF ANTI-COLLAPSE COMPLEX OF POWER SYSTEM

ENERGOSISTĒMAS PRETSABRUKUMA AUTOMĀTISKĀ KOMPLEKSA RADĪŠINA

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Introduction

Nowadays, blackouts of power systems (PSs), which endanger the equipment operation and inflict heavy economic losses, have become a commonplace phenomenon in the world. The problem is still considered unresolved, although in the authors' opinion the solution can be found.

The operating condition of a power system could be:

- normal,
- pre-emergency,
- cascade-like emergency.

For normal operating conditions obligatory reliability standards are provided. Usually, these are linked to the observance of the (n-1) criteria. This means that the emergency disconnection of one important element should not cause a cascade-wise process. However, it could happen that a risk is taken not to observe the mentioned criteria or practically simultaneously two incompatible (from the viewpoint of operating conditions) elements are disconnected. In these situations a pre-emergency or a cascade emergency operation could take place.

Under the pre-emergency operating conditions the disconnection of important elements occurs, however a cascade-like process has not yet begun. Such being the case, mobilization of the main and reserve power capacities could normalize the situation.

When an emergency condition does begin, the process usually develops fast, in a cascade-like manner. The personnel are unable to control the situation, so to avoid a blackout is possible only by means of fast-acting protection automatics, which should be unified and maximally simple. Diversification of protection means evidences that the process has not been solved.

The work describes the methods for solving the problem; these are based on the analysis of a great number of blackouts that have occurred all over the world. It is shown that the needed unified protection complex might include elements of the already existing automatics that could serve for solving new tasks.

The history of the world's blackouts

The reliability of the power systems (as large technical systems) becomes progressively important all over the world, since so far blackouts continue to occur. Therefore the required protection complex should be based on a thorough analysis. With this purpose in mind, it would be helpful to outline the history of blackouts.

The power systems developed as compact load centers linked to the inter-system network. At the beginning such centers were self-balancing; when interconnected, they could give greater output and maintain a common reserve. This led to a mutual dependence and, correspondingly, the power balance became more labile. Since then blackouts have been occurring regularly. In order to find solution of the anti-collapse protection problem, it was necessary to analyze the history of blackouts and their development in time. In this development, the following stages could be marked off:

Stage 1, relates to the 1920-ies. At that time blackouts assumed the form of voltage drop avalanches owing to imperfect excitation regulators of the generators. In the 30-ies, these were perfected, which meant that during the emergency events they were able to force the generator excitation thus disrupting the event.

Stage 2, embraces the period of 1930-ies, when the inter-node links were weak. At their disconnection the blackouts occurred owing to deep frequency fall under the conditions of active power deficit. This, in turn, was caused by decrease in the output of feeding pumps of the boilers. Under the frequency fall conditions the turbine power increases due to the action of its speed governor, whereas the boilers' output decreases, which means mismatch between the turbine and boiler operating conditions. As a result, owing to the steam pressure fall in the boilers the means of technological protection disconnect the generating sources, the power plants are stopped by turn, which gives start to a blackout.

As an anti-emergency means, the automatic stages of fast-acting under frequency load shedding (AUFLS) came under the maintance; at a frequency fall such a means trips the consumers, keeping the power balance at the level of parameters that is lower still not endangering the power plants' operation. The lowered frequency level did not allow restoration of PS integrity and thus of the power supply to the consumers. Into the process the PS personnel was involved, so the power supply restoration lasted for several hours.

Stage 3, began in 1963, when one of the authors (being then the Control-Engineer-in-Chief at the Latvenergo) suggested using the self-organisation principle for elimination of frequency emergencies in a PS. Taking into account that at those times every year PS blackouts occurred, there was an urgent need to find a radical solution of the problem, which would save the personnel from continuous stress. In those years, quarterly circulars were spread, which contained detailed descriptions of regularly happening PS blackouts. The diversity of these events allowed, at a stereotypical approach, each PS blackout to be considered as a unique one. Since to the diversity of the sought-for protection the diversified events should correspond, the task seemed to be irresolvable. The only hope was seen in finding common features in the occurring blackouts, which would make it possible to cope with them by means of simple protection automatics.

The analysis of the mentioned circulars performed during many years showed that, if we sweep aside the secondary facts, the emergency event are not diversified – the more so, they are practically identical, which allows for creation of a simple and reliable anti-emergency system.

As a result, the AUFLS was complemented with the following three elements:

- several slow-acting AUFLS stages (in addition to the fast-acting AUFLS) with selective time delays and high activating settings as well as with automatic resetting at the rated frequency level (which automatically restores the frequency up to the rated value);
- automatic synchronization of PS parts using a synchronism-check device (as a synchronism-catching device) for PS integrity restoration;
- automatic reclosing of consumers' lines.

During the emergency, at the frequency falling the fast-acting frequency load relief stages operate (see Fig.1), which stabilizes this frequency at a lower level. Owing to the operation delays, some extra stages are put into action, which leads to a definite frequency rise, and, after a lapse of the delay time of the slow load relief automatics, it restores up to the rated value, providing a possibility for automatic PS synchronization as a prerequisite for deficit liquidation and automatic reconnection of consumers' lines. Thus the total self-restoration of a power system proceeds within 100 seconds determined by the operation of slow load relief automatics. The main result was that during the long-lasting maintenance in twenty cases of protection automatics operation these processes remained unnoticed by the majority of consumers – as if there were no blackouts at all. This anti-collapse complex was implemented in Latvia in 1964 owing to the support provided by the relay protection personnel, and with this the problem of frequency emergencies was completely solved [1]. The solution was included into the anti-emergency directive recommendations on the scale of the Soviet Union, which opened a way for its wide application.

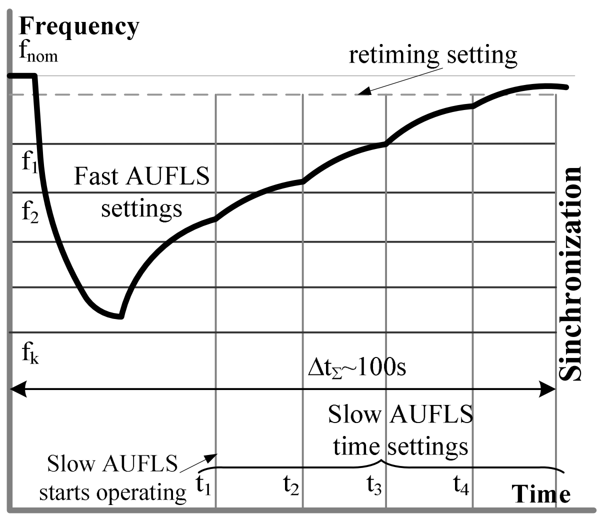

Figure 1. Frequency variations at anti-emergency automatic operation

Stage 4 of the 70-ies, when blackouts in power systems were caused by loss of stability. In this time span the stability loss problems were investigated, and the means for liquidation of this kind of emergency were worked out. At that time also the asynchronous running was investigated, which followed the stability loss. To eliminate this type of emergencies, it was proposed to split the PS on the lines with stability loss.

Stage 5 dates back to the 80-ies, when, following the increase in the number of transmission lines, the power systems' schemes acquire a loop-wise character. At that time many blackouts occurred under the conditions of overloaded cross-sections, when voltage avalanches instead of stability loss were took place. In such situation to the voltage drop the excitation regulators of the generators respond, which causes the overloading of the latter with reactive power and their massive tripping by the means of overload protection. In that span of time special measures were worked out for a pre-emergency situation – for example, disconnection at the appearance of voltage drop or using the centralized channel, which would improve the situation.

Stage 6 relates to the onset of the third millennium. In this time, to the "old" blackouts we can add those in the form of large-scale tripping with excessive sagging of wires until the ground fault occurrence.

The Analysis of major blackouts

The complicated behavior of new-type emergency processes requires a new in-depth analysis of these events, for which a general feature to be responded by rather simple automatic protection means should be sought. To the analysis about 20 world's blackouts were subjected, which occurred in the second half of the 20th century in the USA, Canada, Russia (Moscow), Italy, Brazil, and other countries. The strategy of the analytic work was to find ways for creation of the automatic complex for protection of power systems against blackouts, which could be employed independently of the capacity of a PS. In the work, the experience gained in the 60-ies has been generalized. First of all, here it also was necessary to free ourselves from the "event diversity scourge", even though into the issue new generating sources were involved – gas turbines and nuclear power plants that could respond specifically to the frequency deviations.

The analysis of grave blackouts has shown that the PS collapse processes always accompany the transmission line overload. The cross-sections that are usually marked off and given much attention in the process of operative control are called "dangerous cross-sections". The overloads, depending on the circumstances, are accompanied by different cascading processes, e.g.:

- stability loss;
- voltage drop avalanches at the power receiving end of a cross-section;
- massive tripping of the overloaded lines as a result of ground faults at wire sagging;

- underload below the level needed for operation of power plants.

The hierarchy of the emergency events is shown in Fig.2, from which it is clear that there could be primary and secondary events. If there was reliable fast-acting protection against cross-section overload, no secondary events could happen.

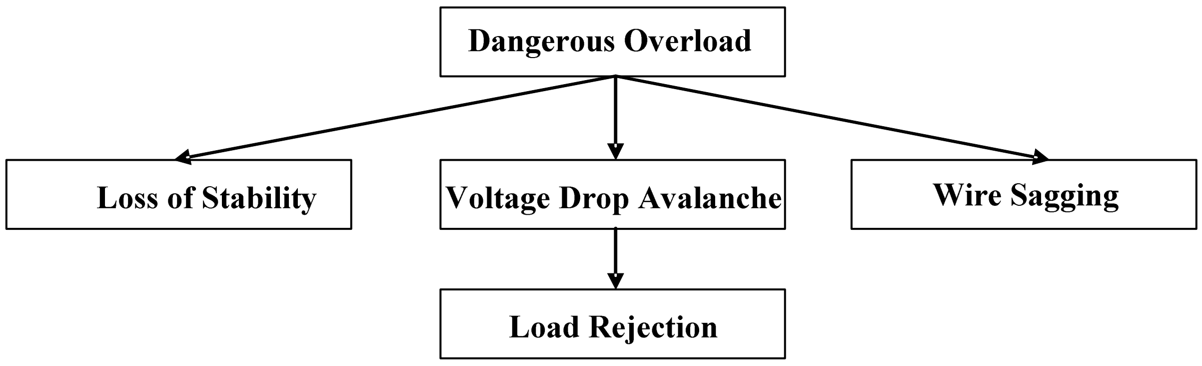

Figure 2. Primary and secondary emergencies

Analysis of existing protection means

Protection against stability loss. For the proper choice of methods for PS protection against emergencies, analysis of the existing protection means is needed. So far, most attention has been concentrated on the protections against stability loss. Since such emergencies arise due to cross-section overloads, special methods for their control and elimination have been created which are operating at the sending and receiving ends of a cross-section. To the sending end a matrix for a definite network scheme corresponds (see Table 1). At the column inter-sections the distribution coefficients α_{ij} are inscribed, where *i* are the nodes and *j* are the branches (lines). Each coefficient α_{ij} indicates what portion of the change in a power plant's power at the *i*-th node will create a change in the power flow through the *j*-th line. For example, the coefficient $\alpha_{35} = 0.4$ implies that through the 3rd line 40% of P_5 power change flows; this means that changing the generation P_5 by ΔP_5, we will change the power flow in the 3rd line by $0.4\ P_5$. To off-load the cross-section by, e.g., *300 MW*, the power at the generation node should be reduced by $P/\alpha_{35} = P/0.4 = 2.5P$. The coefficients are defined in advance, under normal condition, and stored in the memory of the protection system.

Table 1.

Matrix I of power distribution coefficients

		Power sources at the load centers				
		1	2	3	4	5
Lines	1	α_{11}	α_{12}	α_{13}	α_{14}	α_{15}
	2	α_{21}	α_{22}	...	...	...
	3	α_{31}	...	...	...	...
	4	α_{41}	...	...	...	...
	5	α_{51}	...	...	...	...

Approximately, these coefficients could be defined with the help of a d.c. model, replacing in the matrix the electricity conducting lines by Z-type resistances, which in many practical situations provides sufficient precision. In this case it is not necessary to make iterations, and the results can be obtained instantly.

If a cross-section does not contain power plants, at tripping one of its lines the power flow in the remaining lines will increase. This situation is characterized by distribution coefficients in the symmetrical matrix of the cross-section (see Table 2). The limitations on power flows in a loop-wise network are determined by the whole complex of lines in a dangerous cross-section; besides, possible equalization of flows owing to mutual influence of different cross-sections is to be taken into account. In practice, for this purpose a real-time mathematical model of the PS operating condition should serve, by which in the normal operating condition the automatic measures that should be taken in the emergency cases are determined depending on the disconnected line.

Table 2.

Matrix II of power distribution coefficients

		Lines				
		1	2	3	4	5
Lines	1		γ_{12}	γ_{13}	γ_{14}	γ_{15}
	2			γ_{23}	γ_{24}	γ_{25}
	3				γ_{34}	γ_{35}
	4					γ_{45}
	5					

Fast change in the power plants' capacity is achieved by partially disconnection of their turbo generators under load, which requires a forced uncovering of boilers' safety valves for steam release into the atmosphere. For this purpose, electro-hydraulic mechanisms of high-power turbines can be used for their fast load relief.

To achieve that in the emergency cases fast-acting operations be performed the necessary control actions (i.e. the extent of load relief) should be defined in advance, based on the cases of line disconnection in different cross-sections depending on the severity of the controlled normal operating condition. The control doses are stored in the form of a matrix (the splitting places is shown Table 3) in the control system's memory, which are corrected depending on the severity of the operating condition. The doses are chosen as response to the signal about line disconnection transmitted via a channel for logic signals of instantaneous action to a definite address. Such protection systems were employed in real practice and have proved their worth, showing good performance and efficiency [2].

Table 3.

Matrix of control actions

		Complexity of initial conditions				
		1	2	3	4	5
Disconnected line	1	β_{11}	β_{12}	…	…	…
	2	β_{21}	β_{22}	…	...	...
	3	β_{31}	…	...	...	...
	4	…	...	...	...	...
	5	…	...	...	...	β_{ij}

The change of a power plant's capacity for load relief the cross-section is effective under the condition that its topological position with respect to this cross-section is especially advantageous, with the coefficient close to 1 (which is a considerable disadvantage).

In the case of a disadvantageous position of a power plant in the network the cross-section off-loading could theoretically be achieved by tripping consumers at its power receiving end, using for this purpose the centralized load disconnection channel. Unfortunately, this is usually done on the "off-chance", since it is impossible to know beforehand the disconnected capacity whereas the operation should be performed only once.

Protection of transmission lines against overload is a so far unresolved problem. Owing to a line overload the temperature of wires can rise up to approx. 300^{o}C. Then sagging of wires could increase to the extent when they are lying on the ground thus causing the line disconnection. Since heat processes are inertial, the damage persists and the line automatic re-closing will be unsuccessful. As each disconnected line causes still greater overload on the remaining lines, large-scale line disconnection will occur, and the system's blackout becomes unavoidable. It should be noted that at the temperature of conductors rising up to 500^{o}C the wires become unfit and need replacement in overhaul.

In the cases of overloads on the lines there could be no damage indications that are detected by conventional protections. So the damaged lines remain under exploitation, with the above described complications followed. Such being the case, the power system's splitting occurs at the point through which the maximum power is flowing, with the following maximum consumers' disconnection. Therefore an optimal fast-acting load relief of overloaded lines is needed, which allows the lines to be kept in operation thus ensuring the maximum possible use of the line carrying capacity, with the minimum consumers' disconnection.

Impact of frequency fall on the generating sources

In separate cases of the emergency running, suspension of the fallen frequency could occur. It is important to clear up how this situation can affect the generating sources. This to a large extent is determined by coordinated operation of turbines and boilers [3].

The operational speed of the turbine governors is defined by the time constants of the hydraulic amplifier and steam space, which are approx. 0.25 seconds and the rotating mass inertia constant of 10 seconds. When the rotational speed varies insignificantly, the turbine operates with a high speed. Under normal conditions the turbines, responding to the frequency oscillations around 0.1 Hz, fluctuate in a limited power range thus normalizing the frequency in a PS. Taking into account the insensitivity zone of regulation, which can reach 0.3 Hz, some of the turbines respond to the frequency rise while the others – to the frequency fall. When power fluctuates, at its rise the boiler pressure falls and the accumulated heat of water that rapidly evaporates is consumed. Later on, the pressure recovers owing to the following power fall.

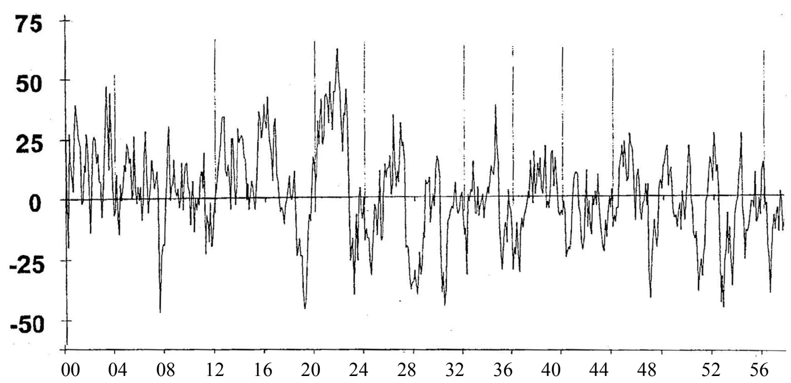

Figure 3. Frequency fluctuations in the stationary operating condition

The process of energy carriers' balance variation at a frequency fall is going differently. If before the emergency in the deficient region there were rotating power reserves, then, responding to the frequency fall, the turbines rapidly take the load up to a definite limit. At the same time, the boilers' time constants reach 200 seconds, and the steam generation decreases since owing to the delay the pressure does not recover. Therefore the operating conditions of turbines and boilers change in this case oppositely, which can entail the tripping of generating sources. Taking into account that the main task of the operation recovery is to keep the generating source working, this could be achieved even at the cost of some load relief for the turbines in order to preserve the mutual coordination of the heat balance.

Apart from that, it should be taken into account that in the case of the turbine power rise beyond a definite fluctuation range owing the steam throttling effect the temperature at the turbine's exhaust hood changes, which can create the temperature stress with a time constant of 15-30 minutes.

Anti-collapse protection system

When a new anti-collapse protection system is created it is worth thinking of the difficulties associated with its implementation. In such cases preference should be given to the principles verified by practice, trying to achieve that only minor improvements are to be done by the personnel in the process of maintenance. With this purpose in view, the existing protection methods should be carefully analyzed – including those meant for other applications that could be used after some perfection.

The duration of collapse is some seconds. Therefore they could be avoided only by means of fast-acting preventive protection systems. Among existing ones there is a preventive system used for protection against stability loss faults; the system acts by off-loading the power plants in a dangerous cross-section of the network on the power sending end. A disadvantage of such a system is the dependence of its effectiveness on the topology of power plants with respect to this cross-section.

There is an alternative – the centralized load shedding on the power receiving end. The flaws of this method is, first, impossibility to dose the amount of load to be shed since there is only a single act of protection, and, second, indefinite duration of load disconnection.
The task therefore is: to combine the advantages of both the methods and eliminate their disadvantages.
The task can be fulfilled if we introduce some minor improvements into both methods. The preventive matrix-form system should be re-oriented from the power plant off-loading towards the optimum sectioning of the power system at the place through which there flows power equal to the cross-section's overload. This place, along with the prototype load relief dose, should be defined beforehand, under normal operational condition depending on its severity and possible line disconnection variants. This done, the blackout in a PS with overloaded cross-section can be nipped in the bud. Simultaneously, the problem of precise dosage of the shed power ceases to exist.
In the isolated part of a power system the power deficit is followed by frequency fall, which is eliminated by the means of fast-acting frequency relief automatics. The slow-acting component of the automatics restores the frequency up to the rated level, which allows for re-integration of split PS parts by the device for synchronism check on one of the lines acting in the synchronism-catching mode. These done, other lines are reconnected instantly, and the mentioned devices start working in the usual mode. After that, the lines supplying consumers are to be re-closed automatically, which removes the problem of the disconnection duration uncertainty for the last consumer.
As a result, at the faulty place within approx. 100 s the power system's self-restoration process occurs, which remains unnoticed for the majority of consumers. Thus the problem of PS blackout is solved completely.

Conclusions

1. Analysis of the processes going at PS blackouts allows revealing their systematic feature to which a simple anti-collapse complex can respond, thus making it possible to eliminate them.
2. For the proposed protection complex the devices intended for other purposes are chosen, whose operation is verified by practice and which need only minor improvements.
3. As the primary indicator of a blackout the cross-section overload is used. To remove it, the preventive automatics is employed, which executes load shedding with the help of optimal PS sectioning thus instantly eliminating the cross-section overload as the cause of the blackout.
4. As a result of sectioning, in the deficient part of the split power system a frequency drop occurs, to which the under frequency load relief automatics responds by and actuates the self-restoration complex.
5. Operation of the self-restoration complex results in frequency equalization in PS parts, followed by their synchronization and re-closing of consumer supplying lines.
6. The normal operating condition is reached within approx. 100 seconds, so that the majority of consumers have no time to realize the danger of blackout.
7. Simultaneously, the proposed methods, raising qualitatively the reliability of PS operation, makes it possible to eliminate such secondary emergencies of power systems as stability loss, voltage avalanches, line disconnections caused by increased wire sagging and load decrease below the level required for operation of thermal power plants.

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Barkāns J., Žalostība D. Energosistēmas pretsabrukuma automātiskā kompleksa radīšana
Energosistēmas sabrukumi, kas rada draudus iekārtām un lielus tautsaimniecības zaudējumus, periodiski notiek visā pasaulē. Sabrukumu procesi ir saistīti ar lielu notikumu dažādību, kas rada iespaidu, ka katrs no tiem ir unikāls. Taču aizsardzībai no šādām parādībām ir jāizmanto automātika, kas spēj reaģēt tikai uz likumsakarīgo. Tā kā aizsardzības daudzveidībai jāatbilst notikumu daudzveidībai, radikālas aizsardzības radīšana var izrādīties problemātiska. Toties dziļa nestereotipiskā notikumu analīze, atmetot nebūtisko, liecina, ka sabrukumu procesi ne tikai nav unikāli, bet no automātisko iekārtu izvēles viedokļa tie ir praktiski vienveidīgi. Starp tiem var izšķirt primāros notikumus (iemeslus) un sekundāros (sekas). Pievēršot uzmanību primārajiem notikumiem, ir iespējams radīt radikālu pretsabrukuma kompleksu. Ieviešanas aspektā jāizmanto aizsardzības elementi, kuru darbspēja ir pierādīta daudzgadējā ekspluatācijā, kaut gan līdz šim tie izmantoti sekundāro notikumu novēršanai, un tāpēc nespēja novērst sabrukumus. Rezultātā tika radīta energosistēmas pretsabrukumu preventīvā kompleksa koncepcija, kas, ievirzot notikumus optimālā gultnē, ātri un automātiski likvidē sabrukumus vairāku desmitu sekunžu laikā uz ekspluatācijā pārbaudīto risinājumu pamata.

Barkans J., Zalostiba D, Development of automatic anti-collapse complex of power system
The collapses of power systems, bringing huge losses to a national economy, periodically occur all over the world. Collapses are accompanied by cascade emergency processes, which could be highly diversified thus creating impression that each of them is unique. On the other hand for prevention of such events it is necessary to use automatics which react only to regularities. It could seem that to this diversity a similar diversity of anti-emergency devices should correspond which raises serious doubts as to the possibility to create such a radical anti-collapse means. The in-depth analysis of the world's blackouts focusing on the most essential has proved that such an impression is erroneous. The emergency processes could be divided into primary (causes of events) and secondary (their consequences). Concentrating on primary creation of a radical anti-collapse complex is possible. From the point of view of its input in operation it is necessary to use such elements of protection which efficiency of use it is confirmed by long-term operation in spite of the fact that before they were applied to prevention of secondary disturbances and could not protect from the blackouts. As a result the concept of the automatic preventive anti-collapse complex has been formulated which is based on the solutions tested by practice; according to this concept, emergency events can be set on the right track, with blackouts fast and automatically elimination within some tens seconds.

Баркан Я., Жалостиб Д, Создание автоматического комплекса против развала энергосистем
Развалы энергосистем, приносящие огромные потери народному хозяйству, периодически происходят во всем мире. Процессы этих аварий связанны с большим разнообразием событий, от чего кажется, что каждый из них уникален. С другой стороны для предотвращения таких событий необходимо использовать автоматику, которая реагирует только на закономерности. Может показаться, что многообразию событий должно соответствовать многообразие противоаварийных средств, и создание радикальной защиты проблематично. Но глубокий нестереотипный анализ аварий показал, что процессы развала энергосистем ни только не уникальны, но и с точки зрения выбора автоматики, являются практически однотипными. Их можно разделить на первичные (причины) и вторичные (следствия). Концентрируясь на первичных возможно создание радикального противоаварийного комплекса. С точки зрения ввода его в эксплуатацию необходимо использовать такие элементы защиты, эффективность которых подтверждена эксплуатацией, несмотря на то, что до этого они применялись для предотвращения вторичных аварий и не могли защитить от развала. В результате была создана концепция автоматического превентивного комплекса защиты от развала энергосистем, которая, направляя события в нужное русло, быстро предотвращает развитие аварии.