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Distributed Load Shedding Algorithm for the Control of Active Power Flows

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Blackout development, cascading line tripping, emergency control, multiagent approach, coordination.

1 INTRODUCTION

Subject of study

Analysis performed in [1], indicates that in the process of development of most system failures in the Western power systems can identify a number of characteristic phases: pre-emergency state, initiating events, cascade development of the accident, the final state, and recovery. In turn, cascade development of the accident can be divided into phases for the slow development of the accident, the phase of the triggering event and the phase of rapid development of the accident, Fig.1.

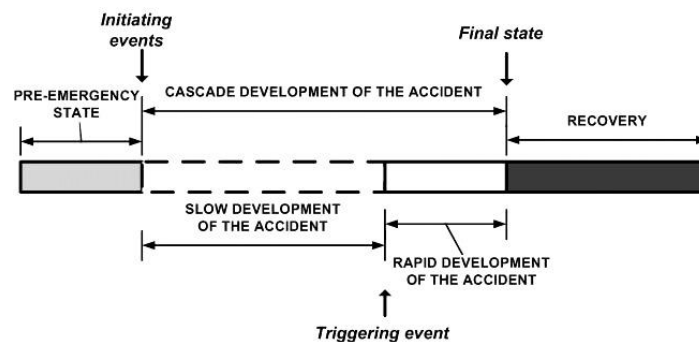


Fig. 1: Characteristic phases of development of system failure

Critical point, after which it was impossible to stop the passage of regular emergency into a major system failure, was the phase of the triggering event. Initiating events were a direct cause of a major accident, or resulted in deterioration of the current regime. As the initiating events were usually performed: short circuit, overload of the equipment, latent failure of the protection systems, the loss of the generator, etc.

Phase of the cascade development of an accident, triggered by the initiating events, accompanied by fluctuations in power and voltage, leading to an increase in current and voltage drop. The increase in currents and low voltages were often perceived as a relay protection systems damage and / or critical overload, which led to a cascading shutdown of lines and generators. Thus, during a phase of slow development of the accident EPS over a relatively long time maintained a balance between generation and consumption, all processes were rather slow and the main problem at this stage was a multiple overload of network elements. At this stage the low speed of the deterioration of the situation provided system operators to implement the operational impact that would prevent further chain of cascading events.

Triggering event usually led to a rapid shutdown of a large number of elements, imbalance between generation and consumption and, consequently, to the collapse of the system. In the phase of rapid development of the accident was usually too late to stop the development of a system crash. Table 1 provides an analysis of different types of disturbances for nine blackouts in the Western interconnections.

Table 1: Various types of emergency disturbances in the development of blackouts in the Western interconnections

Blackout, date, country	Emergency disturbance type			
	Voltage collapse	Frequency collapse	Multiple overloading of system elements	Loss of synchronism
9.11.1965, USA			X	
19.12.1978, France	X		X	
2.07.1996, USA	X		X	
07.08.1996, USA	X		X	
14.08.2003, North-East USA and Canada	X		X	
23.09.2003, East Denmark and South Sweden	X		X	
28.09.2003, Italy		X	X	X
12.07.2004, Athens and South Greece	X			
14.03.2005, South Australia				X

The data presented in Table 1 indicates that the voltage collapse and multiple overloading of the equipment, leading to a cascading shutdown of network elements, were the main types of emergency disturbances encountered in the course of development of most of the blackout in the western interconnections. Thus it is likely that the development of effective measures to counter the voltage collapse and the cascade shut down of network elements, in most cases will stop the further development of the blackout.

The Moscow blackout in May 25, 2005 [2] showed that the problem of voltage stability and cascade line tripping are relevant for UES of Russia too. This fact is associated with the development of complex electric power structures similar to the electricity system of the Moscow megalopolis.

Development of the Russian economy under the market conditions contributes to a development of big industrial and business centers, the properties of the electric power structures of these centers are similar to the structure of Western power systems. This fact indicates the need for the development of algorithms for emergency control, designed to fight against voltage instability and cascade triggering of system elements.

The aim and novelty of the report

At present, the implementation of a centralized emergency control consists in dividing power systems to the areas of emergency management. Further, the cross-flows on the cross sections and partial cross sections are normilized. Normally the borders of the emergency management areas are defined by taking into account both the technological features of the area, and the opportunities to organize reliable and fast information transmission. Different emergency situations lead to the increasing of the power, flowing through the cross sections. In order to prevent the loss of stability emergency control unload cross sections by disconnecting the load or by changing the generation of sending or receiving parts. The described approach is now being successfully applied in the implementation of emergency control in UPS of Russia.

The growth of energy consumption and network building, as well as the accompanying restructuring of the electricity and the transition to a market economy have a significant impact on the functioning of the power system. A further complication of the network of large power districts is likely to lead to the need to establish in these areas emergency control system that will start not to control the power flow through the individual cross sections, but the work of the entire area as a single control object. *Creation of such centralized system for emergency control of large areas with a*

complex structure is one of the possible ways to solve the problem of meshing. As an alternative way can be considered the creation of emergency control complex with partial decentralization of control algorithms.

Currently, there is need for the creation of a decentralized adaptive emergency control systems whose algorithms be able to complement the existing ideology, i.e. to coordinate the local emergency control unit, as well as provide the partial implementation of the functions of centralized systems.

In this paper we propose an algorithm of distributed (decentralized) load shedding with the control of active power flows on the elements of power system. It is assumed that the algorithm will increase the reliability of the emergency control system by means of using of modern information technologies, as well as by raising the intellectual level of high-speed local automation devices that control the loading of elements within emergency control area. It is assumed that a further possible implementation of the algorithm will prevent the phenomenon of cascade tripping of the system elements.

Review of the current level of research

Decentralization of load shedding automation is not in itself a new idea. Different kinds of local automatic load shedding have been using in power systems for a long time. However, these automations, in most cases, work on the basis of local information on the state regime (frequency, voltage, current, etc.). Sometimes these local automations can get information from neighboring substations through the communication channels, but such approach is the exception rather than the rule. At the same time, the development of information technologies and means of automation can improve the intellectual level of the local devices by means of complicating the algorithms, and through the use of the data transmission capabilities among devices via communication channels. The main objectives of raising the intellectual level of local automation is, firstly, increasing its adaptability, and secondly, to minimize the control actions (primarily in the form of load and generation shedding). Thus, in contrast to the classical approach to the implementation of local automation, we are talking about distributed adaptive systems, *so-called multi-agent systems*, which, in our view, represent a cross between a local and centralized emergency control automation.

Development of software for testing of a distributed algorithm for adaptive control (multi-agent algorithm) is itself a fundamentally new challenge. In this article, we will not dwell on issues of program implementation, and give only a general description of the algorithm.

Currently, there are a number of works by authors who, in one form or another, used multiagent approach for the management of EPS. In [3] multiagent approach was used to create agents operating in accordance with a system of rules. This system of rules allows you to control power system regime. Of particular note is the work of [4], which is devoted to the use of multiagent approach to combating the phenomenon of cascading tripping of transmission lines. The authors use the multiagent paradigm to simplify the task of controlling power flow by dividing it into less complex, depending slightly from one another subproblem, which can be solved independently. This approach reduces the complexity of the problem, however, in rare cases, a lack of coordination of the general solution leads to the deterioration of the situation.

2 MAIN PART

The main part of the report describes the proposed algorithm for automatic distributed load shedding for the control of active power flows.

The essence of the algorithm is disclosed by the example of the power system, schematically shown in Fig. 2.

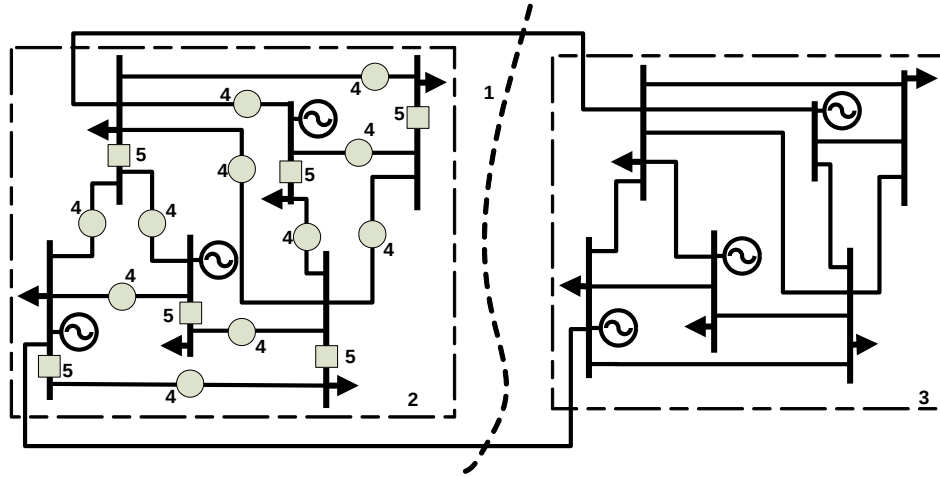


Fig. 2: Network illustrating the essence of the proposed algorithm

Power flow on the interconnection cross section 1 can be monitored using known techniques. However, using known techniques difficult to control the load of the elements within the subsystem 2 and subsystem 3. In this particular case the proposed algorithm can be used to solve the problem of load control of elements in the subsystem 2. To implement the algorithm, we must first implement the following set of actions:

1. Creating a computer model of any characteristic regime of the power system under consideration. For example, the winter peak loads regime. The developed model is used to calculate the influence coefficients for the various post-emergency states (single and double tripping, generators tripping, etc.). The coefficient of influence is defined as the ratio of the change of active power flow through a transmission line to the change of load in a node. For example, the coefficient of influence of the load at node i on the flow on some line j is defined as:

$$k_{ij} = \frac{\Delta P_{line j}}{\Delta P_{load i}}$$

where $\Delta P_{line j}$ - change the power flow on the j -th line and the corresponding change in load $\Delta P_{load i}$ in the i -th node. Influence coefficients are weakly dependent on the mode of power and remain virtually unchanged for a given system topology. If $k_{ij} > 0$, then load shedding in node i will reduce the power flow on the line j , and conversely, if $k_{ij} < 0$, then load shedding in node i will increase the power flow on the connection j .

2. Creation of a database containing information about the coefficients of influence for each line for different types of emergency disturbances. The database should also contain information on the maximum allowable flow of active power for all the elements within the system.
3. Based on database developed by analyzing the values of the coefficients of influence, considered power system must be divided into a set of controllable and uncontrollable subsystems, providing minimal influence. Controlled subsystems are subsystems, which will be implemented by the proposed method of load shedding.
4. On the basis of accepted partition for each of the subsystems an individual database is formed, which contains the coefficients of sensitivity and the maximum allowable active power flows for the elements within the subsystem.
5. All lines and components of the load of each of the controlled subsystems should be equipped with the agents. Line agents (4) and the load agents (5) are intelligent electronic devices, each of which has a unique identification number (the address of the agent). Using the common information space, agents can send each other information messages.

6. Within each controlled subsystem should be implemented information system which is able to organize the transfer of messages between agents. Any agent of the line at any time should receive information about the current network topology, which contains information about the fact of tripping element in the subsystem. In addition, an agent with certain intervals, depending on the level of the critical load of communication channels, should be informed about the current state of load nodes that have the greatest impact on the load of elements within subsystem, controlled by this agent. Information about the current state of the load of the consumers' nodes should include information about the current number of working feeders, about the active power load of every working feeder, as well as the price that must be paid in case of disconnection of every feeder.
7. All line agents in every controlled subsystem receive the appropriate data base sensitivity coefficients and information about maximum allowable flows of active power.

The proposed emergency control algorithm includes the following set of actions (points) performed cyclically:

1. Based on the information on the current network topology, the agents of all overloaded links select the appropriate table of influence coefficients. Based on the tables of influence and information about the current state of the load nodes that have a significant impact on the loading of the overloaded links line agents perform a preliminary calculation of the optimal amount of load shedding. For each j - th overloaded element this calculation is to solve the following linear optimization problem:

$$\begin{aligned} \min \quad & \sum_{i \in B \wedge k_{ij} \geq \alpha} C_i \Delta P_i \\ & P_j^{\max} - P_j^{\text{current}} + \sum_{i \in B \wedge k_{ij} \geq \alpha} k_{ij} \Delta P_i \geq 0 \\ & \forall i \in B \text{ such that } k_{ij} \geq \alpha \\ & 0 \leq \Delta P_i \leq P_i^{\text{current}} \end{aligned}$$

where B - the set of load nodes in the subsystem involved in the automation; C_i and ΔP_i - respectively the cost and volume of the shedded i - th load; $P_j^{\max}$ and P_j^{current} - respectively the maximum and the current flow of active power through the j - th overloaded link; k_{ij} - coefficient of influence, which determines the impact of shedding of the i - th load on active power flow through the j - th link; α - the minimum allowed value of the coefficient of influence ($\alpha \geq 0$); P_i^{current} - the current value of the i - th load. As a result of solving an optimization problem the vector of control actions must be received, which contains an optimal amount of disconnection for load nodes in the controlled subsystem. If the optimization problem has no solution, the algorithm terminates.

2. Based on the current vector of control actions, line agent of every overloaded element generates list of links with the unique negative coefficients of influence. The formation of this list is as follows - if the load shedding in some node $n \in \Gamma$ increases the power flow through some links $m \in L$ (here Γ - the set of load nodes included in the current vector of control actions; L - the set of controlled links in the subsystem), then this link should be included only once in the list of unique links with negative coefficients of influence.
3. Agent of the overloaded link requesting information about the current power flow through the elements from the list of unique links with the negative coefficients of influence. Typically, this list does not contain too many links, because, as a rule, load shedding reduces the active power flow through the most elements in the controlled subsystem.
4. After receiving information about the current flow of active power through the links from the list of unique links with the negative coefficients of influence, the link agent of each j -th overloaded element makes a second calculation of the optimum volume of load shedding. This takes into account the impact of load shedding in connection with the negative coefficients of influence:

$$\begin{aligned}
 & \min \sum_{i \in B \wedge k_{ij} \geq \alpha} C_i \Delta P_i \\
 & P_j^{\max} - P_j^{\text{current}} + \sum_{i \in B \wedge k_{ij} \geq \alpha} k_{ij} \Delta P_i \geq 0 \\
 & \forall i \in B \text{ such that } k_{ij} \geq \alpha \\
 & 0 \leq \Delta P_i \leq P_i^{\text{current}} \\
 & \forall n \in \Gamma \wedge \forall m \in T \text{ such that } k_{nm} \leq -\beta \\
 & \text{if } P_m^{\text{current}} > P_m^{\max}, \text{ then } \Delta P_n = 0, \\
 & \text{otherwise } P_m^{\max} - P_m^{\text{current}} + \sum_{n \in \Gamma \wedge k_{nm} \leq -\beta} k_{nm} \Delta P_n \geq 0
 \end{aligned}$$

where B - the set of load nodes in the subsystem involved in automation; Γ - the set of load nodes within the current vector of the control actions, $\Gamma \subset B$; T - the set of links included in the list of unique links; C_i and ΔP_i - respectively the cost and volume of the shedded load in i - th node; $P_j^{\max}$ and P_j^{current} - respectively, maximum allowable and the current power flow through the j -th overloaded link; $P_m^{\max}$ and P_m^{current} - respectively, maximum allowable and the current power flow through the m -th link, $m \in T$; k_{ij} - coefficient of influence, which determines the impact of changes in the i - th load on the active power flow through the j - th link; α and β - the minimum allowable values of the coefficients of influence, $\alpha \geq 0$, $\beta \geq 0$; P_i^{current} - the current value of the i - th load. As a result of solving an optimization problem one must receive the vector of control actions, which contains an optimal amount of load shedding in the controlled subsystem and taking into account the effects due to negative coefficients of influence. Elements of the control actions vector, obtained by solving an optimization problem, rounded on the basis of preliminary information about the load of the feeders of the load nodes.

5. A list of links that were not previously included in the list of unique links with the negative coefficients of influence must be generated for every element from the control actions vector. List of links that were not previously included in the list of unique links with negative coefficients is formed as follows. If load shedding in some node $i \in B$ from the vector of control actions leads to an increase in power flow through some link $m \in L$ (here L - the set of controlled links in the subsystem), and if this link has not previously included in the list of unique links with the negative coefficients of influence, then this link must be included in the newly formed list of links with negative coefficients of influence. If formed in this way a list of links is empty, then go to step 6, otherwise go to step 2.
6. Each element of control actions vector, obtained in step 5, is included in the information request message and transmitted to the load agent. Load agent handles requests from line agents and implements the requested control actions. If the load agent is unable to perform the requested feeder tripping or if the volume of the load on the requested feeder is significantly lower than requested, it sends back to the line agent an information message about the impossibility to perform the tripping of the requested feeder. The information message contains information about the current state of the load agent: the number of feeders that are at work, as well as the amount of load on each feeder. If the agent can implement the requested control action, it sends back communication message about the successful implementation of the requested control action to the line agent.
7. If, after implementation of control actions flow of active power through at least one of the links in the controlled subsystem exceeds the limits, then consider these changes and go to Step 1. Otherwise, finish the algorithm.

At any step of the algorithm if the flow of active power through the link, controlled by the agent is less than the maximum permissible the line agent completes execution of the algorithm. At any step

of the algorithm operable line agent should respond to requests from other agents about the current flow of active power through the link, controlled by this agent.

3 CONCLUSION

The authors propose an algorithm that can be used to create a distributed automation system, which can realize the load shedding function to reduce active power flows through the elements of power system in case of overloading. For this a complex power system must be partitioned on subsystems, providing minimal mutual influence. Automation of each subsystem monitors the current regime of the subsystem and prevents critical overload of elements by providing load shedding control actions.

The proposed algorithm has high adaptability, and uses only location information and the minimum amount of information obtained from nearby measurement units. Minimizing the amount of information for load control of network elements will increase the reliability of the emergency control system. The proposed algorithm also realizes optimal or suboptimal control actions, which will minimize the amount of load shedding.

Note that the possible implementation of the proposed algorithm does not call for abandonment of the existing system of centralized emergency control whose effectiveness has been tested by time. The proposed method of automatic distributed load shedding is designed to improve the intellectual level of high-speed local automation devices, which control the loading of the elements inside subsystems. Local emergency control devices are always operated in conjunction with the centralized systems. Thus, the possible implementation of the proposed algorithm is aimed at improving the reliability of the emergency control system in general.

Further work aims to develop software for the purpose of performance testing of the proposed algorithm.

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