

# A method of testing relay protection and automation involving exposure to cascading effects for improved power supply reliability and electric power system stability

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**Abstract.** The **Aim** of the paper is to show that improved power supply reliability and electric power system stability are achieved by applying new methods of testing relay protection and automation (RP&A). Major cascading failures in electric power systems are caused by cascading effects, i.e., effects involving several successive effects of various nature. Cascading effects allow extending the functionality while testing RP&A and taking into account the time factor in the context of effects of various nature. **Method.** A method is proposed for testing relay protection and automation taking into account the cascading effect that is used in the process of development, calibration and installation of protection devices for operation in predefined modes for the purpose of improved power supply reliability and unfailing stability of electric power systems. **Result.** Intermittent cascading effects do not allow the relay protection and automation recover the electric power system from the post-emergency mode, thus reducing the dynamic stability to the critical level. The diagram of relay protection and automation exposure allows taking into consideration the environmental effects in the process of testing the relay protection and automation. **Conclusion.** The proposed method of cascading exposure as part of testing relay protection and automation can be used in the process of development, calibration and installation of electric power systems protection and will enable improved stability of electric power systems and reliability of power supply.

**Keywords:** relay protection and automation, cascading effect, electric power system, stability, dependability, normal mode, emergency mode, post-emergency mode, emergency mode with loss of stability.

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## Introduction

Protection and emergency control systems enable sufficiently quick localisation of damaged areas and their removal from operation, while maintaining (with minimal losses) system operability. At the same time, there are major system (cascading) failures that cause the interruption of large numbers of consumers, disruption of parallel operation of power plants and electric power systems.

The major electric power emergency of August 14, 2003 in the US was caused by the power system structure having overgrown the control system capabilities. In the major cascading failure of May 25, 2005 in Moscow, Russia, the cause was the absence of several classes of safety protection and insufficient consideration of the nature of system (cascading) failures [1, 2].

The scope, societal and economic consequences of such accidents depend on the consideration of their nature in the course of the design, development and testing of the methods and means of electric power system protection.

An electric power system is the part of an electric system, in which heat and various types of energy are transformed into electric energy that is transmitted, distributed to consumers, where it is transformed again [3].

Power supply reliability is the ability of an electric power system to supply connected consumers with electric energy of a given quality over any time interval [4].

The stability of an electric power system is understood as the system's ability to recover the original mode of operation after its disruption  $Y_{st}$ ,  $Y_{din}$  [3, 5, 6].

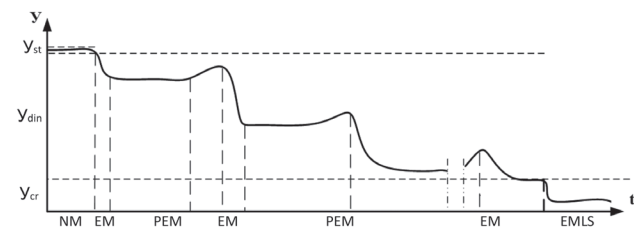
Relay protection and automation include the relay protection, grid automation, emergency automation,

operation mode automation, emergency event and process recorders, process automation of electric power facilities [7].

We will consider RP&A as a single system that is a set of interconnected subsystems of relay protection, automation and emergency event and processes recorders that operate jointly or separately for the purpose of maintaining – at all levels – the equipment operability and protection, control and monitoring of operating modes with the purpose of reliable power supply and unfailing stability of an electric power system (Fig. 1).

Each exposure of the electric power system causes stability degradation (Fig. 2). The role of relay protection and automation in this case comes down to restoring the normal mode of system operation associated with improving the stability.

Repeated exposure causes a gradual decrease in the stability of the electric power system to what can be called the critical level  $Y_{cr}$ , while the electric power system itself goes into the emergency mode with loss of stability (EMLS), in



NM, normal mode; EM, emergency mode; PEM, post-emergency mode; EMLS, emergency mode with loss of stability  
Fig. 2. Graph of decreasing electric power system stability under multiple effects

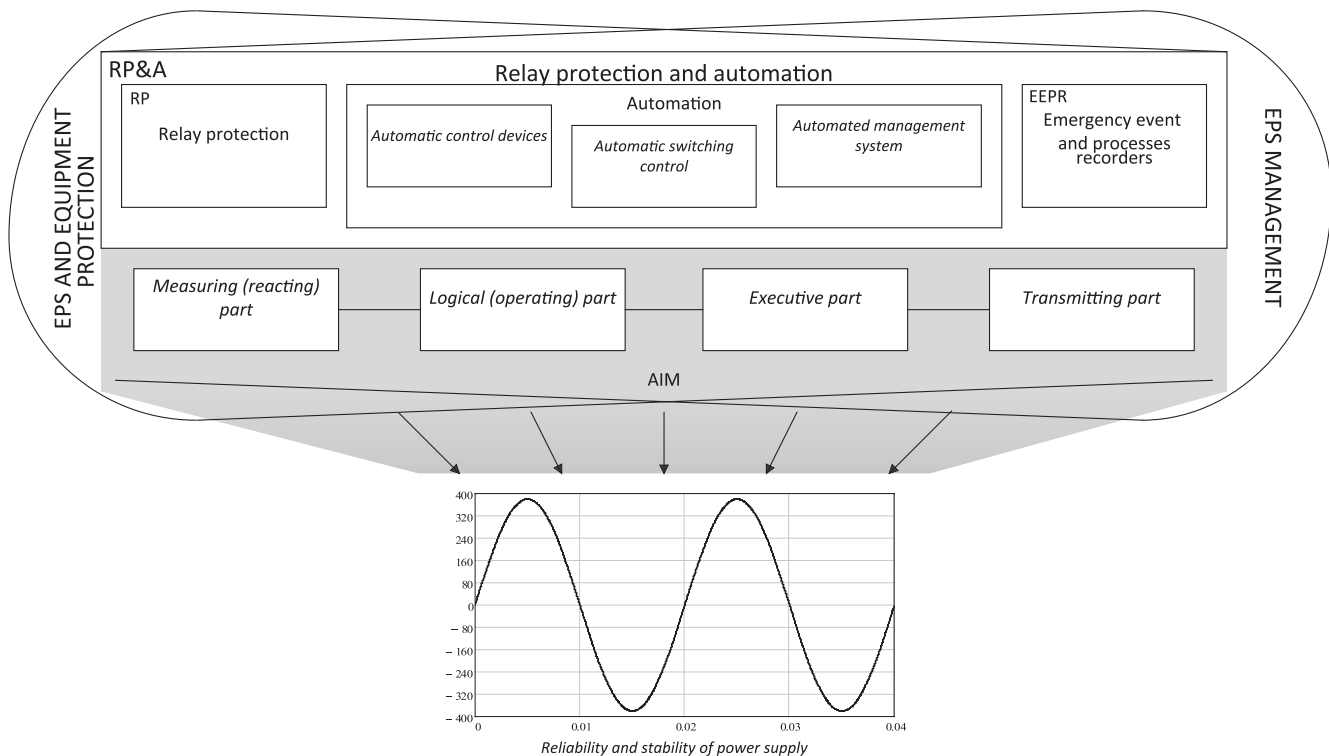


Fig. 1. Relay protection and automation: composition; objectives

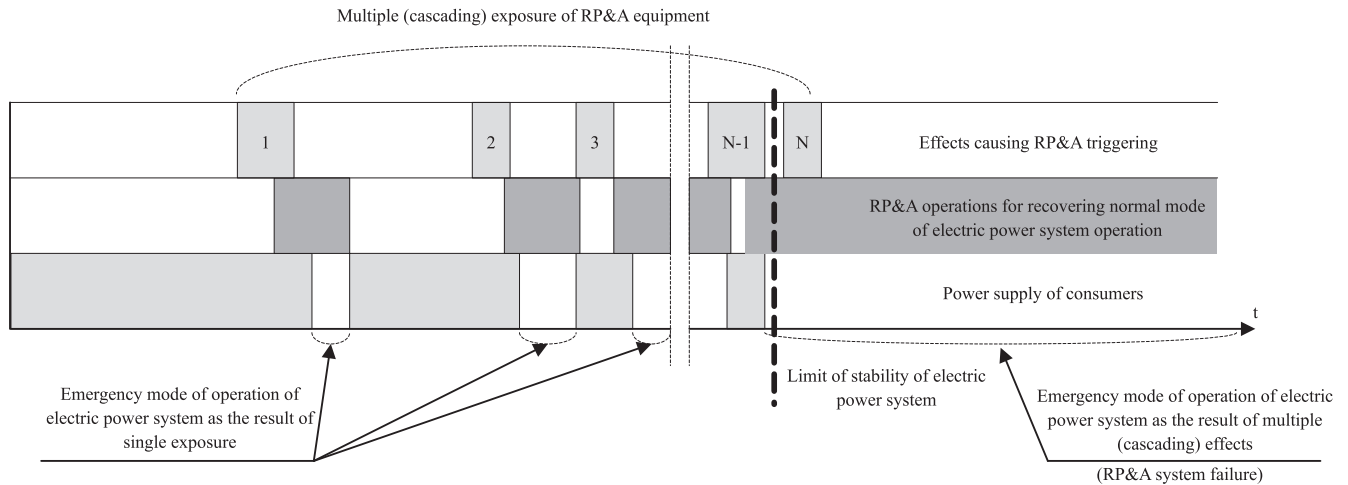


Fig. 3. Performance diagram of relay protection and automation when supplying power to consumers when exposed to effects that trigger its action

which the relay protection and automation are unable to restore its normal operation.

The effects of this repeated exposure are multiple and varied in their nature. Such multiple exposures are a cascading effect, i.e., an effect involving several successive effects of varied nature.

Since the operational state is a state of an item, in which it is able to perform (or is performing) the specified functions, while maintaining the values of the specified parameters within the limits set in the technical documentation [4], with the onset of EMLS, an electric power system is incapable of performing its primary function of transmitting electric power to the consumer. Therefore, an EMLS is a system failure. The failure will be primarily associated with the operation of relay protection and automation as a single system specifically, i.e., a set of interconnected subsystems of relay protection, automation and recorders of emergency events and processes (Fig. 3).

There is a significant number of both means, and methods of constructing and verifying RP&A [8, 9]. However, they are functionally limited to their respective scopes of application and do not imply repeated system exposure in cases of cascading failures.

Improving the power supply reliability and the stability of electric power systems is achieved by extending the RP&A testing functionality at the stages of development, calibration and installation of the protection devices.

## 1. Exposure of relay protection and automation

The diagram of relay protection and automation exposure (Fig. 4) includes direct environmental effects on relay protection and automation, environmental effects through electric equipment of electric power systems and effects of electric equipment.

The direct environmental effects on relay protection and automation may include cyber attacks against computer-based equipment and electronics of terminals; intentional

failure to follow the dispatcher's commands by operating personnel, physical damage of relay protection and automation equipment.

The environmental effect through the electric equipment of an electric power system on relay protection and automation includes deliberate actions, i.e., terrorist attacks against electric power system facilities; use of specialized weapons in the form of graphite munitions in the course of armed conflicts; property abuse associated with theft of metal structures of high-voltage power transmission lines and substation equipment, repeated shooting of power line insulator strings and accidental effects, i.e., natural weather events (wire breaking and short-circuiting due to high wind, falling trees and structures, short circuits due to lightning strike, failure of power transmission line supports due to earthquakes, floods, fires, landslides, etc.); non-observance of overhead clearances of construction and other heavy

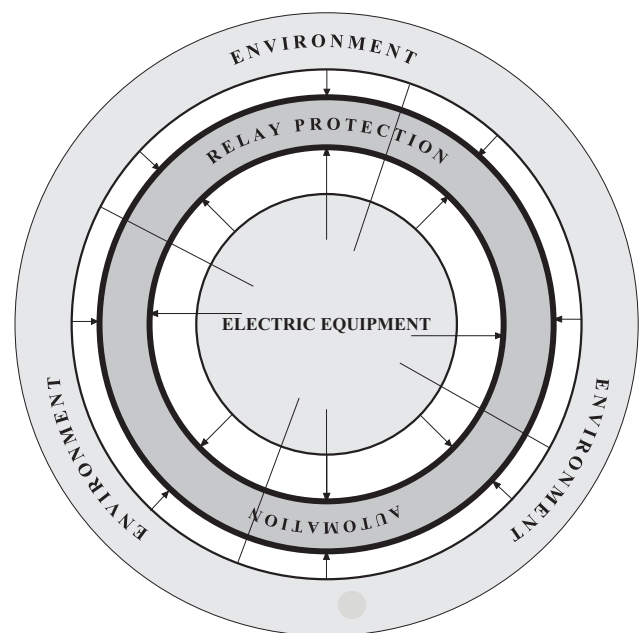


Fig. 4. Diagram of relay protection and automation exposure

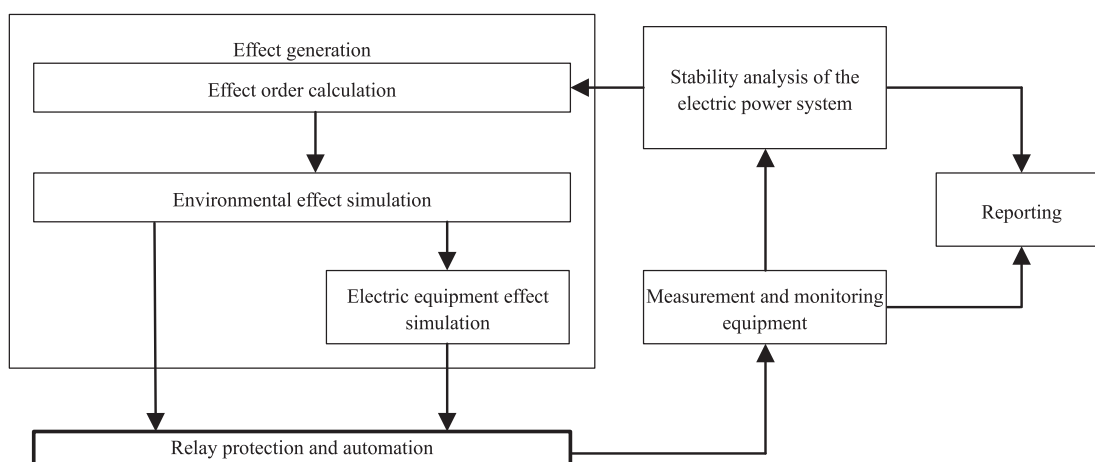


Fig. 5. Testing of relay protection and automation under cascading effects

machinery passing under the overhead power transmission line; light aircraft, unmanned aerial vehicles and balloons falling onto overhead power transmission lines and outdoor switchgear; errors by operating and dispatch office personnel in the course of maintenance, operation and switching at electric power facilities.

The effects caused by the electric equipment of an electric power system that trigger relay protection and automation include equipment failures due to operational deficiencies, repair defects, manufacturing defects, end of life (wear), transmission congestions (power consumption exceeds design limits).

## 2. Testing of relay protection and automation under cascading effects

In the course of development, calibration and installation of protection devices for operation in predefined modes, the

relay protection and automation exposed to cascading effects are tested subject to the changes in the stability of the electric power system and the environmental effects [10].

The testing consists of a set of actions that implement individual functions in a predefined order (Fig. 5).

The electric power system operates in normal mode (NM) until the first exposure. Its static stability  $Y_{st}$  is ensured (Fig. 6).

In the block of effect order calculation, the command to initiate exposure is generated. In the block of environmental effect simulation, the first command is generated to select the exposure of relay protection and automation through electric equipment.

Then, in the block of electric equipment effect simulation, a command is generated to simulate the effect on the block of relay protection and automation caused by the electric equipment. The operation of an electric power system in emergency mode (EM) is simulated.

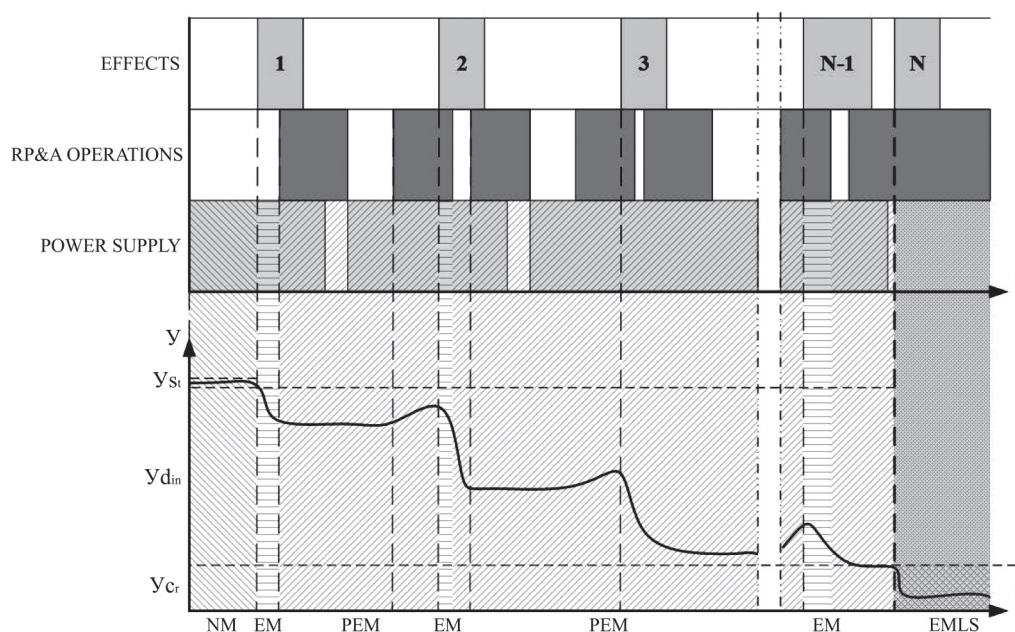


Fig. 6. Combined graph of the decreased level of electric power system stability under cascading effects and diagram of relay protection and automation testing when supplying power to consumers when exposed to cascading effects



In the block of relay protection and automation, the protection algorithm corresponding to the nature of the effect operates. Operating in accordance with its functional purpose, relay protection and automation eliminate the emergency mode (EM) and initiate a sequence of actions aimed at restoring the normal mode (NM) in the electric power system and improving the stability. At that moment, the electric power system is in the post-emergency mode (PEM). Information on the condition of the relay protection and automation components, as well as that reflecting the state of the electric power system – based on the evaluation of the output parameters of relay protection and automation – enters the block of measurement and monitoring equipment.

In the block of stability analysis of the electric power system, the incoming information is processed and – on its basis – the changes in the stability of the electric power system are evaluated.

The electric power system operates in the PEM. Its dynamic stability  $Y_{\text{din}}$  is ensured.

Next, in the block of effect sequence calculation, a command is generated to initiate the second exposure, taking into account the time, within which the relay protection and automation are unable to complete the sequence of actions to restore the NM of the electric power system. In the block of environmental effect simulation, a second command is generated to select the exposure of relay protection and automation through the electric equipment and, in the block of electric equipment effect simulation, a command is generated to simulate an exposure of the block of relay protection and automation through the electric equipment.

The operation of an electric power system in emergency mode (EM) is simulated.

In the block of relay protection and automation, the protection algorithm corresponding to the nature of the effect operates. Relay protection and automation eliminate the EM and initiate a sequence of actions aimed at restoring the NM in the electric power system and improving the stability. At that moment, the electric power system is in the post-emergency mode (PEM). Information on the condition of the relay protection and automation components, as well as that reflecting the state of the electric power system – based on the evaluation of the output parameters of relay protection and automation – enters the block of measurement and monitoring equipment.

In the block of stability analysis of the electric power system, the incoming information is processed and – on its basis – the changes in the stability of the electric power system are evaluated.

The electric power system continues operating in the PEM. Its dynamic stability  $Y_{\text{din}}$  is ensured.

In the block of effect sequence calculation, a command is generated to initiate the next exposure, taking into account the time, within which the relay protection and automation are unable to complete the sequence of actions to restore the NM of the electric power system. In the block of environmental effect simulation, the next command is generated to select the environmental exposure of relay protection and

automation, as well as a command to simulate an environmental exposure of relay protection and automation.

A fault of the relay protection and automation is simulated that is caused by environmental effects. The mode restoration fails and the stability of the electric power system drops. The latter remains in the PEM.

In the block of stability analysis of the electric power system, the incoming information is processed and – on its basis – the changes in the stability of the electric power system are evaluated.

In the reporting block, a report is generated on the current state of the relay protection and automation and on the stability assessment of the electric power system.

In the block of measurement and monitoring equipment, RP&A parameters are measured, the completeness of the requirements for the number and sequence of exposures is evaluated, the achieved and specified parameters are compared for the purpose of decision-making regarding further exposures.

In the block of exposure priority calculation, the exposure sequence is defined based on the set of temporal conditions:

$$\left\{ \begin{array}{l} t_{\text{EI}}^1 > 0, \\ t_{\text{PI}}^1 < t_{\text{ET}}^1 < t_{\text{STLPS}}^1, \\ t_{\text{PI}}^2 < t_{\text{EI}}^2 < t_{\text{PT}}^2, \\ t_{\text{PI}}^3 < t_{\text{ET}}^2 < t_{\text{STLPS}}^2, \\ t_{\text{PI}}^3 < t_{\text{EI}}^3 < t_{\text{ET}}^3, \\ t_{\text{PI}}^4 < t_{\text{ET}}^3 < t_{\text{PT}}^3, \\ \dots, \\ t_{\text{PI}}^{N-1} < t_{\text{ET}}^{N-1} < t_{\text{STLPS}}^{N-1}, \\ t_{\text{PI}}^N < t_{\text{ET}}^N, \\ t_{\text{IEMLS}} \leq t_{\text{EI}}^N. \end{array} \right. \quad (1)$$

where  $t_{\text{EI}}^1, t_{\text{EI}}^2, \dots, t_{\text{EI}}^N$  is the time of effect initiation,  $t_{\text{ET}}^1, t_{\text{ET}}^2, \dots, t_{\text{ET}}^N$  is the time of effect termination,  $t_{\text{PI}}^1, t_{\text{PI}}^2, \dots, t_{\text{PI}}^N$  is the time of protection initiation (relay protection and automation),  $t_{\text{PT}}^1, t_{\text{PT}}^2, \dots, t_{\text{PT}}^N$  is the time of protection termination (relay protection and automation),  $t_{\text{STLPS}}^1, t_{\text{STLPS}}^2, \dots, t_{\text{STLPS}}^N$  is the start time of the short-term loss of power supply after the effect and triggering of protection (relay protection and automation),  $t_{\text{IEMLS}}$  is the time of initiation of emergency mode with loss of stability.

The content of the blocks is any sequence of actions or any method associated with the functional content of the respective block.

## Conclusion

As mentioned above, repeated exposure causes a gradual decrease in the stability of the electric power system, which eventually leads to a situation whereas, after the N-th exposure, the stability falls to a critical level  $Y_{\text{cr}}$ , while the electric power system itself goes into EMLS, in which the relay protection and automation are unable to recover normal operation.

Thus, intermittent exposure to a cascading effect that prevents the relay protection and automation from recovering an electric power system from post-emergency mode, allows reducing the dynamic stability to a critical level, while the use of the diagram of exposure of relay protection and automation allows taking into account the external effects as part of relay protection and automation testing. Additionally, cascading exposure as part of testing of relay protection and automation is an important part of the development, calibration and installation of electric power systems protection that will enable improved stability of electric power systems and reliability of power supply.

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## The authors' contribution

**Koniukhov A.M.** analysed the changes in the stability of an electric power system and its effect on the power supply reliability when relay protection and automation are exposed to adverse effects, as well as the combination of processes under cascading effects, operation of relay protection equipment and automation when supplying power to consumers during triggering effects and changes in the level of stability of an electric power system.

**Khlebnov A.V.** analysed major cascading failures in electric power systems, analysed and structured the effects on relay protection; drawn up the diagram of exposure of relay protection and automation.

**Timanov V.A.** constructed the sequence of testing relay protection and automation exposed to cascading effects taking into account the changes in the stability of the electric power system and the external effects on the relay protection and automation; drew up the block diagram of testing relay protection and automation exposed to cascading effects.

## Conflict of interests

The authors declare the absence of a conflict of interests.