

# Economic efficiency of facts devices in increasing vitality of electric power systems

*Bulat Gaisin<sup>1,\*</sup>, Ildar Shakhmaev<sup>2</sup>, Nikolay Novikov<sup>3</sup> and Alexander Novikov<sup>3</sup>*

<sup>1</sup>Ufa State Petroleum Technological University, Department of Electrical Engineering and Electrical Facilities of Enterprises, Ufa, Russia

<sup>2</sup>Ufa state aviation technical university, Department of Electromechanics, Ufa, Russia

<sup>3</sup>Dept. of New Grid Technologies Scientific and technical center of the federal grid company of the unified energy system, Moscow, Russia<sup>3</sup>PJSC «FGC UES», 117630, Moscow, Akademika Chelomeya str., b.5A; Russia, «MPEI», 111250, Moscow, Krasnokazarmennaya 14; Russia, «JIHT RAS», 125412, Moscow, Izhorskaya st. 13 Bd.2. Russia,

**Abstract.** The article proposes a model of an electric power system (EPS), in which the calculation of normal and emergency modes is carried out, possible trajectories of the development of cascade processes of an emergency nature are determined. On the basis of experimental calculations, a tool is proposed to increase the survivability and reduce the risk of the possibility of the occurrence and development of cascade processes in the EPS. This approach allows you to make sound technical and economic decisions at the design and development stage of the EPS. In accordance with the results of the study, a technical and economic comparison of the options for increasing the survivability of the EPS was carried out.

## 1 Introduction

An important goal of managing the characteristics of electrical power systems (EPS) is to ensure the required level of reliability and survivability required for uninterrupted power supply to consumers. In complex inhomogeneous EPS for various reasons (short circuits, equipment failure, maintenance personnel errors, etc.), disturbances periodically arise. Most of them are eliminated by means of relay protection (RP) and emergency automatics (PA), but some of the disturbances turn into major systemic accidents, often with severe consequences for the EPS and consumers. Such accidents, in turn, show the disadvantages of EPS from the standpoint of reliability and survivability, these issues have been actively investigated [1-10, 13-21] since the 1960s by domestic and foreign scientists, but despite this in EPS around the world systemic accidents occur almost daily.

In the EPS of Russia, the formation of modes based on methodological guidelines for the stability of power systems [1] leads to excessive requirements for the formation of reliable modes in distribution grids 110-220 kV, without ensuring sufficient measures to preserve survivability - preventing the development of cascade processes [2]. This is confirmed by regularly occurring cascade accidents. Table 1 shows the most famous of them that occurred in the EPS of Russia for the period 2016 - 2017.

One of the ways to increase the survivability of EPS is the use of controlled (flexible) AC power transmission systems (FACTS). These devices can provide a more

complete use of the capacity of existing electrical grids [3]:

- transfer of additional electricity from redundant energy systems with lower tariffs to scarce ones with the displacement of less efficient energy sources there;
- an increase in the output of active power of power plants, by increasing the maximum permissible power flows.

**Table 1.** Cascade accidents that occurred in the EPS of Russia for 2016-2017.

Date / Region	Power losses, duration of power outages
02.07.2016, Republic of Bashkortostan	1000 MW, 3h. 35 minutes
22.08.2016, EPS of Siberia	5800 MW, 4h. 3 min.
16.03.2017, EPS South	250 MW
29.05.2017, Khakassia EPS	1433 MW, 2h. 21 minutes
15.06.2017, EPS of the Perm Territory	400 MW, 1 hour. 9 minutes
27.06.2017, EPS of Siberia	4400 MW, 3h. 25 minutes
28.07.2017, EPS South	1000 MW, 5 hours 55 minutes

\* Corresponding author: [GB9688@gmail.com](mailto:GB9688@gmail.com)

In addition, it becomes possible to reduce the dosage of the control actions of the emergency automatics (EA), thereby reducing the volume of load and generator disconnections. The result of this is [3]: a decrease in the need for an emergency reserve in the EPS; reduction of damages at power plants from underproduction of electricity; reduction of compensation payments to consumers for interruptions in power supply; saving fuel for repeated start-ups of power units of power plants switched off by EA.

The use of FACTS devices in EPS for industrial consumers allows to improve the quality of electricity, which leads to a decrease in product rejects, increases the productivity of technological equipment and reduces the cases of its shutdown due to a decrease in voltage and overload due to an increase in voltage above permissible values. In addition, the likelihood of disruption of the normal operation of control systems and technological automation, as well as the rate of wear of technological equipment, is reduced.

The result of this may be: an increase in the gross volume of production, a decrease in its cost and savings in renovation costs, current and emergency repairs of technological equipment, as well as a decrease in the volume of claims against the electricity supplier for compensation for non-fulfillment of contractual quality obligations electricity.

At the same time, the justification of the economic efficiency of the use of FACTS devices should be based on an individual approach for each specific case of their use.

In work [1], a method is proposed for determining the development paths of cascade processes in EPS in accordance with the areas of existing regimes and options for the development of transitions between them. According to this method, a cascading process is considered as a process in which the disconnection of one element unconditionally entails the disconnection of the next element. Then in this model, the cascade process begins long before the avalanche process and continues until the disconnection of each next element leads to the disconnection of the next one. If no further shutdown occurs, the cascade process is terminated. The cascade process does not necessarily end with an accident, loss of stability, including voltage loss. [1, 2] The article proposes to use this method when determining the installation locations of FACTS devices.

In the method [1], it is assumed that the current load of an element of the power system, above the permissible one, leads to its destruction (disconnection). Then a necessary condition for the existence of a cascade process is the inequality:

$$I_{ji} + \Delta I_{ji} > I_{lim\,ji} \quad (1)$$

which must be performed at each subsequent step of the emergency shutdown (-s). Here  $\Delta I_{ji}$  is the current surge on the overloaded element,  $I_{lim\,ji}$  is the permissible current value for this element.

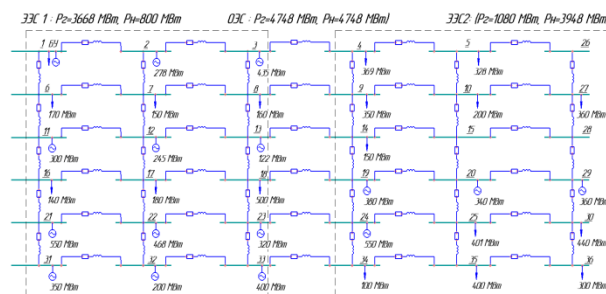
Failure to satisfy inequality (1) leads to the termination of the emergency cascade process.

To prevent the possibility of the occurrence and development of cascade processes in the EPS, in accordance with the method [1], the calculation and technical and economic comparison of the following options for increasing the EPS survivability were performed:

- increasing throughput due to: the use of FACTS devices, construction of an additional power transmission line (power transmission line);
- redistribution of power flows in the grid due to the introduction of additional generation sources into operation.

## 2 Simulation of emergency processes in a test eps

To calculate the normal and limiting static stability modes, provided that a cascade process occurs, a diagram [2, 5] of an united power system (UPS) with a rated voltage of 500 kV (Fig. 1), consisting of 36 nodes, which includes EPS "A" (left half of the nodes) and EPS "B" (right half of the nodes), connected by six intersystem power lines (3-4, 8-9, 13-14, 18-19, 23-24, 33-34).



**Fig. 1.** Estimated scheme of thirty-six nodal interconnected power systems.

The total generated capacity in EPS "A" is 3668 MW, in EPS "B" - 1080 MW. The total power consumption in EPS "A" is 800 MW, in EPS "B" – 3948 MW. In this case, EPS B is deficient in terms of the generated power, as a result of which electricity is transmitted in the amount of 2868 MW through intersystem lines.

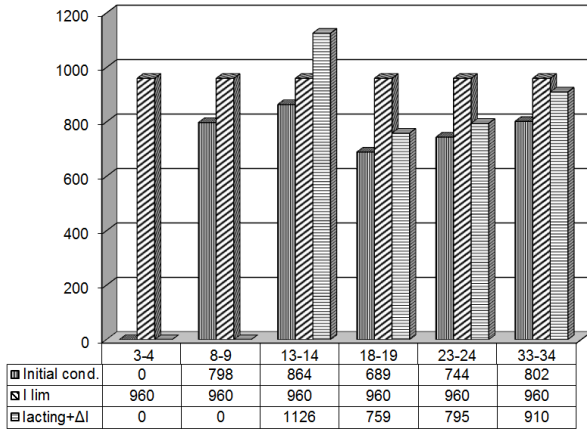
The calculation of the steady-state modes of the EPS was made in the RastrWIN software package. In the course of the calculation, the repair and repair and emergency modes of the UPS were considered. As an example of the calculation, consider the superposition of the repair (branch 3-4) and emergency (branch 8-9) EPS modes, in which the emergence and development of a cascade process occurs with the subsequent division of the OES and the loss of voltage stability.

As a result, a cascade emergency process is formed, developing along a trajectory ending in the area of unacceptable modes: 1 step - 8-9; 2nd step - 9-14, 13-14; Step 3 - 10-15, 18-19, 33-34, 34-35.

The process of changing the currents in the intersystem branches as a result of the cascade process is schematically shown in Fig. 2, where the value of the long-term allowable current  $I_{lim}$  for an UPS element is

represented by histograms with oblique shading, the vertical shading indicates the current values at the initial conditions  $I_{i.c.}$  (before the onset of the cascade process), the horizontal shading shows the current values in the branches  $I_{acting} + \Delta I$  after the transition of the UPS to emergency mode.

Figure 2 shows that emergency shutdown of line 8-9 with line 3-4 brought out for repair leads to an unacceptable overload of the current intersystem line 13-14, which leads to the emergence and development of a cascade process with a subsequent loss of voltage stability.



**Fig. 1.** Estimated scheme of thirty-six nodal interconnected power systems.

One of the options for solving the problem of increasing survivability and preventing a cascade process in an ECO is to prevent a cascade process through the use of devices related to actively adaptive grid elements (FACTS), which increase the line throughput. FACTS devices are considered: a static thyristor compensator (STC), a static reactive power compensator (STATCOM), a controlled longitudinal compensation device (CLCD) and a combined power flow regulator (CPFR).

The calculation of the use of FACTS tools is made in accordance with [3-4]. The study considers an increase in the throughput of a 500 kV intersystem line by half, for this it is necessary to compensate for half of its reactance, as a result of which the current and power of the line will double.

The rated power of FACTS devices for the considered version of the cascade process [3-4], where after a trigger disturbance (short circuit (SC) on transmission lines 8-9), an overload occurs and disconnection of lines 9-14 and 13-14 is 1036.8 MVA [5]. To unload these lines, install the FACTS on line 13-14, which is intersystem and has an inductive resistance of 112.8 ohms.

### 3 Evaluating the economic efficiency of FACTS devices

The assessment of the economic efficiency of FACTS devices was carried out in accordance with the methodology for assessing the technical and economic

efficiency of using FACTS devices in the UNEG of Russia [3], as well as with the application of [4, 10, 11, 12]. The study calculated the following indicators: integral effect or net present value (NPV), payback period, profitability index (ID), internal rate of return (IRR).

NPV from the use of FACTS devices is determined by the formula:

$$NPV_C = -I_C + \sum_{t=1}^T (R_C^{(t)} - D_C^{(t)}) \cdot \frac{1}{(1+E)^t} \quad (2)$$

where  $T = 25$  years is the duration of the device's operation,  $E = 12\%$  is the discount rate,  $I_C$  is the investment in FACTS devices, which, according to expert estimates, are determined approximately (STC 120 \$ / kVA, STATCOM 180 \$ / kVA, CLCD 158 \$ / kVA, CPFR 300 \$ / kVA) [4], with a total capacity of 2038.1 MVA [5] are  $I_C = 3668.58$  million rubles. = \$ 61.14 million,  $R$  - the annual total economic result from the use of the STC device,  $D$  - the annual depreciation and maintenance costs of the devices proposed for commissioning are estimated at approximately 8.4% of capital investments according to the formula

$$D_C^t = \alpha_C \cdot I_C = 0,084 \cdot 61,14 = 5,14 \text{ mln. } \$ / y. \quad (3)$$

In accordance with [3], we will consider the sources of payback of FACTS devices in two ways:

- The first option assumes that the additional electricity transmitted from EPS 1 displaces into EPS 2 the closing generating capacities with high specific fuel consumption and (or) using expensive fuel.

- The second option assumes that the effect of a more complete use of the throughput of the intersystem section is expressed in the possibility of reducing compensation payments for the shortage of electricity.

The use of FACTS devices from the standpoint of the annual total economic effect in the first and second options, respectively, is estimated by the formulas:

$$R_C^{(t)} = P \cdot T_{max} \cdot \Delta C \text{ или } R_C^{(t)} = P \cdot T_n \cdot C_n \quad (4)$$

where  $P = 900 \text{ MW}$  is the increase in MPE using FACTS devices,  $T_{max} = 4000$  hours is the annual number of hours of use of the additionally transmitted power,  $\Delta T$  is the difference between the tariff on the federal wholesale electricity and capacity market [12] and EPS 2 and the selling price of electricity, generated at power plants of EPS 1,  $T_n$  is the number of hours of existence of the maximum undersupply,  $C_n = 1.5 \text{ $ / kWh}$  - compensation payments for undersupply of electricity. In calculations, the difference in tariffs  $\Delta C$  varied from 0.01 to 0.015 \$ / kWh. When evaluating the result  $R_C^t$  in terms of saving compensation payments for the shortage of electricity, the  $T_n$  indicator varied from 25 h to 30 h.

Payback period, profitability index are determined by the formulas:

$$\tau_c = \frac{-1}{\ln(1+E)} \ln \left( 1 - \frac{I_C}{I_C - D_C} E \right) \quad (5)$$

$$ID_C = \frac{(R_C - 3C_C)}{K_C} (x + a)^n = \sum_{t=1}^T \frac{1}{(1+E)^t} \quad (6)$$

the internal rate of return is determined from the equation:

$$\frac{I_C}{R_C - D_C} = \sum_{t=1}^T \frac{1}{(1+IRR)^t} \quad (7)$$

where  $R_C = R_{C(t)}$ ,  $D_C = D_{C(t)}$  - the annual total economic result and the annual depreciation and maintenance costs are taken the same for each year of the device's service life.

As an example, the results of calculating the technical and economic indicators for preventing a cascade process according to the 3-4 - 8-9 scenario for STC, STATCOM, CLCD and CPFR devices are summarized in Table 2.

With the difference  $\Delta C = 0.015 \text{ \$ / kWh}$ , the most profitable solution is the use of an STC, this option has the highest NPV (180.928 million \$), from the point of view of the payback period, the use of this device is also

**Table 2.** Technical and economic indicators of the complex application of FACTS devices for the scenario of a cascade process 3-4, 8-9.

Cascading proc. script, device FACTS	Electricity cost option, where $\Delta C (\text{\$/kWh} \cdot h) T_n (h)$	NPV, mln. \$	Payback period, years	ID	IR R, %	
3-4, 8-9 STC	Var 1:	$\Delta C=0,01$	180,928	2,40	3,96	50,5
		$\Delta C=0,015$	322,104	1,44	6,27	79,9
	Var 2:	$T_n=25$	163,28	2,61	3,67	46,8
		$T_n=30$	216,22	2,05	4,54	57,8
3-4, 8-9 STATCOM	Var 1:	$\Delta C=0,01$	130,22	4,35	2,42	30,8
		$\Delta C=0,015$	271,4	2,40	3,96	50,5
	Var 2:	$T_n=25$	112,58	4,85	2,23	28,3
		$T_n=30$	165,52	3,61	2,8	35,7
3-4, 8-9 CLCD	Var 1:	$\Delta C=0,01$	157,26	3,21	3,08	39,3
		$\Delta C=0,015$	298,44	1,86	4,96	63,2
	Var 2:	$T_n=25$	139,61	3,53	2,85	36,3
		$T_n=30$	192,56	2,72	3,53	45,3
3-4, 8-9 CPFR	Var 1:	$\Delta C=0,01$	9,37	31,9	7,91	3,9
		$\Delta C=0,015$	17,8	18,51	7,98	13

Var 2:	$T_n=25$	8,32	35,13	7,9	2,5
	$T_n=30$	11,48	27,07	7,95	6,4

the most profitable (2.4 years). It should be noted that the use of CPFR for the period under consideration of 25 years will not pay off.

With a difference of  $\Delta C = 0.015 \text{ \$/kWh}$ , the most profitable solution is also the use of an STC.

In the second option, with a more complete use of the intersystem cross-section throughput with a decrease in compensation payments for undersupply of electricity, the considered economic indicators strongly depend on the number of hours of existence of the maximum undersupply (Table 2).

At  $T_n = 25 \text{ hours}$ , the most advantageous solution is to use the STK: the NPV value = 163.28 is the highest. The use of CPFR for the period under review of 25 years will not pay off.

When  $T_n = 30 \text{ hours}$ , the most advantageous solution is also the use of STC. The use of CPFR in this case also does not pay off in 25 years.

#### 4 Conclusion

Thus, the article proposes a tool for increasing the survivability and reducing the risk of the possibility of the occurrence and development of cascade processes in the EPS, which allows making sound technical and economic decisions at the design and development stage of the EPS in order to use FACTS devices. The assessment of the economic efficiency of FACTS devices was carried.

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