Influence of Renewable Energy Sources and FACTS on Out-of-Step Protection Operation

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Abstract

Electric power systems are becoming more complex. This is due to the widespread use of renewable energy sources (RES) and FACTS devices. At the same time, protection devices for equipment and automation of power systems are becoming subject to influence from new devices. The article pays attention to the study of such influence from the side of RES and FACTS devices on the operation of one of the most important automation systems ensuring the stable operation of the power system - out-of-step protection (OSP). At the first stage of the project, the main reasons for the difficulty of setting up resistance control devices of OSP in networks with FACTS devices and RES were identified, which are related to the fact that the parameters of these devices vary depending on the operation mode, therefore, the zone of the OSP resistance relay should also be changed. Based on the analysis, a new approach to the study of the functioning of OSP in power systems with FACTS devices and RES has been developed. The performed experimental studies confirm the theoretical research.

Keywords: Out-of-step protection, Static synchronous compensator, Hybrid simulation, Electric power system.

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1. Introduction

Electric Power Systems (EPS) are the fundamental infrastructure of any modern state and unite its territory into a single grid. Failure of power transmission has significant consequences for national security, the economy and the life of every person. However, EPS is so wide and difficult that it can never be protected absolutely from such a disturbance. At the same time transport, telecommunications, oil and gas, financial and other infrastructures depend on the normal operation of the EPS and even a minor failure can be reason of blackout and bring damage the economy of the country in the whole. Thus, ensuring the reliability of the power system under the influence of the above-mentioned failure is a task of national importance. In the world practice, the solution of this most important task is provided by emergency automation (EA), including the out-of-step protection (OSP). Moreover, due to the large number and variety of possible emergency modes in EPS, including man-made or natural ones, as well as the need for reliable and efficient operation of the EA in different modes of EPS, correct setting of the EA is a non-trivial and actual task [1, 2].

At the same time, EPS is constantly progressing, flexible alternative current transmission systems (FACTS) [3] and renewable energy sources (RES) are being penetration. It is made the task of secure power system stability more complicated.

Meanwhile, it is well known that FACTS and RES are capable of influencing to the action of relay protection and EA. So in [4] describes the need to change the operational characteristics of distance protection in the presence in the grid of the unified power flow controller (UPFC).

According to [5], shunt elements (loads, shunt reactors, etc.) should be taken into account when constructing the hodograph of resistances in the complex plane. The article presents a method for constructing the hodograph anywhere in the power system with shunting elements and without them, as well as a bus definition rule that is suitable for location of OSP.

Studies [6, 7] show that compensation devices, such as static var compensator (SVC) and static synchronous compensator (STATCOM) are mainly installed at the midpoint of the line to increase power transmission and stability of the power system. If the STATCOM located in the middle of the transmission line and a fault occurs behind the device, the STATCOM always enters the fault circuit and significantly affects to the short circuit current. Thus, it adversely affects to the change of resistance during the action of protection devices, which reaches or exceeds the permissible value depending on the level and mode of compensation operation. The research [8] proposed to use an upgraded resistance relay in the presence of the STATCOM on the transmission line. In both cases, the complexity of setting up distance protections lies in the fact that the parameters of the FACTS devices change depending on the operation mode, therefore the zone of relay action are also changed.

The presence of HVDC devices, including converters at wind turbines (WT), in power system also requires a revision of the settings for used relay protection and automation in the rest of the power system equipment. Thus, for example, when commutation failures occur in back-to-back HVDC converter station, there are maloperation of the distance protection at the alternating current transmission lines adjacent to the converter station [9, 10].

Possible solutions to this issue are the optimization of existing algorithms for the operation of various relay protections exposed to converter station effects, or the use of relay protection with a different operation principle, which is not always possible. In [11] the authors propose to use differential protection of transmission lines adjacent to the converter station, instead of distance protection. However, the principle of impedance control is used not only in the distance protection algorithms, but also in most types of OSP, and since OSP cannot be replaced by other types of automation or cannot use another principle, the problem of assessing the adequate operation of such EA type, installed in power systems with FACTS or RES devices, is still unsolved.

At the same time, the international experience in FACTS and RES operation does not take into account the specifics of Russian power systems functioning, including operation algorithms of relay protection and automation.

Thus, the development of new approaches to the EA setting up under the conditions of wide use of FACTS devices and RES facilities is an urgent task.

2. Analysis on causes of influence of FACTS and RES on operation of OSP and EPS as a whole

To eliminate the unstable power swings, the OSP devices must form the appropriate control actions using certain methods of power swing detection. The methods themselves must meet the technical requirements for OSP devices, for example, the standard of JSC "SO UPS" [12]. These requirements differ for devices designed to detect power swings before reaching a critical angle (in the first cycle) and devices detecting power swings after a specified number of power swing cycles or a specified time. The most characteristic feature of loss of stability is an increase in the phase angle between the equivalent EMF of EPS' two parts connected by the power line. However, its direct tracking is technically difficult. At the same time, modern technology of PMU measurements will allow in the future to solve this issue [13, 14]. In this regard, in the majority of currently used OSP devices, EPS operational parameters are controlled, which are depending on the mutual angle. The change of these parameters allows to identify the power swings in EPS [15].

The most common today in Russia and abroad are the OSP devices [12, 16], which use the following features to identify the asynchronous mode:

1. The resistance of the electrical network in a controlled point, as well as the direction of power flow;
2. The angle between the voltage vectors at the ends of the transmission and its rate of rise.

Affected directly by FACTS devices and RES OSP, which use resistance control to identify the asynchronous mode. Thus OSP device simulating the angle between the voltage vectors at the ends of power transmission, also using the calculated resistance which means they can also be affected by FACTS and RES but already at the stage of calculating the threshold for a given part of the network (equivalent resistances may not be calculated correctly, in addition, the algorithms for the operation of devices may not take into account the dynamics of the FACTS operation)

The complexity of setting resistance control devises in EPS with FACTS is that the parameters of these devices vary depending on the operating mode, therefore, the range of the resistance control relay must also be changed. In [17, 18] describes the necessity to change the response characteristics of such a relay in the presence of the UPFC. The UPFC affects the operation of the distance relay during oscillations in the EPS, since the parameters of the power system fluctuate during oscillations. In this case, because of UPFC operation depends on some of these parameters (voltage on the bus, active and reactive power), then the UPFC introduces an oscillating series voltage and receives an oscillating shunt current. These values in turn affect the resistance relay operation, since the resistance controlled by such a relay during the oscillations varies for lines with the UPFC. Similarly, the influence on the EPS and other FACTS devices, such as a thyristor controlled series compensator (TCSC). TCSC during voltage fluctuations quickly changes its reactance and thus affects the parameters of the asynchronous mode. Articles [5, 8] show that reactive power compensation devices for parallel connection (controlled shunt reactors, static var compensator, static synchronous compensator etc.) can also cause the resistant relay to malfunction and should be taken into account when constructing the resistance locus. In [19], it was shown that with the inclusion of STATCOM in a single-machine system in the normal mode, the resistance measured by the differential protection increases, and the inductive one decreases. For damages in the circuit, the opposite pattern is observed: the active resistance decreases, and the inductive pattern increases. One of the factors affecting the electrical network resistance in the presence of the STATCOM is the compensator operation mode. When generating reactive energy into the electrical network, STATCOM increases the impedance, and when consumed it decreases [20].

In addition to the direct impact on protection devices, the introduction of RES through the growth of the use of power electronics in EPS (the main increase in input power is due to wind turbines of the 3rd and 4th types and solar panels [21] connected to the electrical network using power converters used in HVDC) creates new problems. One of the biggest problems associated with the large-scale integration of RES is the reduction of the EPS inertia. When traditional synchronous generators are replaced by wind turbines, the time constant of inertia of the system decreases sharply [22]. In addition, the inertia of the system becomes time-varying due to the constant change in power output by the wind turbine. Systems with less inertia may more easily lose their stability in the event of a serious fault. Asynchronous oscillations in such systems can be mistaken for a short circuit. Thus, controlled network sharing with the help of OSP, as the last stage of protection against uncontrolled development of an emergency, is becoming increasingly important and necessary for low inertia systems. In [23], it is confirmed that the inertia change in the system can affect the coordinated work of generators groups, which can change the groups composition of detachable generators in the asynchronous mode and, consequently, the separation boundary. A reduced time constant of inertia can lead to a higher sliding speed and a rate of change in apparent impedance measured by OSP trigger units. The article [24] noted that in the literature there are practically no detailed studies of the behaviour of OSP launch organs with a reduced and time-varying time constant of inertia of the system. As a confirmation, several examples of wrong actions of OSP in various modes of EPS operation with different share of RES are given. Thus, the main reasons for the influence of FACTS and RES devices on the operation of the EPS in general and in particular on the OSP are:

- Changing the parameters of these devices depending on their operation modes (generation or consumption of reactive power);
- Impact on the EPS mode parameters during the asynchronous mode;
- The suddenness parameters changes in these devices due to failure or features of the control system;
- Reducing the power system inertia when traditional synchronous generators are replaced with wind turbines using HVDC technology.

3. A new approach of solving the problem of assessing the impact of FACTS and renewable energy sources on the functioning of OSP in EPS

Based on the analysis, a new approach to the study of the functioning of OSP in power systems with FACTS and RES devices has been developed. This approach is to use the hybrid modelling concept created with the participation of the author, which allows creating and applying for each significant aspect of the problem being studied the most effective methods, the aggregation of which ensures its successful solution in general [25]. Based on the developed approach, in particular, universal full and reliable OSP mathematical models were synthesized (devices designed to detect the asynchronous mode before reaching the critical angle (in the first cycle), and devices that detect the asynchronous mode after a specified number of asynchronous cycles or a specified time) all the features of its software and hardware implementation, as well as primary and intermediate converters. The mathematical description of the algorithmic part of the OSR model for resistance on the example of one of the starting organs - the resistance relay (RR) is given below.

An example of the model implementation is shown in Figure 1.

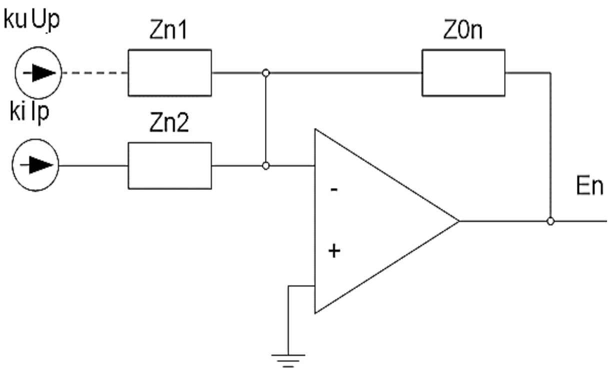

Figure 1. Equivalent scheme for the formation of the n-th compared value

Required measured values:

$$U_{\mathrm{p}} = U_a \cdot e^{j\varphi ua} - U_b \cdot e^{j\varphi ub} \quad (1)$$

$$I_{\mathrm{p}} = I_a \cdot e^{j\varphi ia} - I_b \cdot e^{j\varphi ib} \quad (2)$$

According to this scheme with current and voltage sensors on the inverting input of the operational amplifier supplies a voltage proportional to the primary measured currents and voltages. Z_{ij} is determined by the shape of the operation characteristic of resistance relay on the complex plane, in this case operation characteristic in the shape of a circle (Figure 2).

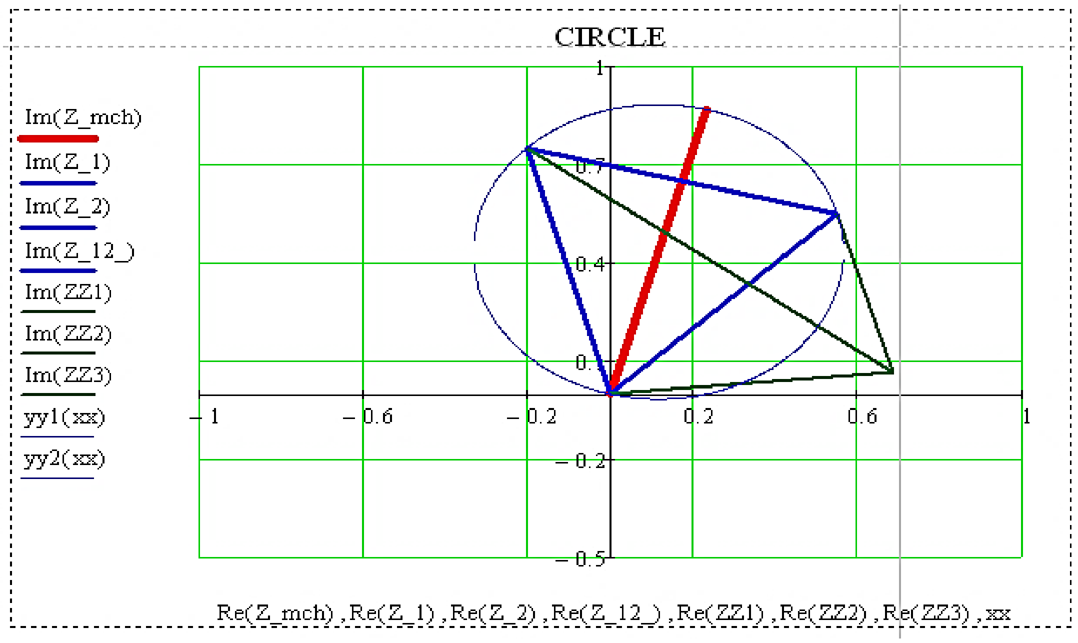

Figure 2. Operation characteristic of resistance relay model

For the scheme on the Figure 1, the method of "directed graphs" is used to determine the transfer function for current circuits W_2 and voltage W_1. Thus, the compared value E_n, is formed according to the expressions:

$$E_n = W_1 + W_2 \quad (3)$$

where:

$$W_1 = -ku \cdot \frac{Z0n}{Z1n} \cdot U_p \quad (4)$$

$$W_2 = -ki \cdot \frac{Z0n}{Z1n} \cdot I_p \quad (5)$$

$$E_n = k_{1n} \cdot U_p + k_{n1} \cdot I_p \quad (6)$$

Hence

$$k_{1n} = -ku \cdot \frac{Z0n}{Z1n} \quad (7)$$

$$k_{n1} = -ki \cdot \frac{Z0n}{Z1n} \quad (8)$$

where:

K_i = 0.01 - intermediate current scaling factor;

K_u = 0.01 - intermediate voltage scaling factor.

The number of compared E_n values depends on the type of response characteristic of the resistance relay (RR), for example, to form a circle, it is necessary to form three such quantities.

4. Results and Discussion

4.1. *Description of the test scheme*

In order to study the behavior of OSP when working in the power system together with FACTS devices, the power system was modelled, including generators, power lines, loads, power and instrument transformers, asynchronous and synchronous motors. STATCOM is one of the most efficient and common FACTS devices, with a number of significant advantages over other devices. Therefore, this type of FACTS device has been used in research.

For the experiment, a 9-bus test system model of the power system was used, which was approved by the standard of Russian System operator [12] for certification testing of OSP devices. The test model is assembled in the real-time digital simulator (RTDS) in accordance with the scheme presented in Figure 3 and has a three-phase execution. The operating parameters of the power system (voltages in nodes, currents and power flows of active and reactive power in the branches, frequency at opposite substations (SS): SS №2 and SS №5) in the steady state can be observed in the diagram presented in Figure 3.

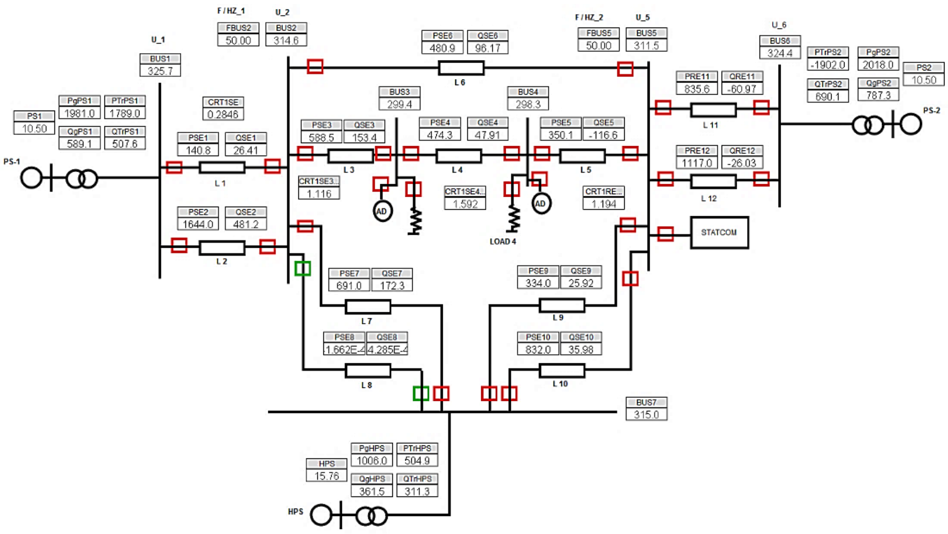

Figure 3. Scheme with STATCOM connected to buses of SS №5.

Steady state mode of the OSP fault detectors are installed at substations №2 and №5 with a voltage of 330 kV. The protected network section includes power lines L-3, L-4 and L-5 with intermediate power take-off.

The paper considers the OSP device, which reacts to a change in resistance and reveals an asynchronous mode after the start of the first cycle. Asynchronous modes are divided into fixed (those in which reliable operation of the OSP device must be ensured) and non-fixed (those in which reliable failure of the OSP device must be ensured). In experiment the fixed asynchronous mode is considered.

Experimental results are shown in Figures 4-7.

4.2. Case study

The main task of the experiment is to confirm the performance of the OSP installed at substation №5 in the presence of intermediate power take-offs in the protected area.

In the event of a two-phase short-circuit to earth with a duration of 0.22 s on the line L-6 near to SS №2, it is switched off. The result is an asynchronous mode, characterized by sustained deep fluctuations in voltage, current and power. In the case of disconnected STATCOM the electric swing centre (ESC) is located on the L-4 line.

After STATCOM is turned on parallel operation with the power system, the experiments are repeated, and the ESC offset value is determined further. STATCOM connection is made to buses with low voltage relative to the rated voltage alternately to different substations of the power system. Substations №3, №4, №5 were selected for STATCOM connection.

Figure 4 shows the oscillograms of the transient process, obtained for the case of the emergence of asynchronous mode due to the loss of the dynamic stability of the generators of the power system without connected FACTS devices.

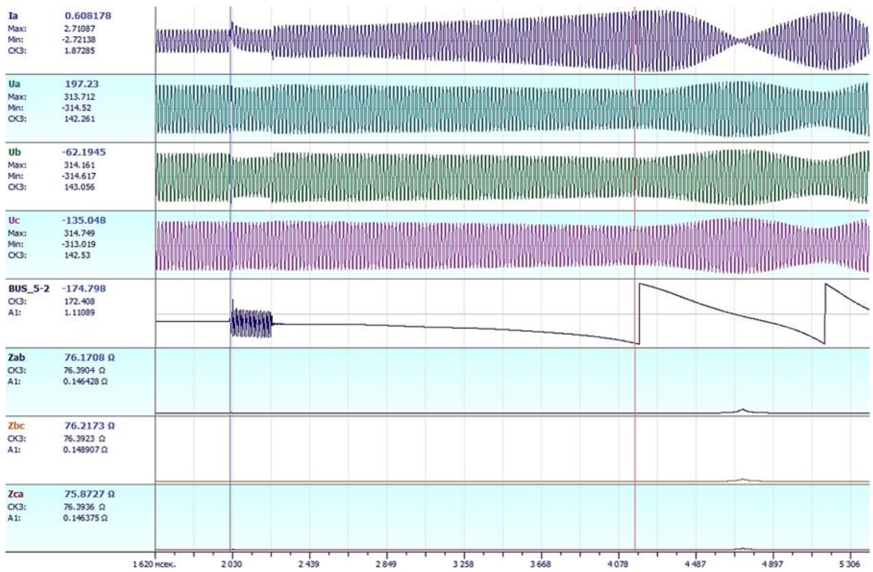

Figure 4. Oscillograms of current phase A, voltages of three phases, angle, resistance in asynchronous mode without connecting STATCOM

For comparison, Figure 5 shows the oscillograms of the transition process, obtained for the asynchronous mode with STATCOM connected at substation №5.

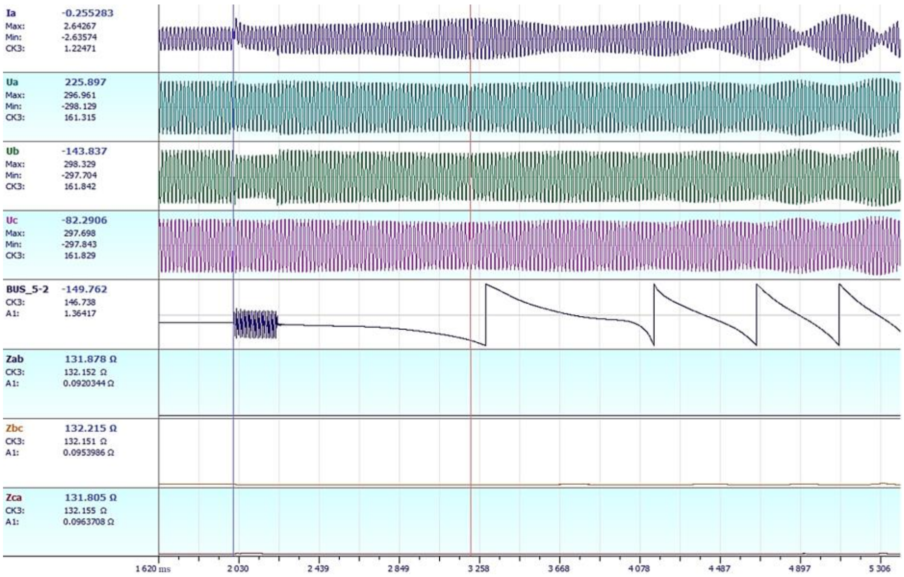

Figure 5. Oscillograms of phase A current, voltages of three phases, angle, resistances in asynchronous mode with STATCOM connected to SS №5 buses

For visual display of the zones of resistance of lines and control of the passage of locuses during the OSP test, the FastView program is used. The program allows you to build zones, and also include the locuses of asynchronous modes. The overlay of the locuses of the asynchronous mode on the zones of resistance clearly shows whether we are in the trigger zone or not.

The obtained simulation results on circular diagrams are shown in Figures 6 and 7.

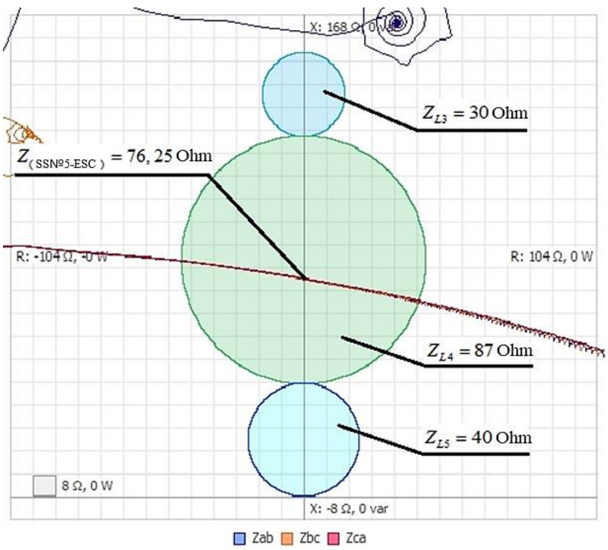

Figure 6. Resistance locus when OSP is checked in the network without connecting STATCOM

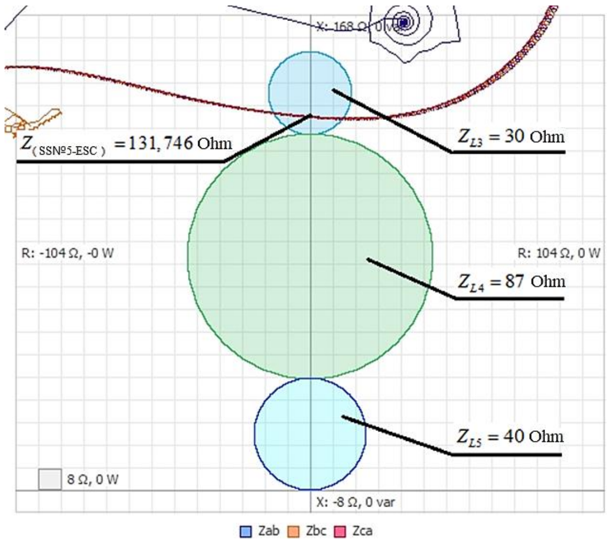

Figure 7. Resistance locus when OSP is checked in the network when STATCOM is connected to SS №5 buses

Figure 6 shows the constructed zones on the R-X plane and the locuses (Zab, Zbc, Zca) are added. In this case, the origin of coordinates conventionally coincides with the buses of the substation on which the OSP device is installed, and the direction “into the protected line” from substation №5 is taken as the positive direction of the axis of ordinates. When the first stage is triggered in the zone of action, the sign of the active power should change.

The results of the simulation of the power system in different cases are summarized in Table 1.

Table 1. Simulation results

Connection point	SS №5 (STATCOM is dis-connected)	SS №3	SS №4	SS №5
U, kV	304,8	299,4	296,2	311,5
Angle, ^{0}	-174,8	-149,7	-175,4	-149,8
Short circuit start moment, ms	2018	2018	2006	2005
Asynchronous mode start moment, ms	4167	4162	3213	3214
Resistance to ESC, Ohm	76,2	131,85	75,50	131,87
Umax, kV	313,712	298,13	318,12	296,96
Imax, A	2,71	2,64	2,69	2,64

From Table 1, it follows that with the integration of STATCOM, there is a change in resistance from SS №5, on which OSP is installed, to the ESC point.

Moreover, the smallest change is observed in the case of connection to the buses of Substation №4, to which the ESC point is closest under the initial conditions.

Simulation and subsequent construction of the resistance locus showed that the magnitude of the resistance, measured from the OSP installation point to the ESC, changes when connected with STATCOM. This happens for the following reasons.

First, due to the increase in voltage on the buses to which the device is connected, due to the generation of reactive power.

Secondly, the STATCOM control system operates in the conditions of dynamic change of the mode parameters, for example, when a load is connected /disconnected, and thus changes the compensation value. Also, the influence on the resistance value to the ESC point is exerted by the connection point of the FACTS device.

In this case, the smallest change is observed in the case of connection to the buses of substation № 4, to which the ESC point is closest under initial conditions.

4. Conclusion

The complexity of setting resistance control organs in networks with FACTS is that the parameters of these devices change depending on the operating mode, therefore, the effective area of the resistance control relay must also be changed. Analysis of existing practices allowed to determine the main reasons for the impact of FACTS devices and RES on the operation of EPS in general and in particular on OSP. The performed experiments confirmed the theoretical studies.

At the same time, an analysis of literary sources confirmed that at the moment the standards and recommendations for setting up the OSP do not take into account the influence of the connected FACTS devices.

The project is expected to develop a methodology for solving this problem.

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