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Specific features of the settings of a power swing control system in digital substations. Permissible values of the tap-off load of the branch under control

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Abstract

The paper deals with the influence of the tap-off load of the branch under control on the operation of a power swing control system in a digital substation. The paper gives estimates of the permissible tap-off load with respect to the location of the power take-off point and the load type at which the calculation error of the mutual angle between the voltages at the branch ends does not exceed 5^0.

Keywords: digital substation, power swing control system, power swing control device, tap-off load, electrical center.

Introduction

Modern digital substations in a power transmission network are equipped with logical nodes for the measurements of power regime parameters. The nodes include measurement transformers for voltage and current combined with the means for calculating their vector values (Gelfand A.M., 2012, IEC 61850-7-4:2010, IEC TR 61850-90-5:2012).

The measurement data of a logical node can be used in the relay protection and emergency control systems (Narovlyansky, 2004).

One of the functions of the emergency automation system is the detection and termination of a power swing regime. For high voltage power lines such an emergency control system should be a local and selective one. (Gonik YA.E., 1988). Locality means that only the current and voltage values obtained at the mounting locations of power swing control devices are used. (Narovlyansky, 2009). Selectivity here means that only specific changes of regime parameters are detected and the detection area is limited to the branch under control only.

A power swing regime is mostly detected by the mutual angle between voltage vectors at the ends of the branch under control. When the parts of a power system operate asynchronously and when the center of the electrical swing is located on the branch under control then the value of the mutual angle at the both ends of the branch starts to increase, reaches a value of 180^0 and then exceeds it. This allows one to identify the fact of an irreversible transition to a power swing regime.

The locality requirement does not allow the voltage vector value from the far branch end to be used even if there is a measurement unit available. Therefore the voltage vector at the far branch end has to be calculated at the location of the power swing device using the values of the voltage, current and branch impedance. It is important to note that the presence of the tap-off load in the branch under control leads to an error of this calculation. The paper addresses the problem of the permissible tap-off load such that it does not affect the operation of the emergency automation system.

Subject Domain

A power swing regime (PS regime) is an emergency transient in the power system characterized by an asynchronous rotation of a part of the generators relative to the rest of the system.

Power swing control system is intended for the detection and termination of the asynchronous regimes of individual generators, power plants and parts of the power system (National standard of the Russian Federation – GOST R 55105-2012). The system is implemented as a set of local power swing control (PSC) devices mounted in the power plants and substations of the power system and coordinated on control zones and conditions of the PS regime detection.

PSC devices must provide the detection and termination of full-phase and not full-phase PS regimes of the electrical power grid as well as a generator PS regime.

The issues of a violation of the parallel operation of generators in the power system, the behavior of regime parameters during the development of an instability and methods of the PS regime termination are presented in detail in the works of Gurevich, Yu.E. (1990), Gonic YA.E. (1988), Barinov V.A. (1990), Portnoy M.G.(1978), Lebedev S.A.(1934), Zhdanov P.S.(1979), TikhonovYu.A. (1976), Kogan F.L.(2010).

Technical solutions for the termination of a PS regime must provide a high reliability of its detection and termination. A high reliability must be achieved by meeting the reliability requirements for PSC devices, a redundancy of devices, a high-quality implementation of the algorithms of the PS regime detection and the generation of control actions (Faibsovitch D.L., 2006, General technical specifications to microprocessor type protective relay and automatics, 1997, GOST R 50746-2000, Design Standards for Seismic-Resistant Nuclear Generating Stations, 2001, GOST R 51321.1–2000). Here are some aspects of the subject domain essential to the present paper.

In the process generally called "a power swing regime" it is useful to differentiate between two stages: the transient process of a PS development and the steady PS state.

Measures for an emergency termination are mostly taken at the first stage.

A PS regime can be a result of: a violation of the static stability due to an overload of the power transmission lines; a violation of the dynamic stability caused by accidental disturbances; a loss of the generator excitation (Specifications, 2012).

The main features of a PS regime are: sustained deep fluctuations of voltages, currents and powers; a growth of the mutual angle between the voltages in various points of the power system up to the values over 360°.

In the practice of power systems operation there are cases of PS regimes when more than two groups of generators move asynchronously. In the present paper the term "multi-machine PS regime" is used to refer to this type of PS regimes. The process when an internally synchronous group of generators moves asynchronously relative to the rest of the power system is called a dual-machine PS regime.

Usually a multi-machine PS regime develops from a dual-machine one so it is important to terminate the dual-machine PS regime quickly preventing its transformation into a multi-machine PS regime.

In a PS regime there is a point on an electrical link between the parts of the power system where the voltage periodically falls to zero. This point is called the electrical centre of swings (EC).

The transition of a dual-machine PS regime into a multi-machine one leads to a repeated movement of EC from one link to another creating a danger of the development of an avalanche-like network accident. In a multi-machine PS regime the conditions for triggering the action of a PSC device may appear sporadically or not appear at all. There is a probability of a simultaneous or cascade division of the power system, a resynchronization becomes improbable and taking measures to facilitate the resynchronization by unloading the appropriate links becomes difficult.

A PS process is accompanied by a monotonic change of the mutual angle between the equivalent EMFs of internally synchronous groups of generators. The change of the angle leads to specific changes of the regime parameters measured at the points of the location of PSC devices.

The selectivity of operation with respect to EC assumes that the action is triggered only when EC lies within the branch under control and provides a division of the network exactly by the links belonging to the PS regime sections. There are PSC devices which act selectively or non-selectively. The selectively acting PSC devices must respond if there is a PS regime in the power system and the branch controlled by the device is a part of the PS regime section. The non-selectively acting PSC devices must respond if the behavior of regime parameters at the location of the PSC device indicates the presence of a PS regime in the power system.

The voltage vector at a node of the electrical power network divided by the current vector in the adjacent (to this node) branch is referred to as impedance (impedance at the node). The trajectory of the end of an impedance vector in the impedance complex plane is referred to as the impedance hodograph.

The detection of a PS regime corresponds to the detection of the fact of crossing the boundaries of the operating zone by the impedance hodograph in the impedance complex plane. The geometry and parameters of the operating zone are configured in such a way that all the hodographs of possible PS regimes in the controlled area of the power system cross this zone and all other hodographs including those related to other emergency regimes do not.

To obtain the rate of change of the impedance a second operating zone covering the first zone is used. The rate of change is then evaluated by the passage time of the impedance hodograph between the boundaries of the two zones. If the impedance hodograph passes the zone boundaries in a time greater than a pre-set time value then such a case is interpreted either as swings or as a PS regime. A higher impedance rate of change is interpreted as a short circuit.

An offset from synchronous oscillations is provided in the following way: in the case of oscillations the impedance hodograph does not cross operating zone through but goes back to the zone across the entrance boundary.

The operating zones are defined by a set of the impedance hodographs corresponding to the results of the calculation of the totality of normal, repair and emergency operating regimes.

Identification of the PS regime by the mutual angle between the voltage vectors at the ends of the branch under control

The main and direct indicator of a PS regime is a monotonic change of the angle between the generators of the non-synchronous parts of the power system. Since direct monitoring of this angle is impossible for a number of reasons the measurement of the angle between the voltages at the ends of the branch under control is used to detect a PS regime in practice.

One of the specific distinctions of the behavior of the angle in the branch with EC is an increased rate of change during a PS regime compared to the angle between the generators. Moreover, the lower the electrical length of the branch under control, the greater the rate of change is an implementation of such a PSC device assumes a measurement of the voltage and current vectors at the location of the device, setting the electrical parameters of the branch under control, a calculation of the voltage vector at the far end of the branch and a calculation of the angle between these voltage vectors.

This method makes it possible to detect a multi-machine PS regime. If a PSC device using this method is configured to act on the first cycle even a short time presence of EC in the branch under control leads to issuing a control action providing a high probability of the termination of a multi-machine PS regime.

Power swing control system must detect a PS regime, provide the execution of various PS termination scenarios and a coordinated operation of the PSC devices.

To provide an operation of the power swing control system the PSC devices must have the following key functions:

- Detection of PS regime in the power system

- Output of a signal (operation of the device) for the generation of a control action. This signal is then used by the external power system automation equipment to produce the control action.
- In case of the detection of an unsuccessful attempt to terminate the PS regime – output of a signal for the generation of a control action to another circuit breaker
- Reset of the device to the initial state upon the stop of the PS regime or after a predefined timeout

In addition PSC devices must have the functions which ensure the correctness and quality of operation of the power swing control system:

- selectivity
- offset from synchronous oscillations
- exclusion of false operations:
- – in case of short circuits and switching operations in the power system
- – while switching the device power supply on and off
- – in case of faults in the operational current circuits

In other respects PSC devices must have functions which ensure the reliability of operation of the power swing control system and the compliance with the general requirements to relay protection and emergency control devices of the power system including:

- Periodic software and hardware self-diagnostics, blocking the device operation upon the detection of a fault and signaling about it
- Monitoring of the input measuring circuits to the extent sufficient for their connection schemes
- Blocking the device operation in case of faults in current and/or voltage measuring circuits
- Recovery of the device with the pre-defined settings and functioning algorithm in a time less than 10 seconds after powering up
- Internal recording of analog signals and discrete events to the extent sufficient for the analysis of the functioning of the device
- Transmission of the data about the functioning of the device to an external automated control system
- Support of at least two groups of operating settings

The requirements to technological algorithms for the implementation of the specified functionality are described in section 3.

Technological algorithms for the implementation of PSC device functions

Algorithm of the detection of a PS regime

The technological algorithm of a PSC device must provide:

- Detection of full-phase and not full-phase PS regimes
- Tripping of device stages in a PS regime characterized by the following parameters (see Appendix A):

- – for the stages operating on counting PS cycles (for example, current fluctuation or changes of the sign of the power) with cycle durations from 0.2 to 10s
- – for the stages detecting a PS regime by the angle or by the impedance hodograph with the angle between the voltages at the ends of the branch under control reaching a value of 260 rad/s (15 000 ^{0}/s) during a cycle
- Counting of PS regime cycles
- Selectivity of operation which means that the algorithm of a selective action must respond to the presence of a PS regime if EC is located in the branch under control and must not respond if EC is located in adjacent areas
- Determination of excessive and deficient parts of the power system which allows one to leave a substation and its load in the excessive part of the system when generating a control action for the division of the network
- Offset from synchronous oscillations which means that the algorithm must not generate the control signal in case of synchronous oscillations
- Output of a signal for the generation of a control action for the division or re-synchronization of the power system. The control action is produced by an external power system automatics with respect to the device.
- Output of another signal for the generation of a control action for the division of the power system if the previous control action has not terminated the PS regime
- Reset of the device to the initial state upon the stop of the PS regime or after a predefined timeout

Algorithm of the generation of output binary signals

The algorithm of the generation of output binary signals must ensure the generation of device trip signals and, if necessary, a signal indicating an inoperable device state in case of faults.

The algorithm of the generation of device trip signals must be implemented in the form of stages – blocks of procedures executed sequentially during the development of a PS regime and the generation of control actions for its termination.

The algorithm must consist of at least three stages.

The first stage must detect the PS regime, determine the direction to the excessive part of the power system and act i.e. issue a control signal for the generation of a control action.

The second stage must check whether the PS regime is still present after the operation of the first stage. If the PS regime is still present the second stage must act i.e. reissue the control signal after a pre-set number of PS cycles.

The third stage operates similarly to the second one. The third stage is also used for the coordination of the operation of PSC devices.

After the action of a stage there must be a pause defined either by a time interval or by a number of the cycles of the next stage. The length of the pause is determined by the duration of the actions to terminate the PS regime.

The algorithm of the generation of output binary signals must ensure the control of the output relays of the device.

When a stage acts the technological algorithm of a PSC device must generate two signals:

- Control signal
- Device trip signal (local and central signalization)

Algorithm of the processing of input binary signals

For the operational control of the device and the coordination of its work the algorithm of the processing of input binary signals must ensure:

- Switching the device to the operational mode
- Switching the device to the test mode. In the test mode it must be impossible to pass signals to the relays of the units which produce control actions. The change of the state of the binary input (or inputs) for switching the device from the operational mode to the test mode must be enabled by an external switch which must provide a reliable break between the device output circuits and the relays producing control actions.
- Selection of the operating settings of the device from a predefined set
- Device trip blocking

Algorithm of blocking

A PSC device must have two types of blocking:

- Device trip blocking (blocking of the generation of control signals)
- Device operation blocking

The purpose of the device trip blocking algorithm is to suspend the operation of the device in the situation when its operation could result in unnecessary or false trips.

The algorithm of device trip blocking must ensure:

- Reset of the process of the detection of a PS regime when disturbances are not related to the development of a PS regime (such as short circuit, line switching, abrupt load changes, etc.) or when the input binary blocking signal is present
- Restoration of the process of the detection of a PS regime after a pre-set time

The purpose of the device operation blocking algorithm is to disable the operation of the device in case of its malfunction, faults of its measuring circuits, loss of power. The stop of the operation of the device must be indicated by an output binary signal.

To verify the above mentioned requirements to technological algorithms to improve the reliability of the power swing control devices at various operating modes of a power supply system let us analyze the impact of the value of a tap-off load to a calculation error of the mutual angle.

Method of the calculation of the impedance parameter setting of a PSC device

In Figure 1 a model of the branch under control is shown.

Measurements are made at the node "1" and the voltage at the node "2" has to be calculated.

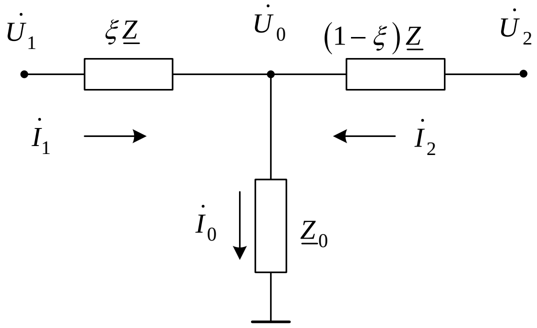


Figure 1: Model of a T-circuit controlled area

The system of equations for this model is given by:

$$\left.\begin{aligned} \dot U_1-\dot U_0 &= \xi\underline{Z}\dot I_1 \\ \dot U_2-\dot U_0 &= (1-\xi)\underline{Z}\dot I_2 \\ \dot U_0 &= \underline{Z}_0\dot I_0 \\ \dot I_1+\dot I_2 &= \dot I_0 \end{aligned}\right\} \tag{1}$$

Let us denote the voltage and the current at the node "1" by $\dot U_1$ and $\dot I_1$, and the voltage at the node "2" by $\dot U_2 = \nu U_1 e^{j\alpha}$, where ν - the ratio of the voltage modules, α - the angle relative to the voltage at the node "1".

Let us define the values of the model impedances as $\underline{Z} = Ze^{j\varphi}$, $\underline{Z}_0 = Z_0 e^{j\varphi_0}$ and introduce $\underline{\lambda} \equiv \lambda e^{j\theta} = \underline{Z}/\underline{Z}_0$, then $\lambda = Z/Z_0$, $\theta = \varphi - \varphi_0$.

Solving the system of equations (1) we obtain the model current at the node "1" as follows:

$$\dot I_1 = \frac{\left(1-\nu e^{j\alpha}\right)\lambda e^{j\theta} + (1-\xi)}{\lambda e^{j\theta} + (1-\xi)\xi} \cdot \frac{\dot U_1}{Z} \tag{2}$$

Now we assume that the vectors $\dot U_1$ and $\dot I_1$ are measured, the value of the longitudinal branch impedance $\underline{Z}$ is set and the value of the load impedance $\underline{Z}_0$ is unknown.

The voltage at the node "2" is calculated as follows:

$$\dot U_{2,calc} = \dot U_1 - Z\dot I_1 . \tag{3}$$

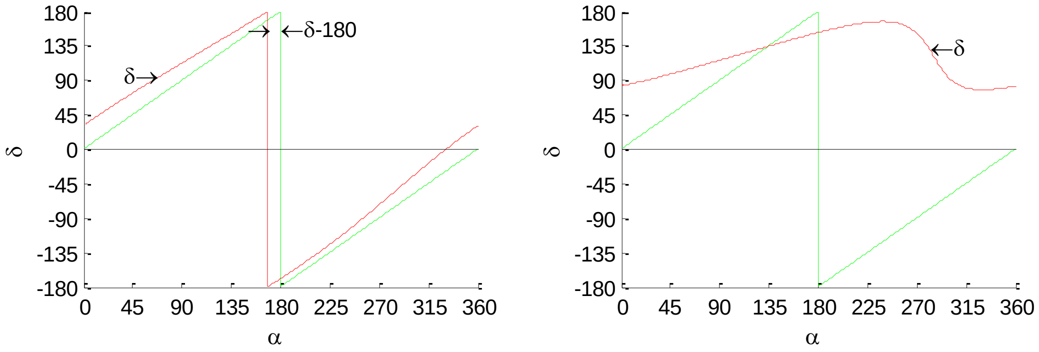
Substituting (2) into (3) we obtain:

$$\dot U_{2,calc} = \frac{\nu\lambda e^{j(\theta+\alpha)} - (1-\xi)^2}{\lambda e^{j\theta} + (1-\xi)\xi} \cdot \dot U_1 . \tag{4}$$

The mutual angle of the voltage vectors $\dot U_1$ and $\dot U_{2,calc}$ is obtained as:

$$\delta = \arg\left(\frac{\nu\lambda e^{j(\theta+\alpha)} - (1-\xi)^2}{\lambda e^{j\theta} + (1-\xi)\xi} \right) . \tag{5}$$

Examples of the estimated behavior of the mutual angle when rotating the voltage vector $\dot U_2$ are shown in Figure 2.



a

b

Figure 2 : The change of the mutual angle in the case of a permissible (a) and unacceptable (b) load. The green line shows the actual change of the mutual angle. The red line shows the behavior of the mutual angle according to the formula (5).

It can be seen that in the case of "permissible" values of the load impedance (Figure 2a) the results of the calculation of the mutual angle differ from its actual change only by some nonlinear behavior of the angle and by a shift of the point where the angle crosses a value of 180^0.

In the case of "unacceptable" values of the load impedance (Figure 2b) the behavior of the calculated mutual angle differs fundamentally from its actual behavior which makes it impossible to identify a PS regime.

To detect a PS regime correctly and timely it is sufficient to keep the mutual angle in the range of $175^0 \div 185^0$. For this the error of the calculation of the mutual angle has to be less than 5^0 when its actual value is equal to 180^0.

From (5) we obtain the condition of the correct operation of PCS devices with a varying load:

$$err_\delta(\alpha=\pi)=\left|180^0-\frac{\nu\lambda e^{j\theta}+(1-\xi)^2}{\lambda e^{j\theta}+(1-\xi)\xi}\right|\le 5^0 \qquad (6)$$

Results

Let us estimate the permissible load values such that the error of the calculation of the mutual angle remains less than 5^0 when the mutual angle between $\dot{U}_1$ and $\dot{U}_2$ is equal to 180^0.

As the branch is a high voltage one the angle of its impedance $\underline{Z}$ can be assumed to be equal to 90^0. In practice $Z<Z_0$, so λ <1.

The calculations of two types of $\underline{Z}_0$ are presented below. In the first one the load is nearly inductive: $\varphi_0=75^0$, so $\theta=90^o-75^o=15^o$ while in the second one the load is nearly active: $\varphi_0=15^0$, so $\theta=90^o-15^o=75^o$.

The results of the calculation of the error of the mutual angle for ξ = {0.1..0.9} are shown in the tables below.

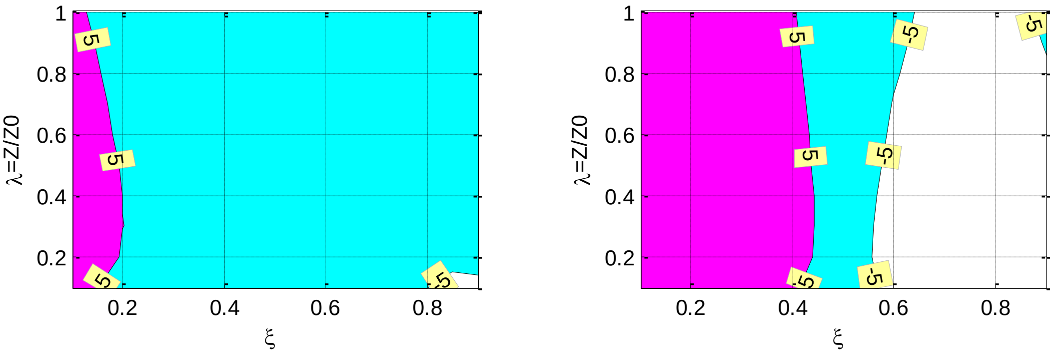
Table 1 : Error of the mutual angle $err_{\delta}(\alpha = \pi)$ for $\nu = 1$, $\theta = 15^{o}$

ξ λ	0.1	0.2	0.3	0.4	0.5	0.6	0.65	0.7	0.75	0.8	0.9
1	9.89	6.19	3.46	1.45	0	-0.96	-1.28	-1.48	-1.57	-1.54	-1.09
2	5.13	3.31	1.89	0.80	0	-0.53	-0.70	-0.81	-0.85	-0.83	-0.57
3	3.46	2.26	1.30	0.55	0	-0.37	-0.48	-0.56	-0.58	-0.56	-0.38
4	2.61	1.71	0.99	0.42	0	-0.28	-0.37	-0.43	-0.44	-0.43	-0.29
5	2.10	1.38	0.80	0.34	0	-0.23	-0.30	-0.34	-0.36	-0.35	-0.23
6	1.75	1.16	0.67	0.29	0	-0.19	-0.25	-0.29	-0.30	-0.29	-0.19
7	1.51	0.99	0.58	0.25	0	-0.16	-0.22	-0.25	-0.26	-0.25	-0.17
8	1.32	0.87	0.51	0.22	0	-0.14	-0.19	-0.22	-0.23	-0.22	-0.15
9	1.18	0.78	0.45	0.19	0	-0.13	-0.17	-0.19	-0.20	-0.19	-0.13
10	1.06	0.70	0.41	0.17	0	-0.12	-0.15	-0.17	-0.18	-0.18	-0.12

Table 2: Error of the mutual angle $err_{\delta}(\alpha = \pi)$ for $\nu = 1$, $\theta = 75^{o}$

ξ λ	0.1	0.2	0.3	0.4	0.5	0.6	0.65	0.7	0.75	0.8	0.9
0.1	44.77	27.52	15.27	6.34	0	-4.14	-5.44	-6.25	-6.55	-6.34	-4.32
0.2	20.27	13.24	7.62	3.23	0	-2.14	-2.82	-3.23	-3.37	-3.29	-2.19
0.3	13.34	8.80	5.10	2.17	0	-1.44	-1.90	-2.17	-2.27	-2.18	-1.46
0.4	9.97	6.60	3.83	1.64	0	-1.09	-1.43	-1.64	-1.71	-1.64	-1.10
0.5	7.97	5.28	3.07	1.31	0	-0.87	-1.15	-1.31	-1.37	-1.32	-0.88
0.6	6.64	4.41	2.56	1.10	0	-0.73	-0.96	-1.10	-1.14	-1.10	-0.74
0.7	5.67	3.78	2.20	0.94	0	-0.63	-0.82	-0.94	-0.98	-0.94	-0.63
0.8	4.98	3.31	1.93	0.82	0	-0.55	-0.72	-0.82	-0.86	-0.83	-0.55
0.9	4.42	2.94	1.71	0.73	0	-0.49	-0.64	-0.73	-0.76	-0.73	-0.49
1.0	3.98	2.65	1.54	0.66	0	-0.44	-0.58	-0.66	-0.69	-0.66	-0.44

Based on Table 1 and 2 the areas where the error of the mutual angle is less than 5^0 when the mutual angle between $\dot{U}_1$ and $\dot{U}_2$ is equal to 180^0 are shown in Figure 3. The areas lay between the lines corresponding to errors of -5^0 and 5^0.



a) $\theta = 15^o$ b) $\theta = 75^o$

Figure 3: Lines (-5^0, $+5^0$) of the error of the mutual angle $err_\delta(\alpha = \pi)$ in the plane {ξ, λ}. The areas where abs($err_\delta(\alpha = \pi)$)< = 5^0 lay between the lines corresponding to errors of -5^0 and 5^0 and are marked by the blue color.

It can be seen from Figure 3 that for any particular values $[\varphi, \varphi_0]$ it is useful to make similar calculations of the permissible values of the tap-off load.
In the case of $\varphi = \varphi_0$ the error $err_\delta(\alpha = \pi)$ is equal to zero in the entire plane {ξ, λ}.

Conclusions

If PSC devices in a digital substation are configured to work without taking the tap-off load of the branch under control into account their correct functioning is possible only up to a certain value of the tap-off load. The permissible tap-off load value depends on the location of the power take-off point and varies for different values of the angle of the load.
The analytic expression derived in the paper allows one to evaluate the permissible tap-off load for specific values of the impedance parameters of the branch under control and specific load parameters.
The maximum load is permissible nearer to the branch center.
The results presented in the paper are valid for all types of PSC devices which are configured using the impedance parameters of the branch under control.

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[20] GOST R 51321.1–2000 (IEC 60439–1–92) Low-voltage switchgear and controlgear assemblies. Part 1. Type-tested and partially type-tested assemblies. General technical requirements and test methods.