FAST-ACTING CONTROLLED SHUNT REACTORS TO BE UTILIZED IN THE UNEG OF RUSSIA AND ABROAD

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Controlled shunt reactors (CSR) are gaining increasing interest in the world today. For example, eight CSRs were installed in the Norwegian 420 kV power network in 2012–2013, with two more reactors in 2016. Seven CSRs were installed in 400 kV networks in Denmark in 2013–2015. Four CSRs were delivered in the USA in 2013–2015 to be installed in 345 kV and 143 kV networks.

Keywords: controlled shunt reactors; transformer-type controlled shunt reactors (TCR); CSR with on load tap changer control (OLTC).

Exterior view of the TCR at the Svetlaya 220 kV substation

Four CSRs were delivered in the USA in 2013–2015 to be installed in 345 kV and 143 kV networks

INTRODUCTION

Shunt reactors (SR) are required to maintain the work cycles of power networks on ultra-high voltage (UHV) lines operating in the modes of transmission of less-than-natural power; their purpose is to limit overvoltages. However, in order to transmit power up to the natural one along the same line, it is necessary to decrease the charge capacity compensation ratio [1]. The compensation ratio of a line can be changed in different ways: 1) by switching SRs on or off; 2) through indirect compensation by installing controllable synchronous compensators (SCs) in parallel with noncontrolled SRs; 3) by using controlled shunt reactors (CSRs). The first method is not widely accepted because of the overvoltages that occur when the reactor is switched. The second method had been widely used on UHV lines in the USSR (and later in Russia) until the time when more efficient (with no indirect compensation) controlled SRs were designed and introduced [1].

Besides limiting the voltages and increasing the power capacity of lines, CSRs allow to [1–3]:

1. Prevent synchronous generators from operating in the work cycles that cause deep consumption of reactive power;
2. Improve the static and dynamic stability of the power system;
3. Reduce the number of switching operations of static capacitor banks and decrease the number of switching operations of transformer OLTCs.

The tasks listed above are solved by using the so-called bus CSRs — reactors connected as shown in Fig. 1a. When connected to the line (Fig. 1b), specially designed CSRs can solve four additional tasks [4 7]:

1. Decrease the quasi-steady-state overvoltages of a line with one side of the line idling;
2. Avoid the aperiodic component in the currents of the CSR power windings and in the currents of the line circuit breaker when voltage-testing a transmission line;
3. Lower the arc fault current in the single-phase auto-reclosing (SPAR) cycle;
4. Prevent the resonant voltage spike potentially possible in open-phase modes of a CSR compensated line at a degree of compensation close to 100%.

Currently, two CSR types are in current operation in Russia: magnetically controlled shunt reactors (MCSR) [2, 9] and thyristor controlled shunt reactors (TCR) [3–9], whereas, normally, CSRs are utilized abroad, and they are close in their design to an OLTC transformer. The differences in the CSR control principles determine the differences in the response times of the reactors. For example, the time of power change from idling to nominal mode in a TCR is around 0.03 s, while for an MCSR it is usually about 0.3 s. In an OLTC-based CSR the time of switching from its technological minimum (50 % of the rated capacity) to nominal mode is approximately 300 s.

Design and functions of fast-acting thyristor-controlled transformer-type shunt reactors

TYPES OF CSR CONNECTION TO NETWORK

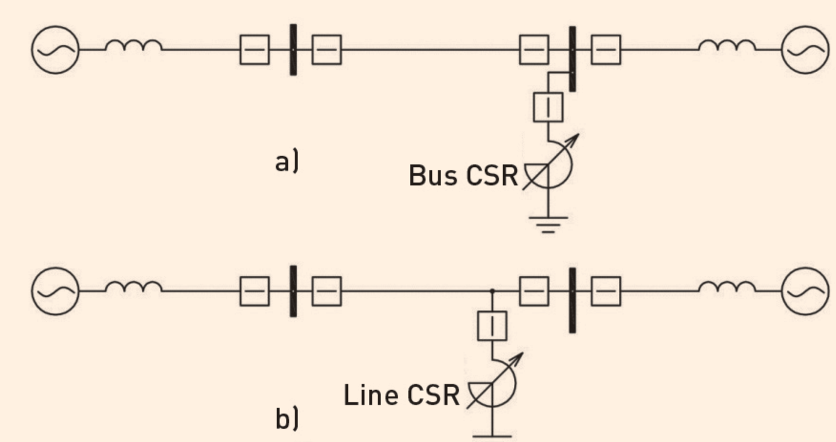

Fig. 1

The operational principle of fast-acting thyristor-controlled transformer-type shunt reactors (TCR) is based on varying the magnitude and duration of a current passing through the reactor in every industrial frequency cycle by means of pulse-phase control of thyristor valves. The theoretical basics of functions of a TCR (designed by G. N. ALEKSANDROV) are set forth in a textbook [3], and the experience of pilot implementation of a TCR in 2009 is summarized in a research paper [10]. The described reactor was designed without splitting the valve-side windings and with a compensation winding to which low-power harmonic filters were connected for the filtration of higher current harmonics.

In 2012, JSC R&D Center at FGC UES developed a technical concept of a 500 kV TCR with a new design that would require no higher harmonic filters and ensure an improved harmonic composition of the reactor current consumed from the network by using split valve-side windings (Fig. 2). The 500 kV TCR's electromagnetic component (EMC) consists of three separate phases, each comprising a core-type magnetic circuit, two power winding sections (PW1 and PW2) spread on the core legs, and a valve-side winding split in two (VW1 and VW2). The first leg holds the power winding section PW1 and the valve-side winding half VW1; the second leg holds the power winding section PW2 and the valve-side winding half VW2. Between the core legs, the magnetic flux is closed through end-face yokes. Valve-side winding halves VW1a, VW1b, and VW1c are connected in delta, while valve-side winding halves VW2a, VW2b and VW2c are connected in star. The TCR's valve part (VP) consists of two groups with three thyristor valves (TV) in each. The thyristor valves of both groups are connected in delta.

At present, the TCR equipment with split valve-side windings has been manufactured for the voltage classes of 110 kV, 220 kV, and 500 kV (Table 1), and three reactors are commissioned in Russian electrical networks, including such a critical facility as the receiving side of the Crimea Power Bridge, i.e., the 220 kV Kafa substation.

BASIC DATA ON THE MANUFACTURED TCRS WITH SPLIT VW

No.	Facility	Rated voltage, kV	Rated power, Mwar	Service years	Customer
1	Bystrinskaya 110 kV substation	110	25	Commissioned in 2017	PJSC MMC Norilsk Nickel
2	Svetlaya 220 kV substation	220	2 × 50	In operation since 2014	PJSC FGC UES
3	Kafa 220 kV substation	220	100	In operation since 2016	PJSC FGC UES
4	Pikhtovaya 220 kV substation	500	63	Commissioned in 2017	PJSC Rosneft
5	Mozdok-2 500 kV substation	500	180	Delivered to site in 2017	PJSC FGC UES
6	Ust-Kut 500 kV substation	500	180	Delivered to site in 2017	PJSC FGC UES

Table 1

CIRCUIT DIAGRAM OF A TCR WITH SPLIT VW

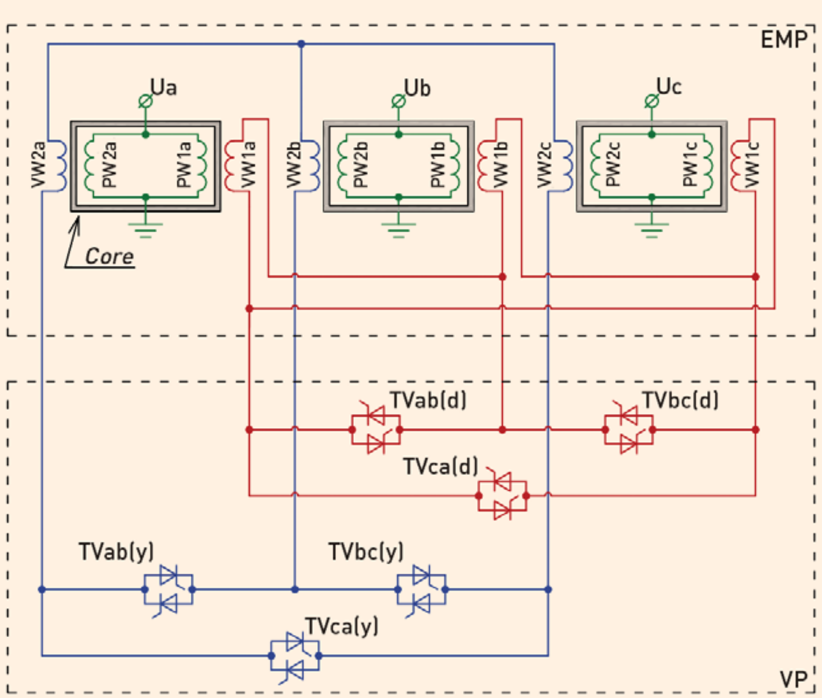

Fig. 2

In 2016, JSC R&D Center at FGC UES on order by PJSC FGC UES upgraded the TCR control system for the TCR to function as a line reactor and studied the operational modes of the line TCR and the network equipment.

The studies yielded the following findings:

1. The TCR with split valve-side windings connected in star and in delta allows decreasing the feed current and reducing the statistical average arc duration of a single-phase-to-ground fault in a transmission line. Equipping a transmission line with such a line TCR and line relay protection able to detect the extinction of the arc of a TL phase-to-ground fault will help reduce the SPAR cycle time (Fig. 4) [5]. For 500 kV lines with the statistical average length of 280 km, the use of a TCR can reduce the arc feed current in the SPAR cycle from 50 A to 15 A (Fig. 3, 4), which corresponds to the reduction of the estimated SPAR cycle time from 1.11 sec to 0.46 sec with 95% probability. Application of the given TCR design will enhance the SPAR efficiency and power system reliability.
2. Fast switching between TCR operation modes prevents the evolution of voltage resonance (Fig. 5) in an open-phase mode of the transmission line occurring after the arc extinction at a line compensation ratio close to 100% [6].
3. Pulse-phase control of TCR thyristor valves allows switching the TCR on without the aperiodic component in the currents of the reactor and the OHTL (Fig. 6). Utilization of a TCR on lines (instead of a SR) allows eliminating the cause of damage to the line breaker in the rated

DEPENDENCY OF SPAR DURATION VS. NETWORK PARAMETERS

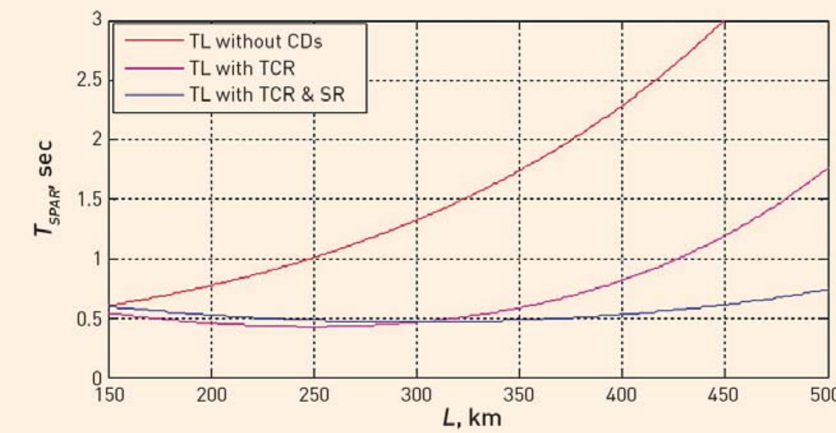

Fig. 3

TCR OPERATION IN SPAR CYCLE OF A 280-KM 500 KV LINE

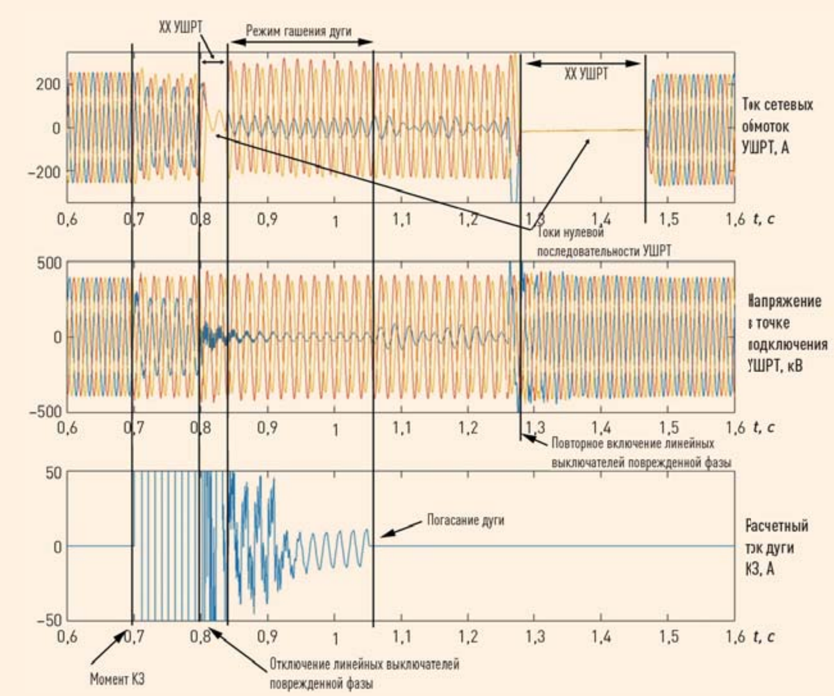

Fig. 4

"on/off" cycle without using any additional special measures such as controlled switching or using pre-insertion resistors [7].

4. Fast action of a TCR enables transferring the reactor into idle mode from any operational mode (also from the mode with the current lower in magnitude than the maximum permissible value of 80 A per GOST R 52565-2006) in shorter time than the industrial frequency cycle, which helps avoid dangerous overvoltages on the reactor breaker caused by current chopping. The transient oscillogram at the chopping of the highest possible TCR idling current with the voltages recovered across the circuit breaker contacts staying within the rated transient recovery voltage (TRV) of the breaker is shown in Fig. 7, from which it can be seen that successful opening of the circuit breaker is guaranteed [8]. As a result, when the reactor's idling current is chopped off, the TCR circuit breaker should merely meet the requirements of the applicable GOST R 52565-2006.

VOLTAGE TRENDS OF THE DAMAGED TL PHASE IN A SPAR CYCLE WITH DIFFERENT TCR CONTROL ALGORITHMS

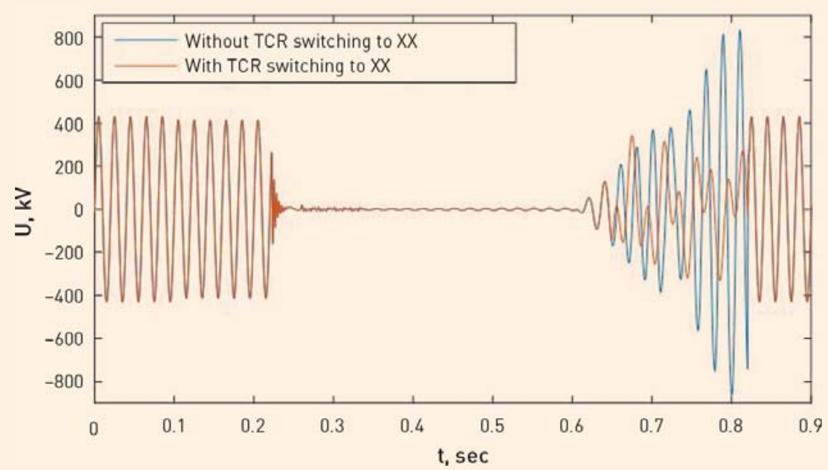

Fig. 5

TCR USE EXPERIENCE AND OUTLOOKS

The features of a TCR with split valve-side windings listed above have promising outlooks for the unit to be used as a line reactor. At present, the investment program of PJSC FGC UES provides for utilization of two line TCRs with split valve-side windings. The first facility is the 500 kV Mozdok-2 substation; the second is the 500 kV Ust-Kut substation. The electromagnetic segment of the TCR for those facilities is being manufactured by LLC Togliatti Transformer and OJSC Elektrozavod, respectively. Basic data on the manufactured TCRs with split VW are shown in Table 1.

As part of pre-commissioning of the line TCR, a program and procedures for network testing as well as guidelines for the trial operation of the TCR for the pilot facility '500 kV Nevinnomyssk — Mozdok OHTL with 500 kV Mozdok substation' were developed. Network tests of the TCR are conducted, in particular, to verify the proper performance of the TCR with RPA devices with an adaptive SPAR function in industrial production conditions and the efficiency of using the TCR to reduce the SPAR reclosing dead time.

As of now, Ltd EKRA Research and Production Enterprise, in pursuance of a cooperation agreement with JSC R&D Center at FGC UES, has performed tests on a real-time digital simulator (RTDS) to check the interaction of a linear 500 kV 180 Mwar TCR with split valve-side windings with line relay protection with an adaptive SPAR function. It has been determined that the adaptive SPAR and the main and standby line

INFORMATION

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protections implemented in cabinets SHE2710 582 (phase differential protection), SHE2710 591 (line differential protection), SHE2710 538 (directional differential protection) and SHE2710 521 (graded protection) operate properly on the lines equipped with the 500 kV line TCR with split valve-side windings, and that safety setpoints should be selected in accordance with applicable procedures.

Pulse-phase control of TCR thyristor valves allows switching the TCR on without the aperiodic component in the currents of the reactor and the OHTL

CSR ABROAD

Attempts to design various types of controlled shunt reactors abroad were made by BBC (now part of ABB Inc.). A 100 Mwar magnetically controlled shunt reactor for 10 kV was manufactured in 1955, and a transformer-type controlled shunt reactor (a TCR analog) was built in the 1970s.

Nevertheless, CSRs were not widely used abroad in the 20th century due to unacceptable losses, vibrations, and a number of other technical issues [2].

However, as noted in the paper by ABB specialists at the 2014 CIGRE session, today interest in CSRs is revitalized abroad [11]. In particular, eight CSRs were installed in the Norwegian 420 kV power network in 2012–2013, with two more reactors in 2016. Denmark installed seven CSRs in its 400 kV networks in 2013–2015. Four CSRs were delivered in the USA in 2013–2015 to be installed in 345 kV and 143 kV networks [12]. It must be noted that the CSRs listed above are designed as a non-controlled shunt reactor with taps through which the reactor's power can be changed using an OLTC device.

Some specific features of this CSR design are slow response, narrow control range (compared with CSRs made in Russia), and stepwise (not continuous) change of power. The time required to change the power from the lower boundary (50% of power) to the upper one (100% of power) may reach 5 minutes [13].

Today, some companies, e.g., Siemens [14], Trench [13], and Hyosung [14], are beginning to offer OLTC controlled CSRs. NREnergy (China) offers a transformer-type CSR that is closer in its design to a TCR but has a different principle of improvement of the harmonic composition of the reactor currents [16]. It is worth mentioning Afritech which offers a CSR based on the electromagnetic component of the Zaporozhye Transformer Plant [17]. It must be noted, however, that there are risks associated with the use of MCSRs due to the fact that the electromagnetic component of these reactors is manufactured at the Zaporozhye Transformer Plant (Ukraine).

Foreign manufacturers specify the following key applications for the CSRs:

CURRENT TRENDS IN TCR TV WITH THE CONTROL ANGLE SETPOINT CHANGED IN STEPS

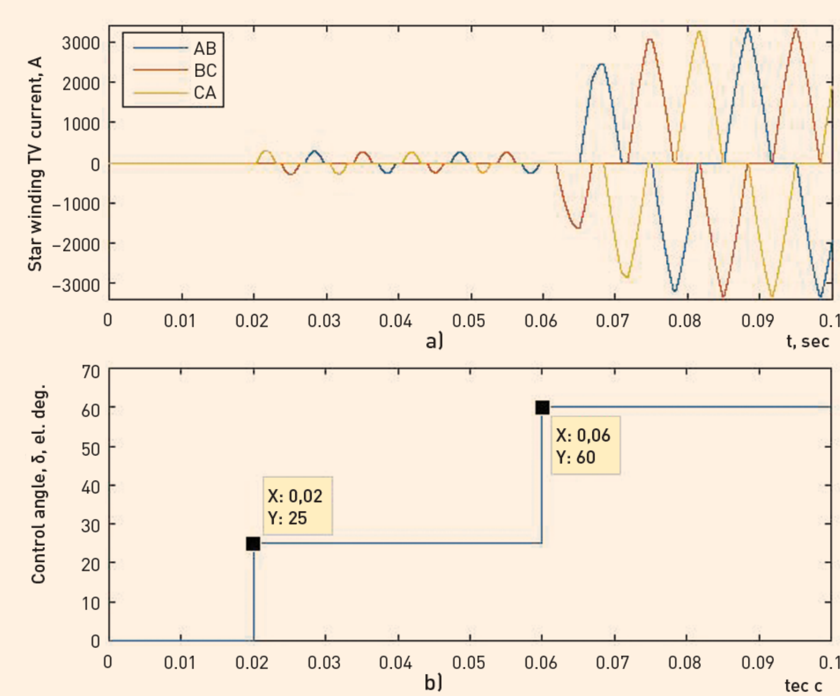

Fig. 6

VOLTAGE TRENDS OF TCR CIRCUIT BREAKER WHEN SWITCHING OFF THE REACTOR FROM IDLING WITH CURRENT CHOPPING

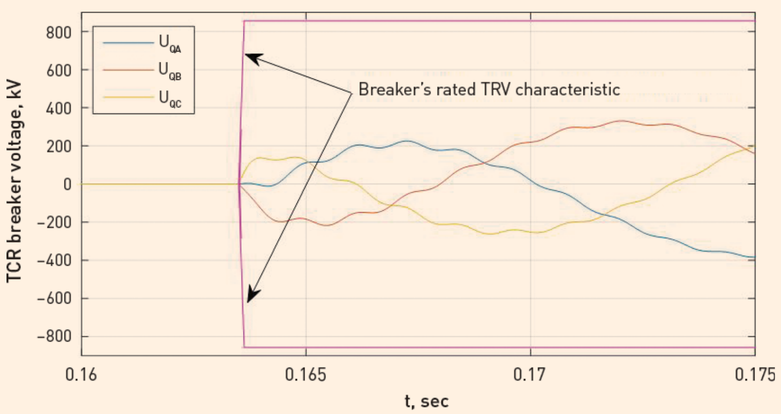

Fig. 7

Pulse-phase control of TCR thyristor valves allows switching the TCR on without the aperiodic component in the currents of the reactor and the OHTL

1. Voltage stabilization in a distributed generation network [12, 13].
2. Voltage stabilization of variable loads fed by long overhead or cable lines [12, 13, 15].
3. Reduction of line losses [14].
4. Increase of transmission line capabilities [14, 16].
5. Compensation of the arc feed current for higher auto-reclosing efficiency [16].

CONCLUSION

Today, there is a revitalized interest in CSRs in the world. The experience accumulated by PJSC FGC UES in the area of application of CSRs is the most advanced in the world. Russian fast-acting CSRs offer many technical advantages (wider power control range, faster response, wider spectrum of tasks solved) in comparison with foreign analogs and can potentially be in demand on the global market.

REFERENCES

1. Extra-high and ultra-high voltage grids. Theoretical and practical basics. Vol. 2. Edited by A.F. DYAKOV. Moscow, NTF Energoprogress of Integral Electric Power Complex Corp., 2012.
2. M.V. DMITRIEV, A.S. KARPOV, E.B. SHESKIN et al. Magnetically controlled shunt reactors. Edited by G.A. EVDOKUNIN. St. Petersburg, Rodnaya Ladoga, 2013.
3. G.N. ALEKSANDROV, V.P. LUNIN. Controlled reactors. Textbook. St. Petersburg, CPKE, 2005.
4. V.V. BAZUTKIN, V.P. LARIONOV, Y.S. PINTAL. High voltage engineering. Insulation and overvoltages in electrical systems. Moscow, Energoatomizdat, 1986.
5. A.M. MATINYAN, M.V. PESHKOV, V.N. KARPOV, N.A. ALEKSEYEV. Use of TCR with split windings for reduction of SPAR cycle time in 500 kV lines. Elektricheskie Stantsii, 2016, No. 8, 39–45.
6. A.M. MATINYAN, M.V. PESHKOV, V.N. KARPOV, N.A. ALEKSEYEV. TCR features that prevent voltage resonances in the SPAR cycle of a line. Elektricheskie Stantsii, 2016, No. 11, 36–40.
7. A.M. MATINYAN, M.V. PESHKOV, V.N. KARPOV, N.A. ALEKSEYEV, Z.E. PUGACHENKO. TCR features that enable safe testing of 500 kV transmission lines. Elektricheskie Stantsii, 2017, No. 1, 33–37.
8. A.M. MATINYAN, M.V. PESHKOV, V.N. KARPOV, N.A. ALEKSEYEV, Y.A. GORYUSHIN. Simulation of the breaking process by TCR low inductive current circuit breaker. ELEKTRO. Elektrotekhnika, elektroenergetika, elektrotekhnicheskaya promyshlennost, 2017, No. 2, 16–20.
9. A.G. DOLGOPOLOV, V.N. IVAKIN. Controlled shunt reactors. Overview and benchmarking. Novosti elektrotekhniki, 2013, No. 6, 30–35.
10. V.S. CHUPRIKOV, D.S. MOLOGIN. Implementation of the pilot CSRT (TCR) project in the Nortede Angola power system. Energoexpert, 2010, No. 1, 14–20.
11. C. BENGTOSOON, K. RYEN, O. A. RUI, T. OLSSON. Variable shunt reactors: Applications and system aspects. CIGRE 2014.
12. Shunt reactors. Optimizing transmission voltage system. Zahra NOROUZIAN. ABB Transformer and Reactors. Sep 6, 2016. [URL]: http://3rd.transfo.ir/editor_file/itce16-norouzian.pdf
13. Variable shunt reactors for reactive power compensation. [URL]: http://www.trenchgroup.com/en/Products-Solutions/Coil-Products/Variable-Shunt-Reactors/node_727
14. Variable shunt reactors for flexible grids. [URL]: http://www.energy.siemens.com/br/en/power-transmission/transformers/reactors/reactors.htm#content=Variable%20shunt%20reactors
15. Shunt reactors. [URL]: http://www.hicoamerica.com/catalogs/HICO_shunt%20reactors%20catalog_%201504_single%20page_low%20res.pdf
16. PCS-9578 controllable shunt reactor. [URL]: http://www.nrec.com/en/product/PCS-9578.html
17. Transformers and electrical reactors. [URL]: http://www.afriteksa.co.za/Transformers_Electrical_Reactors.php

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