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Magnetically controlled shunt reactor operation experience in 110-500 kV power grids

Belyaev A.N.
Peter the Great St.Petersburg Polytechnic University

Bryantsev A.M.
LLC “ESCO”

Smolovik S.V.
JSV “STC UPS”

Russia

SUMMARY

Controllable shunt reactors (CSR) are widely used in the electric energy systems of Russia and some other countries, especially in the 330-400-500 kV substations and power lines. Now the best-known CSR is the magnetically controlled shunt reactor (MCSR), using magnetic circuit saturation to control reactive power consumption. MCSR application ensures continuous voltage control, as well as reducing power losses in grids, improving their operational reliability by decreasing the number of switch-overs of on-load tap-changing transformers; enlarging stability margin and improving power system damping, minimizing use of synchronous generators as a controlled sources of reactive power. Starting from 1999 some 8.4 GWA of MCSR have been produced and installed in HV and EHV grids of Russia and other countries.

The experience gained in the operation and studying of this technology in terms of feasibility shows that a power system may basically use three installation options of the MCSR and the reactive power sources (RPS) based on them: long transmission lines of voltage classes 330, 500 kV; buses of substations (power plants) with a large number of outgoing transmission lines, or transmitting power through long lines; autonomous or remote power systems with loads that require high quality voltage. It should be noted that the largest number of RPS based on MCSR is installed in the grids of 110 kV oil-gas production systems to stabilize the voltage, to provide for the high-capacity motor starting operation and eliminate the excessive flows of reactive power.

Oil and gas producing systems are large and critical power consumers. They are located in such regions as West Siberia and operate over extensive territories with severe climatic conditions using a wide range of electrical facilities.

In case of power supply interruption, particularly during oil extraction, the equipment stops operating within several seconds after emergency outage, and the system gets restored in a hour or two at earliest or sometimes in several days only. Therefore, the highest priority in design of new oil-field power supply systems, which, in their majority, are isolated, shall be provision of uninterrupted, reliable and high-quality electric power supplies as well as system resistance unpredictable disturbances. It is also well known, that power interruptions during exploration drilling could cause much worse consequences.

The greatest number of MCSR are installed in 110 kV grids of autonomous or remote consumption nodes, characterized by high requirements to voltage quality (nodes with the motor load, oil and gas systems, etc.). In these circumstances, significant resources for reactive power control are required to stabilize voltage by removing reactive power flows in the grid. RPS based on MCSR meets the specified requirements. Their use shows that together with a capacitor bank of large capacity they are capable to stabilize and maintain the voltage in the operating conditions.

KEYWORDS: Controllable shunt reactors, power system small-signal and transient stability, reactive power source

smolovik@ntcees.ru

Controllable shunt reactors have proved efficient in increasing the reliability of the Unified Power System (UPS) network of Russia due to the normalization of operating parameters of the transit transmission lines and power generators operating conditions [1,2]. Operation of long transmission lines of high and extra-high voltage classes showed that for the full utilization of the flow capacity it is required to ajast the line reactors consumption of reactive power to the active power transmission. The most vivid example was the reduction by more than half the natural power capacity of 1150 kV overhead line "Ekibastuz-Kokshetau-Kostanai-Chelyabinsk" due to use of unregulated shunt reactors for reactive power compensation when putting the line in test operation in 1984.

Today, a bias-controlled shunt reactor using the extreme saturation of the magnetic circuit sections has become the most widespread option [1,2].

MCSR implementation began in 1997, when a pilot MCSR prototype of RTU-25000/110-U1 version was produced. In 1998, the reactor passed comprehensive tests and subsequent trial operation at the VEI STC test site in Togliatti. Afterwards the reactor was sent to the Northern Electric Networks, Permenergo and was installed on the 110 kV substation "Kudymkar". In September 1999 it was put into operation, together with the existing battery of static capacitors (BSC) with capacity 52 Mvar. It is the first successful experience of the MCSR in commercial operation. The MCSR (110 kV 25,000 kVA) installed at substation "Kudymkar" Permenergo has been for more than 15 years [1] already. In fact, a controllable source of reactive power (SRP) was implemented, featuring a parallel connection of MCSR and the capacitor bank to provide a smooth regulation of reactive power both in the mode of consumption (within the rated power of the reactor) and in the mode of generation (within the rated power of capacitors).

To date in Russia and some other countries (Kazakhstan, Belarus, Lithuania, Angola) a large number of controlled shunt reactors with a total capacity of more than 8000 MVA (fig.1, Table 1), have been commissioned. Most of them, with total capacity of more than 6200 MVA, are installed in Russia.

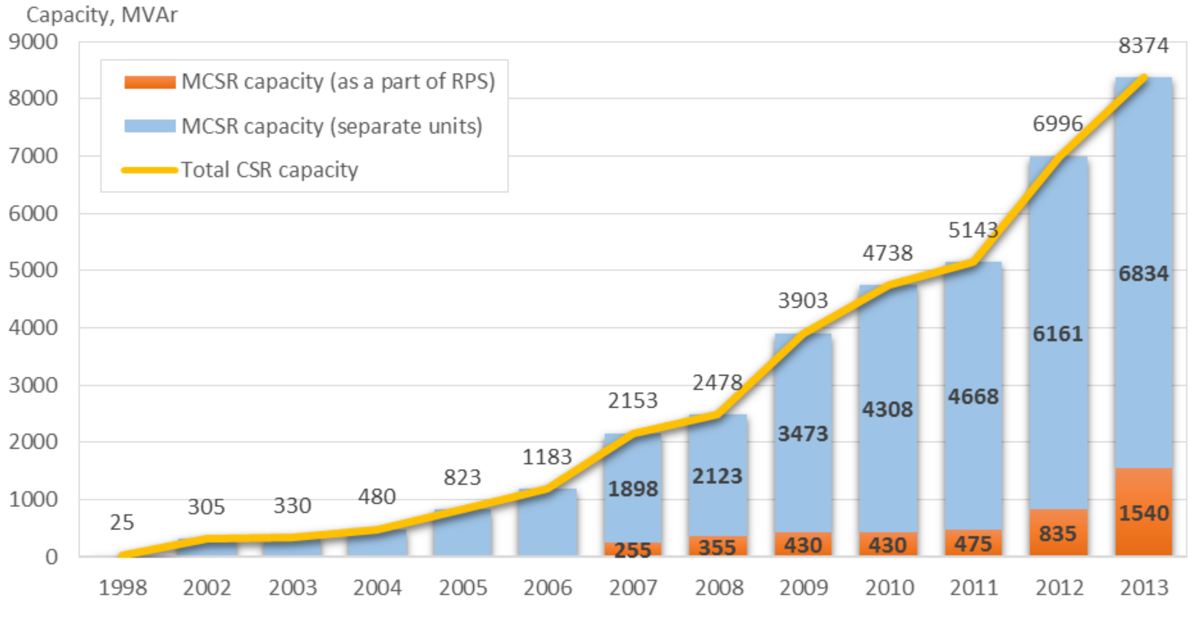

Fig.1. Total capacity of MCSR produced, January 2014.

Table 1

CSR characteristics of different voltage classes

Voltage class, kV	Quantity	Power, MVA	Country
10	6×10	60	Russia Kazakhstan
35	9×25 + 4×10	265	Russia Kazakhstan
110	31×25 + 1×63	838	Russia Kazakhstan
220	2×25 + 1×60 + 7×63 +20×100	2551	Russia, Kazakhstan, Angola
330	4×180	720	Russia, Belarus, Lithuania
400	7×100	700	Angola
500	18×180	3240	Russia Kazakhstan
total	110	8374	

As of today, there is no information about the failure of the equipment specified in Table 1, and the first-installed CSR has been in operation for more than 16 years already.

330 kV switchyard of the Ignalina nuclear power plant (NPP) is a major distribution node of the Lithuanian high-voltage power grid, which is part of the Baltic UPS. Six of 330 kV overhead line (one of which is dimensioned to 750 kV requirements) are connected to switchyard buses, to connect with the power systems of Lithuania, Latvia and Belarus.

Maintaining acceptable voltage and its stabilization in the nodal points of the power system are critical for ensuring the operational reliability of the equipment. Until 2008, voltage regulation in a 330 kV grid caused some difficulties because of the limited choice of control facilities. Excessive reactive power generated by power lines in Ignalina power center (up to 400 Mvar), made it necessary to limit the voltage levels during the summer and daily minimums.

In this connection, reactive power and voltage at Ignalina site were controlled by two NPP turbine generators working in an underexcitation mode and consuming up to 280 Mvar. Consumption of reactive power by generators was limited to the power system stability conditions and usually did not exceed 150 Mvar.

In accordance with international agreements, one of the conditions of entry of Lithuania into the European Community was to close the Ignalina NPP, followed by the possible construction of several new units on the site. Thus for at least for 10-15 years the 330 kV switchyard would remain without controlled facilities for compensation of reactive power, which is generated by above transmission lines at minimum loads leads to unacceptable rise of operating voltages.

In this regard, in accordance with the research findings it was recommended to install a controllable shunt reactor at 330 kV busbars of Ignalina NPP. The reactor was installed in August 2008.

The main purpose of CSR and the CSR-based RPS is voltage stabilization, reactive power distribution optimization, and reduction of losses in the grids of higher voltage classes. At the same time the problem of increasing of aperiodic and dynamic stability indices can be solved. The accumulated operating experience and research-based recommendations show three options of MCSR and the MCSR-based RPS are feasible for installation in power systems:

- as part of extensive intersystem transmission lines of 330, 500 kV;
- at substation (power plant) busbars with a high quantity of outgoing power transmission lines or lines transmitting power through an extensive overhead line;
- in autonomous power systems (or power systems located remotely from high-capacity sources) with a load having higher requirements to the voltage quality parameters. It should be noted that most of the MCSR-based RPS are installed in 110 kV grids of the oil and gas producing systems for voltage stabilization, facilitation of motor start operation, and removal of reactive power flows in the grids.

To confirm the need of MCSR implementation into extra-high voltage grids below as an example, the characteristics of some operation modes of several substations belonging to the 500 kV of Center of Russia Intersystem Power Grid (IPG) with significant deviation of the voltage levels of the nominal value are shown. Table 2 provides information on the distribution of voltages and reactive power flows with respect to the power facilities located in the territories served by the IPG Center based on control measurements produced in 2013. ΔU_{nom} column shows the deviation from the nominal operating voltage (in absolute units) in different load conditions. Q_{ent} column shows the total value of the reactive power flowing to the node (or outgoing from it) of all adjacent power lines in the considered operation modes.

This analysis allows elaborating recommendations for installing MCSR (or MCSR-based RPS) to stabilize the voltage, to prevent overflows of reactive power in the adjacent grids and reduce losses.

Table 2. Facilities in the 500 kV network IPG Center with deviating voltage levels

Name	ΔU, kV				Q_Σ, Mvar			
	Wint. Max	Wint. min	Sum. max	Sum. min	Wint. Max	Wint. min	Sum. max	Sum. min
Metallurgicheskaya	-23,24	-12,46	-2,7	5,1	87	95	50	18
Staryj Oskol	-21,15	-10,4	-4,61	3,8	296	302	198	131
Cherepoveckaya	0	0	-18,66	-9,22	0	0	147	153
Vologodskaya	0	0	-8,46	2,18	0	0	153	160
Kaluzhskaya	-7,9	-6,67	0	0	98	74	0	0
Novovoronezhskaya NPP	7,01	11,97	-7,55	-2,7	-45	-21	-167	-112
Trubnaya	-5,33	-3,14	-0,83	-2,92	163	161	163	161
Tambovskaya	-4,54	5,38	4,78	15,2	160	166	166	173
Volzhskaya HPP	-2,37	0,37	2,1	-0,5	-395	-466	-399	-466
Borino	-1,32	6,03	0,12	8,76	164	168	164	169
Zvezda	0	0	-1,09	2,8	0	0	163	165
Volga	-1,06	3,61	4,14	2,36	198	207	199	207
Voronezhskaya	-0,73	8,4	-0,56	7,86	130	83	122	89

Figure 2 shows the deviation of the operating voltage at the nodes from the rated one. Each facility marked on the x-axis corresponds to four color column, characterizing the variation of the voltage in different load modes (indicated on the explanation for the figure).

Hollow bars indicate the reactive power that is included in the node in the corresponding mode.

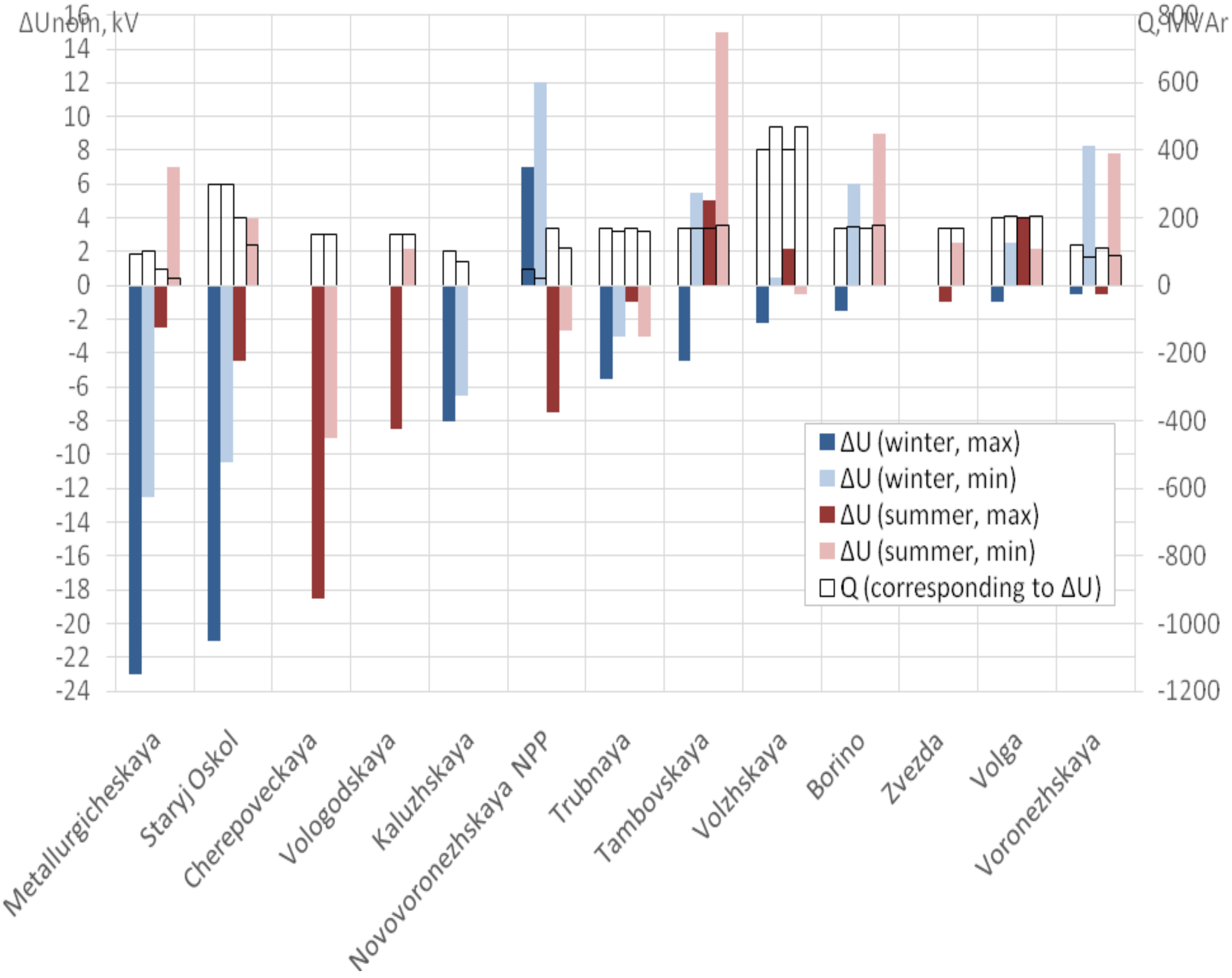

Figure 2. Facilities in the 500 kV grid of IPG Center with deviating voltage levels

This example highlights the relevance of the extended implementation of controlled shunt compensation devices in high-voltage grid of Russia and other countries with well-developed transmission system.

As an example of successful application of 180 MVA MCSR over the 500 kV power transmission line, see below the charts of voltage change at 500 rV Agadyr substation busburs at the "North-South" transit system of the Republic of Kazakhstan (Figure 3). Figure 4 shows the change in voltage before the commissioning of MCSR, Figure 5 - respectively, after putting MCSR into operation.

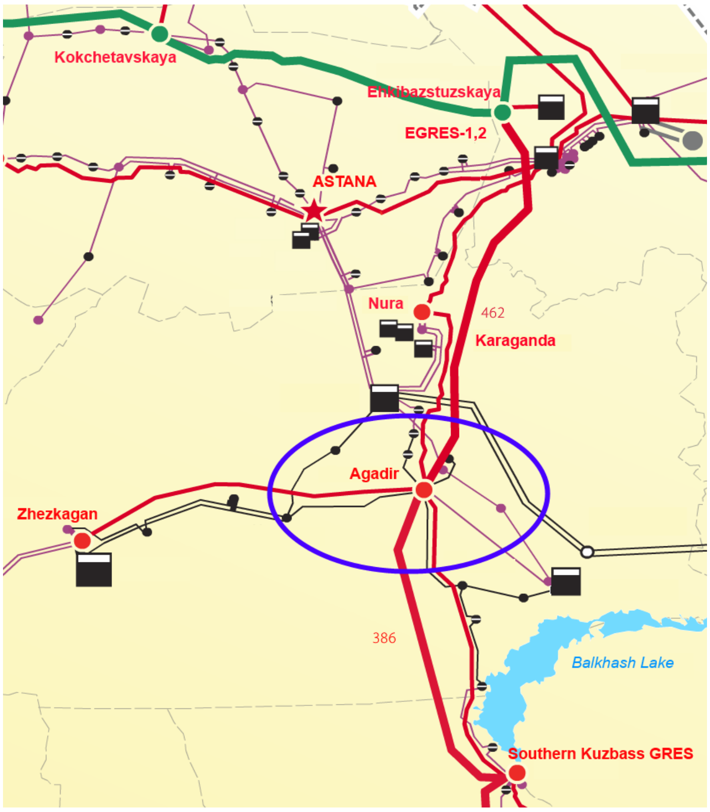

Figure 3. "North - South" 500 kV transit system of the Republic of Kazakhstan

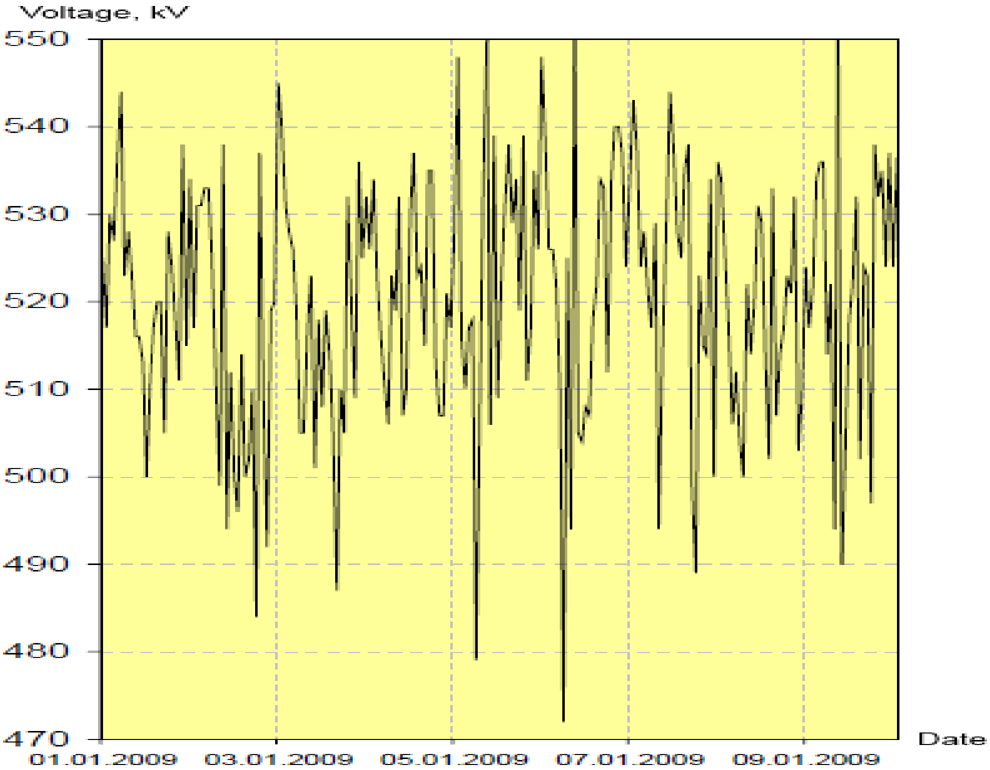

Figure 4. The chart of voltage change at the 500 kV Agadyr substation before MCSR commissioning

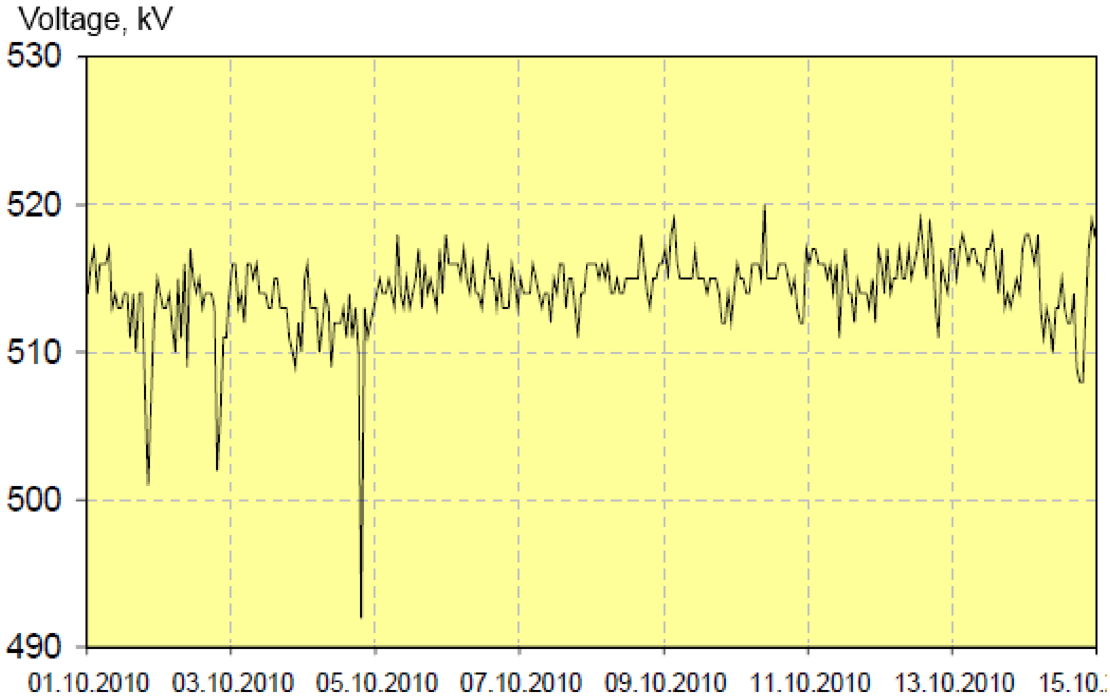

Figure 5. The chart of voltage change at the 500 kV Agadyr substation after commissioning MCSR 500 kV, 180 MVA

After the commissioning of MCSR in the period indicated that lasted for about two weeks voltage almost fits into the range of 510 - 520 kV.

Quality parameters of transients in extensive power system of 500 kV class, and the impact on these figures by MCSR parameters and settings are discussed in detail in [1]. It has been shown that the damping properties of power systems are due mainly to setting up automatic voltage (excitation) regulators (AVR) of physical and equivalent generators. As a rule, it appeared that the change of the time constant (Tcsr) of MCSR (using continuous MCSR control law on voltage deviation) within a wide range has little effect on damping performance. On this basis, it was concluded that a quick response of MCSR for system issues is not required. As an example, below there are the results of the eigenvalues calculation for the model of a simple transmission system with long transmission line when MCSR installed at power plant high voltage buses. It was assumed that the power generators operate at two different power factors (cos (φ) = 0.992, mode 1, and cos (φ) = 0.9, mode 2).

Table 3. The results of eigenvalues calculations

№ Mode	Tcsr=0.05 sec	Tcsr=0.1 sec	Tcsr=0.5 sec	Tcsr=1 sec
Mode 1	-0.429 ±8.233i -0.270	-0.413 ±8.20i -0.268	-0.456 ± 8.016i -0.256	-0.554 ± 7.975i -0.242
Mode 2	-0.373 + 8.566i -0.289	-0.360 + 8.536i -0.2872	-0.418 + 8.366i -0.273	-0.514 + 8.337i -0.257

Real root shown in Table 3, in the second mode is larger in absolute value, which illustrates the effect of the conditions of steady-state operation (large value of generator EMF and a smaller transmission angle). A pair of complex roots shows that the parameters of MCSR insignificantly affect the dynamic stability performance - by increasing the time constant of the reactor the damping rate is improved. The determining factor is the availability of automatic excitation controls with stabilization channels in generator (voltage frequency deviation and voltage frequency derivative).

Work [3] shows that the losses in the rotor and stator circuits of power generators in case of power factor (cos (φ)) close to unity is much smaller compared to the operation at nominal power factor. According to [3] for electric power plant of 2000 MW potential savings amount to 30 million rubles ($ 1 million) a year.

For the simplest power system (generator - infinite bus) the critical fault-clearance time with a time constant of the reactor Tcsr = 0.1 sec was calculated. The results are shown in Table. 4. Kcsr - reactor control based on the voltage deviation.

Table 4. Results of critical fault-clearance time calculation

The length of the line, km.	SC Type	Mode	critical fault-clearance time, sec	
			Kcsr=10	Kcsr=50
600	Three-phase	Pg=0,8; Qg=0,1.	0.1451	0.1452
		Pg=0,8; Qg=0.	0.1377	0.1377
		-	-	-
		Pg=0,8; Qg=0,387.	0.1561	
	Two-phase to ground	Pg=0,8; Qg=0,1.	0.1910	0.1911
		Pg=0,8; Qg=0.	0.1807	0.1807
		-	-	-
		Pg=0,8; Qg=0,387.	0.2087	
300	Three-phase	Pg=0,8; Qg=0,1.	0.2021	0.2021
		Pg=0,8; Qg=0.	0.1973	0.1973
		Pg=0,8; Qg=-0,038.	0.1953	0.1953
		Pg=0,8; Qg=0,387.	0.2103	
	Two-phase to ground	Pg=0,8; Qg=0,1.	0.3067	0.3071
		Pg=0,8; Qg=0.	0.2962	0.2962
		Pg=0,8; Qg=-0,038.	0.2917	0.2917
		Pg=0,8; Qg=0,387.	0.3319	
150	Three-phase	Pg=0,8; Qg=0,1.	0.2304	0.2304
		Pg=0,8; Qg=0.	0.2266	0.2266
		Pg=0,8; Qg=-0,053.	0.2245	0.2245
		Pg=0,8; Qg=0,387.	0.2330	
	Two-phase to ground	Pg=0,8; Qg=0,1.	0.6163	0.6192
		Pg=0,8; Qg=0.	0.5531	0.5532
		Pg=0,8; Qg=-0,053.	0.5264	0.5264
		Pg=0,8; Qg=0,387.	0.6745	

The most important result is the fact that the critical fault-clearance time is always greater than the rated fault-clearance time (0.12 sec). Transmission mode with power Pg = 0.8 p.u. and length of 600 km close to the natural mode of the power line operation, respectively, consumption of reactive power by generator is not reached.

As already mentioned, the greatest number of MCSR is installed in 110 kV grid of autonomous consumption nodes or consumption nodes located far from the main power system. These nodes require high quality voltage (nodes with the motor load, oil and gas producing systems, etc.). In these circumstances, significant resources of reactive power control are required to stabilize voltage by removing reactive power flows in the grids. RPS based on MCSR meets the specified requirements. Their use shows that together with a capacitor bank of large capacity they ensure stabilization and maintenance of the voltage in the operating conditions.

A powerful resource of reactive power control allows to implement original engineering solutions to ensure reliable power supply of responsible consumers connected to the grid by "weak" ties.

As an example, the diagram of power supply of oil and gas enterprises of JSC "Turgai Petroleum" (Republic of Kazakhstan, Figure 6) is given below.

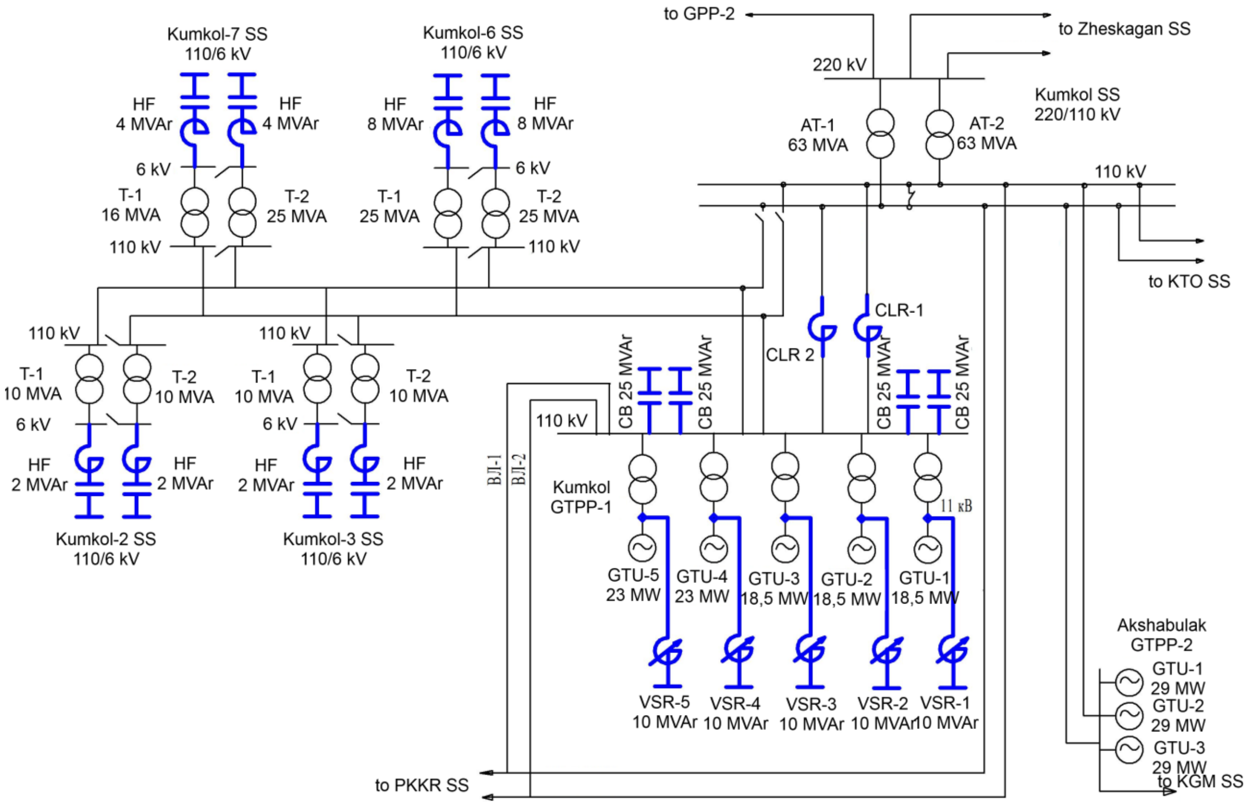

Figure 6. Scheme of reactive power compensation and voltage stabilization, distributed by voltage classes

The most essential part of the proposed comprehensive solution was a proposal to use a series-connected reactors with large inductive impedance (40 ohms), allowing to electrically "distance" a gas turbine power plant (GTPP) with capacity of 105 MW from a quite "weak" 220 kV grid. It should be noted that before the reconstruction the system was characterized by a low voltage in the connection point of 220/110 kV autotransformers, voltage surges which impacted negatively the process of extraction, decrease in own generation because of the consequent shortage of fuel gas, loss of stability of parallel operation of generators with power system.

Voltage stabilization is achieved by connecting a powerful capacitor bank (4 110 kV static capacitor banks, each 25 MVA) to the 110 kV bus. Voltage is controlled in the grid by the joint action of excitation control systems of GTPP generators and 5 MCSR, each with capacity of 10 MVA, connected to the generator terminals. Low harmonic content is provided by using 8 filter-compensating devices connected to the 6.3 kV bus bars. Their total capacity is 32 Mvar, these devices are additional sources of reactive power. Commissioning of the package allowed:

1. To stabilize the 110 kV grid voltage with accuracy ± 0,5% with fluctuations in the 220 kV power supply grid voltage to ± 15% of rated value;

2. To ensure stable operation of the 110/6 kV grid in case of remote short circuit in the 220 kV grid, deep short-term dips of voltage (up to 30%) and during the asynchronous operation in 220 kV grid;
3. To ensure stable operation of the gas turbine units with a predetermined cos φ (within the range of 0.9 - 0.98) with a maximum output of active power;
4. To increase the flow capability of its own grid of 110/6 kV by 15 - 25%;
5. To reduce power losses by 15-20% due to the exclusion of reactive power flows from the power supply grid and stabilize the 110 kV bus voltage;
6. To reduce the number of switch-overs in transformer on-load tap-changers in normal operating conditions.

CONCLUSION

1. The experience of the application of bias-controlled shunt reactors in grids of different voltage classes has been summarized. The proposed technology of voltage stabilization and control is much needed by domestic and foreign power industry. Total power of devices based on MCSR is more than 8 GWA and continues to increase.
2. The basic installation options of MCSR in grids are: as a part of extended power interconnections of voltage classes 330, 500 kV; at substation busbars with numerous outgoing power lines; in autonomous power systems (or systems located remotely from powerful sources) with high consumer requirements to the parameters of voltage quality.
3. The high efficiency of the use of on-grid controllable inductive-capacitive devices to stabilize and regulate voltage in the power supply scheme connected to the power system by “weak” link. In the latter case a system effect may also be achieved due to the stabilization of the voltage at an intermediate point of an extensive transmission system of 110 - 220 kV.

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