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

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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 voltage class substations. Now the best-known CSR is magnetically controlled shunt reactor (MCSR), using magnetic circuit saturation to control reactive power consumption. MCSR application allows ensuring continuous voltage control; active power losses decreasing in networks and improving their operational reliability by reducing the number of switching in on-load tap-changing transformers; enlarging small signal stability margin and improving power system damping; minimizing of synchronous generators using as a controlled sources of reactive power. Starting from 1999 until now some 8.4 GWA of MCSR were produced and installed in HV and EHV networks of different countries.

The accumulated experience in the operation and justification of the application of this technology shows that in a power system are mainly implemented three options for installing 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 isolated power systems with loads that require high quality voltage. It should be noted that the largest number of RPS based on MCSR is established in the networks of 110 kV oil-gas complexes to stabilize the voltage, relieve of motor starting operation and eliminate the excessive flows of reactive power.

Oil- and gas-producing companies are large and heavy-duty power consumers. It is specific for operators in regions such as West Siberia to operate over great territories with severe climatic conditions possessing wide range of various electrical facilities.

Interruptions of the electric power supply, in particular during oil extraction process, have resulted in disorderly closedown during few seconds after emergency with further system restoration not earlier than one or two hours or even a few days in a limited number of cases. Therefore, the highest priority in design of new oil-field power supply systems, which, on numerous occasions, are isolated, should be devoted to ensuring uninterrupted, reliable and qualitative electric power generation as well as system survivability under variety of unpredictable incidents. It is also well known, that power interruptions during exploration drilling could cause much worse consequences.

The greatest number of MCSR installed in the autonomous or remote from the main power grid 110 kV networks. Power consumption characterized by high demands on voltage quality indicators (nodes with the motor load, oil and gas complexes, etc.). In these circumstances, significant resources of reactive power control are required to stabilize voltage by offloading network of reactive power flows. RPS based on MCSR meets the specified requirements. The practice of their application shows that the presence of the capacitor bank of large capacity provides the conditions to stabilize and maintain the voltage in the operating conditions.

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

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Controllable shunt reactors have proved an effective means of improving 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]. Operating experience of long transmission lines of high and extra-high voltage classes showed that for the full utilization of the transfer capability required to change the line reactors consumption of reactive power as a function of the transmitted active power. The most striking example was the reduction by more than half the natural power capacity of 1150 kV overhead line "Ekibastuz-Kokshetau-Kostanai-Chelyabinsk" because of use as a reactive power compensation unregulated shunt reactors when entering the line in test operation in 1984.

To date, the most widespread construction of CSR is a design using the extreme saturation of the magnetic circuit sections [1,2].

MCSR Implementation began in 1997, with the head industrial design MCSR type of RTU-25000/110-U1 unit production. In 1998, the reactor was passed comprehensive tests and subsequent trial operation on the VEI STC test site in Togliatti. Afterwards the reactor was sent to the Northern Electric Networks, Permenergo and was mounted on the 110 kV substation "Kudymkar", and in September 1999 put into operation, together with the existing battery of static capacitors (BSC) with capacity 52 Mvar. The experience of the successful commercial operation of MCSR 110 kV 25,000 kVA at substation "Kudymkar" Permenergo is already more than 15 years [1]. In fact, the controllable source of reactive power (SRP) was realized, which is a parallel connection of MCSR and the capacitor bank to provide a smooth regulation of reactive power on the mode of consumption (within the rated power of the reactor) to the mode of its generation (within the rated power of capacitors).

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

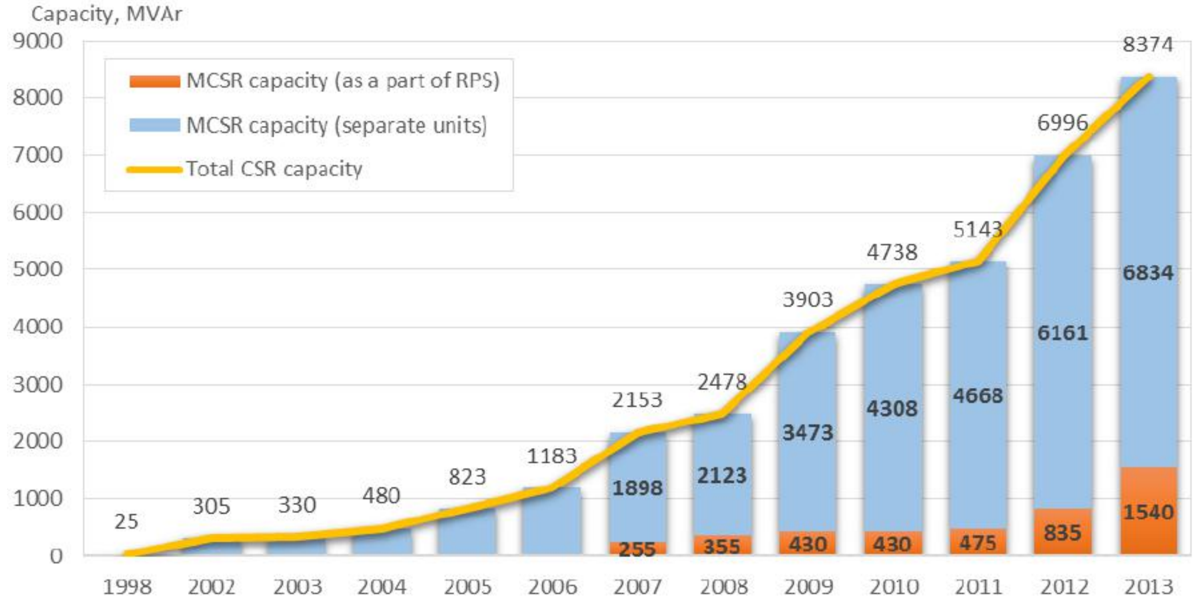

Fig.1. Manufactured MCSR total capacity, 1998-2013 yrs.

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 time of the first CSR life is already more than 16 years.

One example is the installation of CSR in outdoor switchgear (OSG) of the Ignalina nuclear power plant (NPP). Outdoor 330 kV switchgear of the Ignalina NPP is the important point of the Lithuanian high-voltage power grid, which is part of the Baltic UPS. Six of 330 kV overhead line (one of which is in the dimensions of 750 kV) comes to switchyard connected buses, to communicate with the power systems of Lithuania, Latvia and Belarus.

Maintaining acceptable voltage levels and its stabilization in the nodal points of the power system is a priority in ensuring the reliability of the equipment. Until 2008, regulation of voltage 330 kV caused some difficulties because of the limited choice of control facilities. Excess reactive power generated by power lines in Ignalina power center (up to 400 Mvar), led to the need to find means to limit the voltage levels during the summer and daily lows.

In this regard, the levels of reactive power and voltage at Ignalina site controled by two NPP turbo-generators for this reason working in the underexcitation mode and consumed up to 280 Mvar. The value of consumption of generator reactive power limited conditions and the stability of the power system was typically less than 2×150 MVA.

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 on the site of several new units. Thus for at least for 10-15 years the 330 kV OSG would remain without controlled compensation resources of reactive power, which generated by transmission lines and in lows loads leads to unacceptable rise of operating voltages.

In this regard, based on research-based recommendations a controllable 180 MVA shunt reactor at 330 kV busbar of Ignalina OSG was installed. The reactor was installed in August 2008.

The main purposes of MCSR and the RPS on their basis are voltage stabilization, reactive power distribution optimization, and reduction of losses in the networks 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 mainly implemented options for installing the MCSR and the RPS based on them in power systems:

- as part of extended intersystem transmission lines of 330, 500 kV;
- at substation (power plant) bus-bars with plenty of off-line power or transmit power through an extended overhead lines;
- in autonomous (or isolated) power systems with a load having increased requirements to the voltage quality parameters. It should be noted that most of the RPS with MCSR are installed in 110 kV networks of the oil and gas drilling and pumping systems for voltage stabilization, facilitation motor starting modes, and discharge networks from the of reactive power flows.

To confirm the need of MCSR implementation into extra-high voltages networks below for an example, the characteristics of some operation modes of several substations belonging to the 500 kV network 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 flow to the substations located in the territories served by the IPG Center based on control measurements 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 to make recommendations for installing MCSR (or RPS based on them) to stabilize the voltage, to prevent overflows of reactive power in the adjacent network and reduce losses.

Table 2

Objects 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 object is 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.

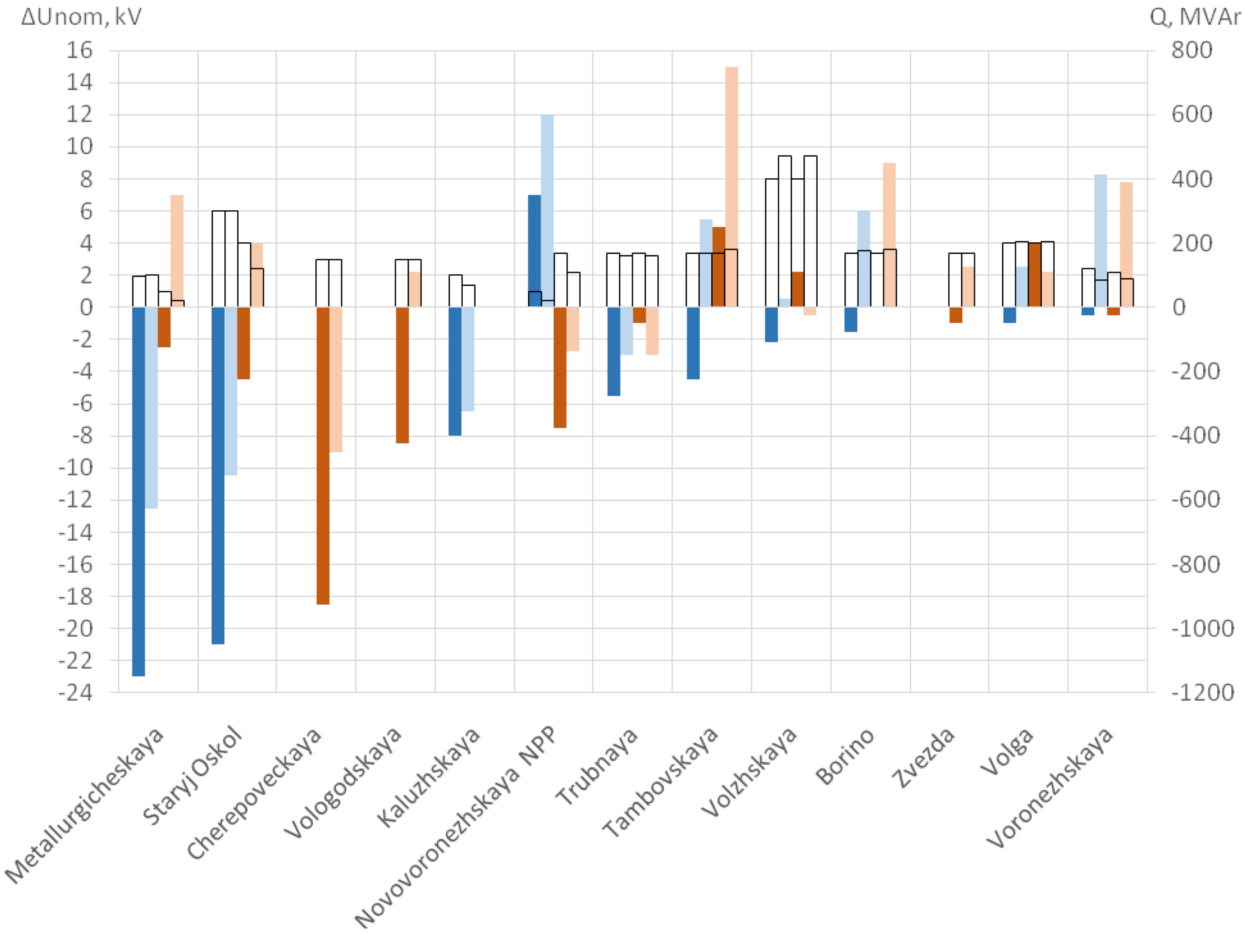

Figure 2. Objects in the 500 kV network IPG Center with deviating voltage levels

This example highlights the relevance of the extended implementation of controlled shunt compensation devices in high-voltage networks 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 below is a graph of voltage change at Agadyr substation on "North-South" interconnection 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.

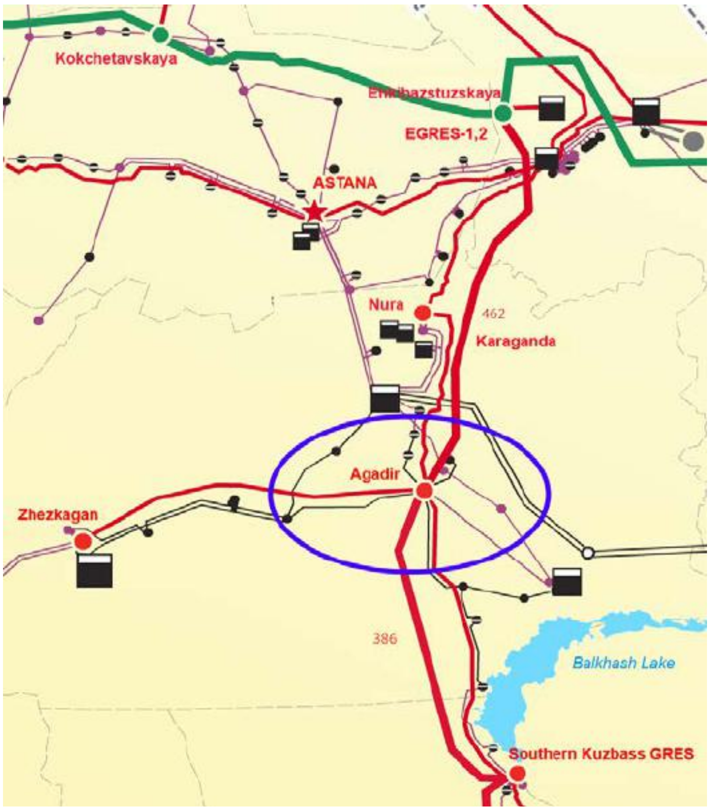

Figure 3. "North - South" 500 kV interconnection of the Republic of Kazakhstan

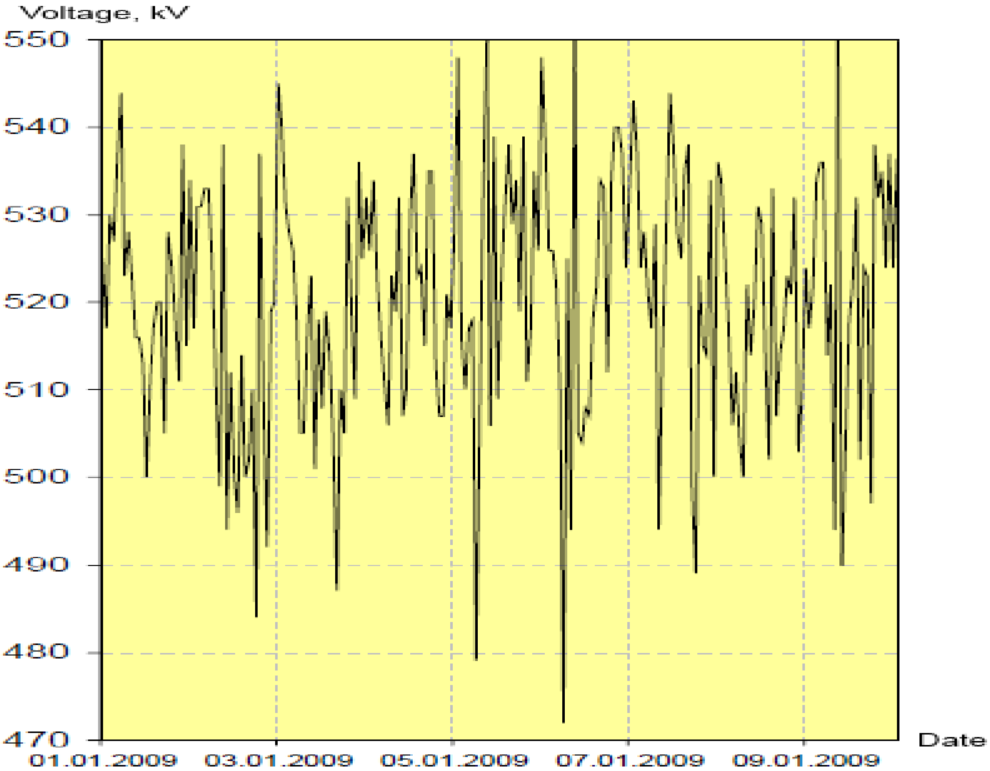

Figure 4. The graph of voltage at the 500 kV Agadyr substation before MCSR commission

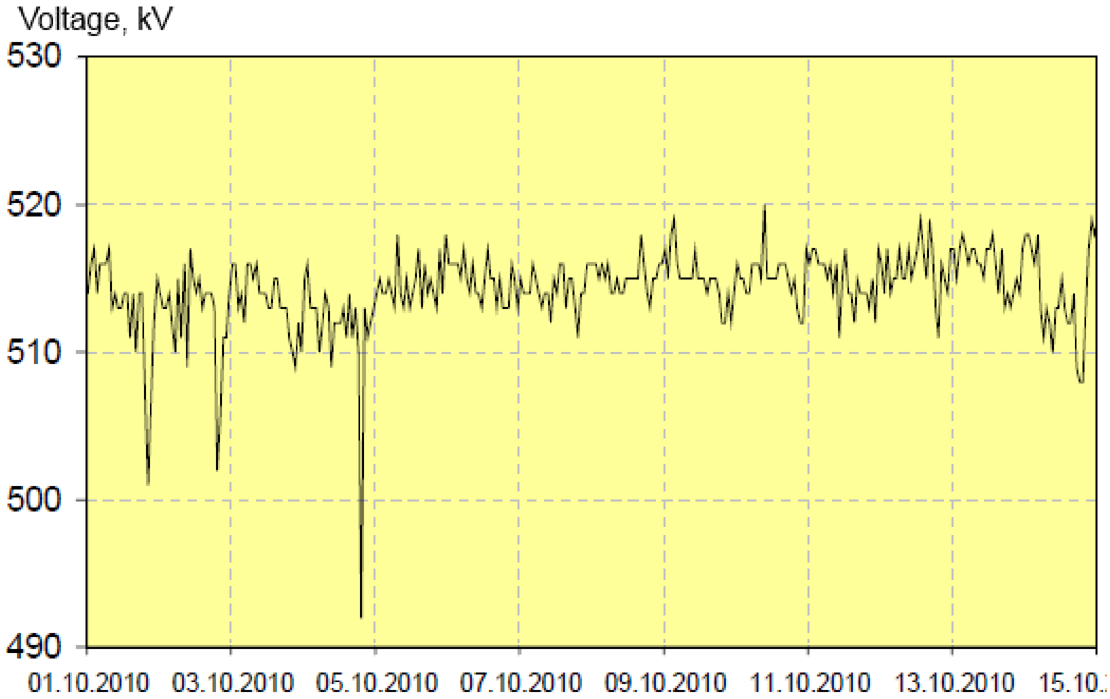

Figure 5. The graph of voltage at the 500 kV Agadyr after commissioning MCSR 500 kV, 180 MVA

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

Quality parameters of transients in extended power system of 500 kV class, and the impact on these figures MCSR parameters and settings discussed in detail in [1]. It has been shown that the damping properties of power systems due mainly to setting up automatic voltage (excitation) regulators (AVR) of physical and equivalent generators. As a rule, it appeared that the change in a wide range of the time constant (Tcsr) of MCSR (using continuous MCSR control law on voltage deviation) has little effect on damping performance. On this basis, it was concluded that the high speed of MCSR regulating for solutions of system issues is not required. As an example, in Table 3 are the results of the eigenvalues calculation for the model of a simple transmission system with long transmission line when MCSR installed on 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 EMF generator 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 generators AVR stabilizing feedbacks (voltage frequency deviation and voltage frequency derivative).

In [3] it was shown 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 were calculated. The results are shown in Table. 4. Kcsr - control factor of the reactor on the voltage deviation.

Table 4. Results of calculation of critical fault-clearance time

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 installed in the autonomous or remote from the main power grid 110 kV networks. Power consumption characterized by high demands on voltage quality indicators (nodes with the motor load, oil and gas complexes, etc.). In these circumstances, significant resources of reactive power control are required to stabilize voltage by offloading network of reactive power flows. RPS based on MCSR meets the specified requirements. The practice of their application shows that the presence of the capacitor bank of large capacity provides the conditions to stabilize and maintain the voltage in the operating conditions.

The presence of a powerful resource of reactive power control allows to implement ingenious 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).

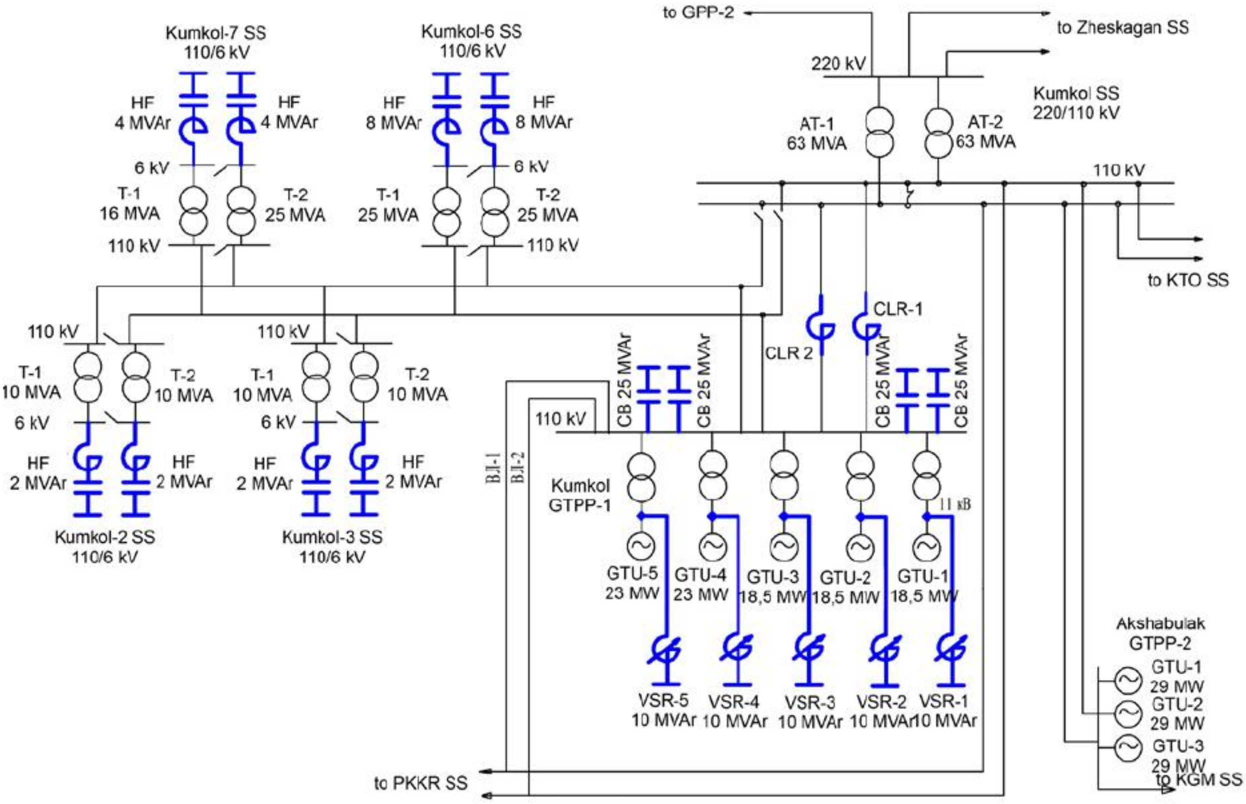

Figure 6. Distributed by the different levels of the voltage scheme of reactive power compensation and voltage stabilization

The most essential part of the proposed comprehensive solution was the proposal to use a series reactors with large inductive impedance (40 ohms), allowing electrically "alienate" gas turbine power plant (GTPP) with capacity of 105 MW enough off the "weak" 220 kV mains. It should be noted that before the reconstruction the system was characterized by a low voltage level in the connection point of autotransformers 220/110 kV, heavy power surges which caused a violation of 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 control is achieved by connecting powerful capacitor bank (4×25 MVA) to the 110 kV bus and carried out by the combined action of excitation control systems of generators and 5 MCSR capacity of 10 MVA, connected to the generator terminals. Providing low harmonic content is achieved by using 8 filter-compensating devices connected to the 6.3 kV bus bars. Their total capacity of 32 MVAR, these devices are additional sources of reactive power. Commissioning of the complex had allowed:

1. To achieve the stabilization of voltage 110 kV with accuracy ± 0,5% with fluctuations in the mains voltage of 220 kV to ± 15% of the rated;

2. To ensure the stability of the network 110/6 kV in case of remote short circuit in the 220 kV network, deep brownout (up 30%) and during the asynchronous operation in 220 kV network;
3. To ensure stable operation of the gas turbine driven generators in a predetermined cos φ (within the range of 0.9 - 0.98) with a maximum output of active power;
4. To increase the transfer capability of its own network of 110/6 kV by 15 - 25%;
5. To achieve a reduction of power losses by 15-20% due to the exclusion of reactive power flows from the mains voltage and stabilize the 110 kV bus;;
6. To reduce the number of switching in on-load tap-changing transformers.

CONCLUSION

1. The experience of the application of magnetically controlled shunt reactors in networks of different voltage classes had been summarized. The proposed technology of stabilization and voltage control proved to be in demand in 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 networks are: as a part of extended power interconnections of voltage classes 330, 500 kV; substation busbar with numerous power lines; in autonomous (or isolated) power systems with increased requirements of consumers to the parameters of voltage quality.
3. The high efficiency of the use of controllable inductive-capacitive devices to stabilize and regulate voltage in the power supply network connected to the power system by “weak” link. In the latter case it may also be achieved a system effect due to the stabilization of the voltage at an intermediate point of an extended transmission system of 110 - 220 kV.

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