

Research of Thyristor Voltage Regulator Effect on Power Flows Control in Distribution Electric Networks

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Abstract. The article is devoted to the power flows redistribution process research in distribution electric networks (DEN) with thyristor voltage regulator (TVR). TVR is intended to regulate power flows and voltage stabilization in the medium-voltage network of 6-20 kV. The problems in the medium-voltage network of 6-20 kV were analyzed and solutions were determined. It was established that the key development trend of DEN is the engineering and adoption of devices based on D-FACTS technologies. In addition, we considered the features, technical characteristics and control system of TVR. The research of power flow distribution in electric system was based on a simulation model of DEN with TVR. TVR allows to regulate power flows by changing the amplitude and phase angle of the voltage, with the help of longitudinal-transverse regulation. The results have shown that the TVR allows to align load schedules, to stabilize the voltage level in complex networks with unevenly loaded nodes and to realize optimal distribution of power flows in the electrical network.

1. Introduction

One of the actual problems of modern electric power industry is the development of power flow controlling devices. This is especially true for electric distribution networks (DEN) of 6-20 kV [1]. These networks are characterized by: high length, unbalanced load of transmission lines, high electric power dissipation and continuous growth of loads. Power flows occur in loop and ring circuits with multilateral power supply they causing suboptimal distribution of energy flows in the DEN. It is not always advisable replacing electrical equipment with more powerful and increasing the cross-section of power lines. Therefore, the crucial solution of the problems of DEN is the introduction of technologies D-FACTS (distribution flexible alternative current transmission systems) [2]. Devices implementing D-FACTS technologies include unified power flow controller – UPFC [3], interline power flow controller – IPFC [4], distributed static series compensator – DSSC [5], thyristor controlled phase angle regulator – TCPAR [6], thyristor switched series capacitor – TSSC [7], smart transformers – SmartTrafo [8]. A comparative characteristic of these devices is presented in Table 1.

Devices based on D-FACTS technologies allow to realize the following functions:

- generation or consumption of active and/or reactive power to change the voltage at the connection point. This leads to an increase of carrying capacity of transmission lines and a decrease of power losses in the electrical networks;
- inclusion of a controllable voltage source or a controllable resistance in the network to regulate power flows [9].



D-FACTS technologies allow to switch from an electric network with a "passive" structure of electric energy transmission to an "active" one, which realizes the functions of operating modes control [10]. However, D-FACTS devices are still under development [11].

Table 1. Comparative characteristic of devices based on D-FACTS technologies.

Functions	Devices D-FACTS					
	UPFC	IPFC	DSSC	TCPAR	TSSC	SmartTrafo
Power flow control	+	+	+	-	-	-
Active-power generation	+	+	-	-	-	-
Reactive power compensation	+	-	+	-	+	-
Voltage amplitude regulation	+	-	+	+	-	+
Phase angle regulation	+	-	-	+	-	-
Integration of renewable energy sources into power network	-	+	+	-	-	-

Scientists of NNSTU are developing an experimental prototype of the thyristor voltage regulator (TVR), representing an automatic thyristor regulator of the value and phase of the voltage with parallel and serial transformers. This electrical installation is designed for intelligent DEN 6-20 kV. TVR belongs to the class of controlled devices that reduce electrical losses and increase the carrying capacity of power lines. Scientific and technical solutions for the development of TVR are based on modern technologies of power electronics [12].

The aim of the work is to study the process of redistribution of power flows in the medium voltage distribution network with TVR.

2. Materials and methods

2.1. TVR Description

TVR is a high-speed 6 kV power semiconductor device based on transformer-thyristor voltage regulators [13]. It is intended to control power flows and voltage regulation in medium voltage DEN. A simplified TVR circuit is shown in Figure1 [14].

The principle of TVR operation is based on the shared use of longitudinal (change the magnitude) and transverse (change the phase) voltage regulation. The TVR power circuit contains a parallel transformer TV1 and a serial transformer TV2. The primary windings of the TV1 transformer are connected to the input terminals of the TVR (6-20 kV network). The secondary windings of TV1 are connected to the primary windings of the TV2 transformer via the transverse and longitudinal control modules. The secondary windings of the transformer TV2 connected between the input (A, B, C) and output (A2, B2, C2) TVR terminals (circuit break), making a longitudinal-transverse component of the voltage regulated by the thyristor switches in phase and magnitude.

The transverse control module is based on thyristor switches VS1-VS8. This module generates 90° shifted out-of-phase voltages at the terminals of the secondary windings of the TV1 transformer. This allows to implement amplitude control of the TVR output voltage.

The longitudinal control module is based on thyristor switches VS9-VS16. This module introduces a variable inphase or antiphase with the phase voltage of the source EMF value. This allows you to realize the regulation of the value of the output voltage TVR.

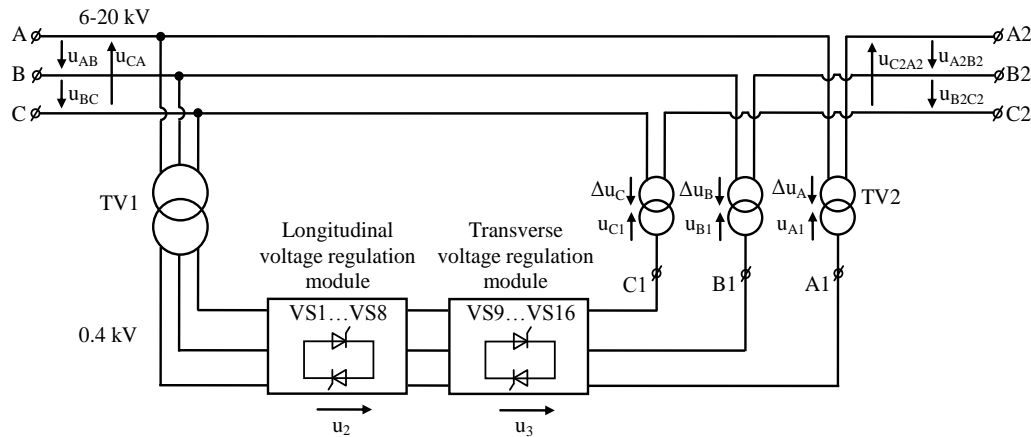


Figure 1. Simplified TVR circuit.

Both modules can be switched on or off from the power supply circuit of the primary windings of the TV2 transformer using the adopted circuit connections of thyristor switches. The combined use of transverse and longitudinal control modules allows for longitudinal and transverse regulation of the TVR output voltage. Vector diagrams of the input and output line voltages when the longitudinal and transverse control modules work together are in Figure 2.

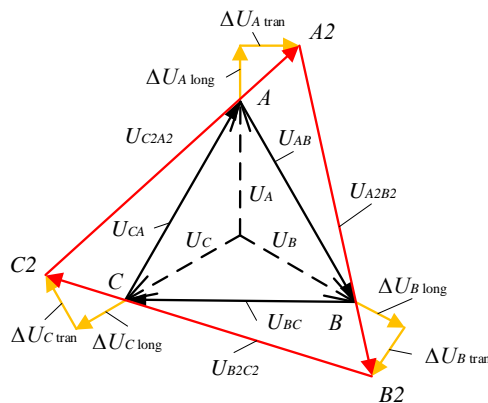


Figure 2. Vector diagram of longitudinal-transverse voltage control.

Summation of the longitudinal and transverse components of the voltage provides a wide range of regulation of the EMF boost. This allows the output voltage vector to be shifted relative to the input voltage by ± 5 electrical degrees and $\pm 10\%$ amplitude. Thus, in the longitudinal-transverse mode of TVR there is a change in the magnitude and phase of the voltage, which allows influencing the flows of active and reactive power:

$$P = \frac{U_1 \cdot U_2}{x_{TDL}} \cdot \cos \delta; \quad (1)$$

$$Q_{l(2)} = \frac{1}{x_{TDL}} \cdot (U_{l(2)}^2 - U_1 \cdot U_2 \cdot \cos \delta); \quad (2)$$

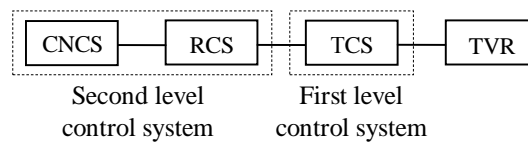
where U_1 and U_2 – power transmission line voltages; x_{TDL} – power transmission line reactance; δ – angle between U_1 and U_2 voltages vectors.

Technical specifications of the TVR experimental prototype are shown in the Table 2.

Table 2. Technical specifications of the experimental TVR sample.

Parameter	Value
Nominal voltage (supply voltage)	6 kV $\pm 10\%$;
Range of variation of the angle voltage phase α	$\pm 5^\circ$
The measurement resolution of the phase shift voltage α	1.5°
The range of regulation voltage	$\pm 10\%$;
Discreteness of regulation of the voltage amplitude	$\leq 1.5\%$
Load power	≤ 1000 kVA
Shunt-wound transformer power	106 kVA
Series transformer power	3x28 kVA

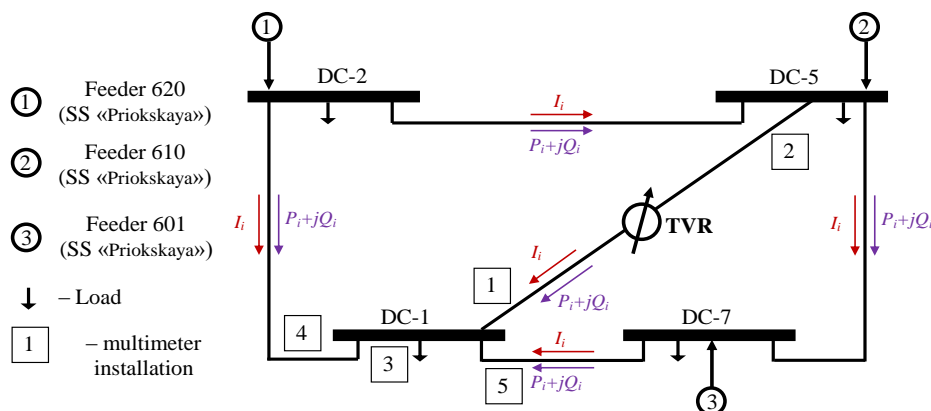
TVR has an active-adaptive control system (AACS) which consists of two levels (Fig. 3).

**Figure 3.** TVR AACS structure.

The first level of AACS consists of a centralized network control system (CNCS) and a regulator control system (RCS). The CNCS provides centralized control of the TVR group, and the RCS performs monitoring and controlling tasks the TVR. The second level of AACS includes a technological control system (TCS). The TCS is required to physically execute the TVR control commands coming from the first level control system.

2.2. Simulation model of DEN with TVR

The object of the research is the 6 kV DEN section. This section of the electric network has a ring configuration with several power sources. In the Fig. 4 is a simplified scheme of a fragment of the DEN 6 kV with TVR in one of the lines. Power comes to the ring network from three feeders from the substation "Priokskaya". Distribution of power flows between distribution centers (DC) is carried out via cable lines. A simulation model (Fig. 5) was developed to investigate flow distribution in the DEN with TVR. The simulation environment is the Simulink application of the Matlab software package. Simulink has the ability to simulate a wide range of ready-made electrical devices. The TVR model is a development of the authors [15].

**Figure 4.** The fragment of the DEN 6 kV with TVR.

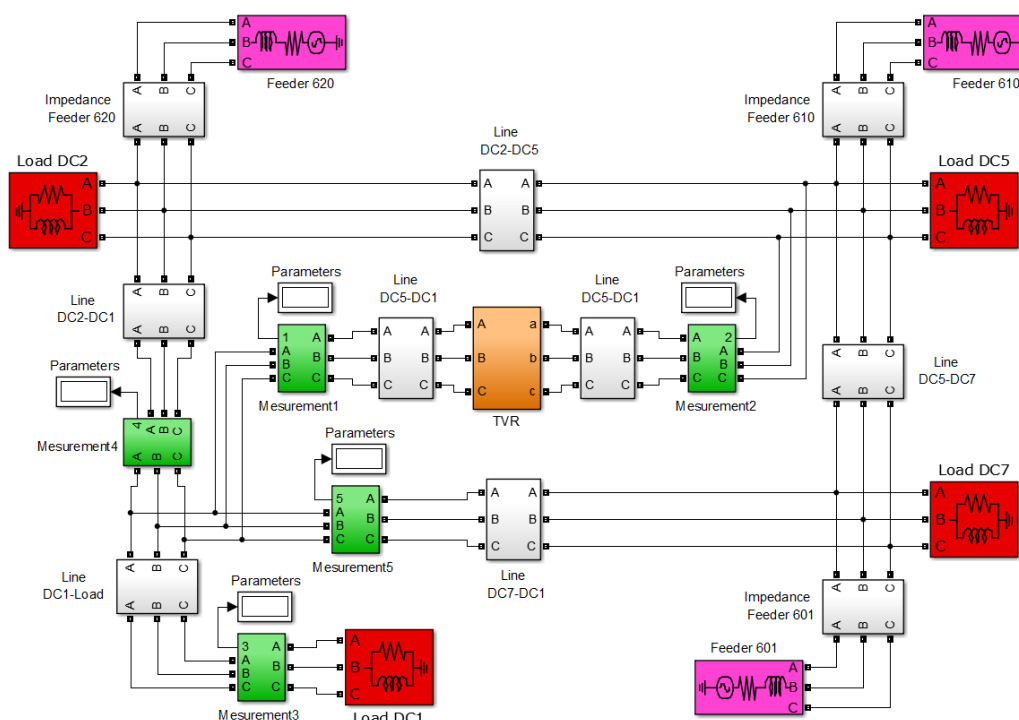


Figure 5. Appearance of the simulation model of the DEN with TVR (Initial conditions).

To measure the value of power flows in the simulation model, measurement units (multimeters) are provided.

The source data for the simulation are: the type and length of cable lines, the nature and nominal power of the electrical load, circuitry and parameters of TVR (Table 2, 3, 4).

Table 3. Parameters of cable lines of DEN with TVR.

Line name	Mark and cross section of the line	Line length, km	The resistivity of the line, Om/km	
			active	reactive
Feeder 620	AAB-6 2(3×185)	2.5	0.064	0.040
Feeder 610	ASB-6 2(3×185)	2.5	0.064	0.040
Feeder 601	AAB-6 2(3×240)	2.5	0.049	0.039
DC-2-DC-1	ASB-6 2(3×150)	0.8	0.080	0.041
DC-2-DC-5	ASB-6 2(3×120)	1.0	0.098	0.042
DC-5-DC-7	ASB-6 2(3×240)	0.9	0.049	0.039
DC-5-DC-1	AAB-6 3×150	1.2	0.159	0.081
DC-7-DC-1	AAB-6 2(3×120)	1.1	0.098	0.042
DC1-Load	AAB1-6 3×35	0.7	0.890	0.087

Table 4. Parameters of electrical loads in DEN with TVR.

Consumers	Voltage, kV	Frequency, HZ	Active power, kW	Reactive power, kA
DC-1	6	50	809.2	142.8
DC-2			4154.4	733.1
DC-5			3655.8	645.2
DC-7			2622.7	462.8

The following assumptions are made during the developing a simulation model of DEN with TVR:

- infinite power sources are used as supply lines;
- the active conductivity of the insulation of the electrical network is insignificant and therefore not taken into account;
- electric network parameters are unchangeable in time;
- load factor of power transformers 6/0.4 kV is assumed to be 0.85;
- load power factor $\cos\varphi = 0.85$;
- the electrical network is symmetrical.

3. Results

The influence of TVR on flow distribution in a close network was investigated using a simulation model of DEN with TVR. The dependences of the active power on the control angle α of the TVR are obtained (Fig. 6) by changing the phase angle of the TVR in the range from 0° to 90° (in increments of 1.5° degrees) and the voltage amplitude (in increments of 0.1 kV). In Fig.6 represented the flow distribution in the line without TVR (line from DC2 to DC-1), and in Fig.7 in line with TVR.

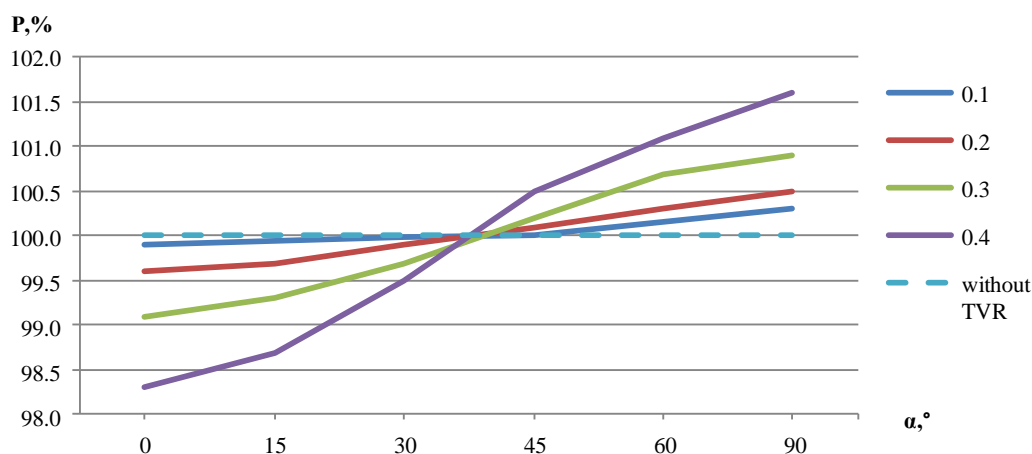


Figure 6. Dependence of the active power on the phase angle of the output voltage TVR in the line without TVR.

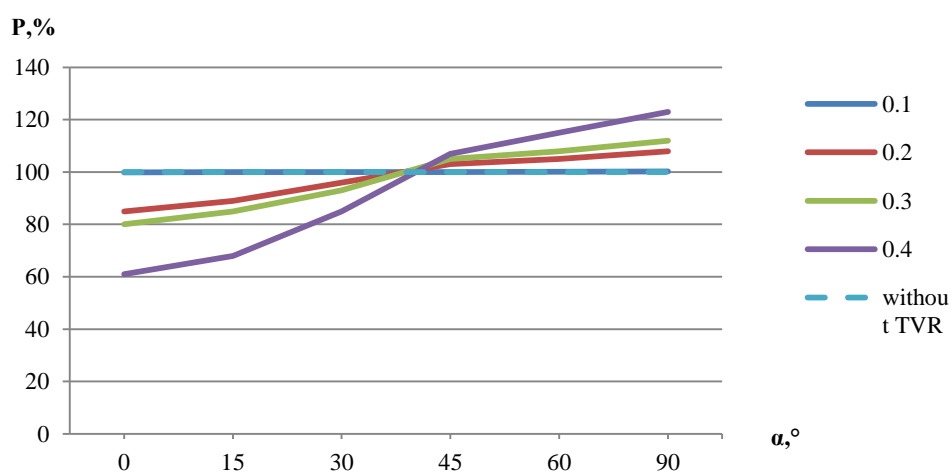


Figure 7. Dependence of the active power on the phase angle of the output voltage TVR in the line with TVR.

The research of the redistribution of power flows in DEN with unevenly loaded DC was performed similarly. In the simulation model, the TVR phase angle was changed in the range from 0° to 120° . Graphs of the dependence of the active power on the phase angle of the TVR control were formed based on the readings of the measurement units (Figure 8) for the following lines:

- from DC-5 to TVR;
- from TVR to DC-1;
- from DC-1 to the load;
- from DC-2 to DC-1;
- from DC-7 to DC-1.

Measurement points 1, 2, 3, 4, 5 correspond to the installation locations of measurement units (multimeters).

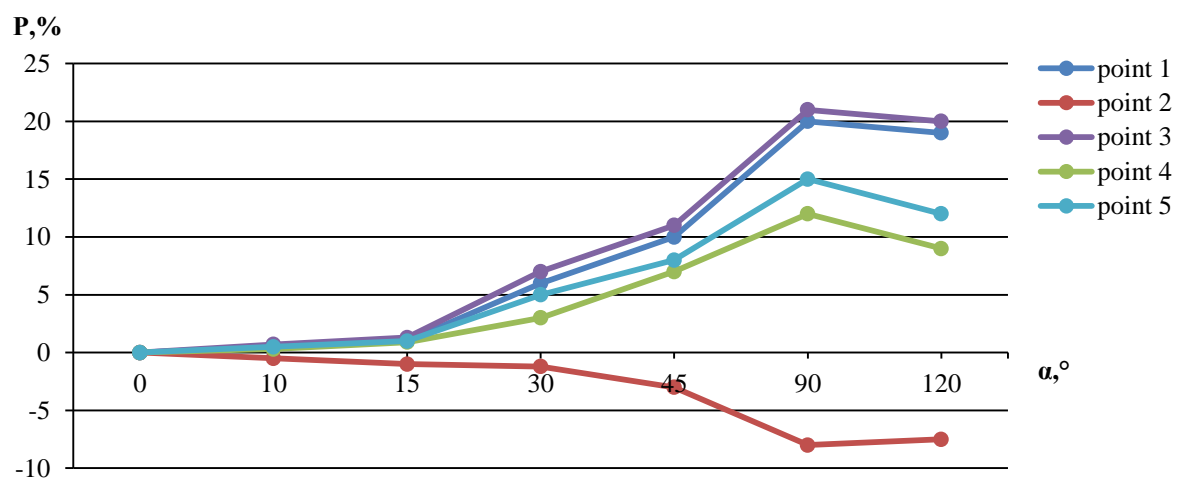


Figure 8. Dependence of the active power on the phase angle of the output voltage TVR in unevenly loaded DEN.

The construction of line dependencies between DC2 and DC5, DC5 and DC-7 was not done due to a minor change in the capacity of these lines.

4. Discussion

Analyzing dependence of the active power on the angle of the output TVR voltage in the line with TVR and without TVR we can find that the highest percentage of regulation occurs in lines close to TVR. This is because the network has a long length, and the TVR power is much less than the total power of the power supplies. In lines remote from the TVR, the change in power flows is negligible, about 0.2-1.5%.

Analysis of the researching results of uneven load distribution centers (DCs) showed that the installation of TVR near the overloaded DC allows you to achieve the uniform load DEN in common. The location of the TVR is chosen in such way that the DC1 is powered by all the feeders supplying the ring complex-closed network with a power shortfall on DC1.

5. Conclusion

The development and implementation of devices based on D-FACTS technologies is one of the crucial factors in the transition to DEN with an "active" energy transmission structure. This approach best meets the requirements of the electric network of complex closed configuration with multi-power supply. The problem of redistribution of power flows between unevenly loaded DEN nodes is acute in such networks.

The influence of TVR on the DEN parameters regime has been studied with the help of simulation modeling. The results of the research prove the effectiveness of TVR application for solving the problem of DEN power flow regulation. TVR allows to regulate power flows by changing the amplitude and phase angle of the voltage, with the help of longitudinal-transverse regulation. TVR allows you to align load schedules and stabilize the voltage level in complex networks with unevenly loaded nodes.

Thus, TVR can be successfully used in 6-20 kV DEN, implementing flexible flow distribution in networks with multi-circuit configuration and multiple power supplies.

Acknowledgments

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