Control system for vector regulation of power flows in medium voltage network

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Abstract. The article is devoted to the device for automatic control of power flows in smart grids of medium voltage. A description of proposed method of vector regulation of power flows in a power transmission line using a solid-state voltage regulator (SSVR) is given. SSVR allows one to adjust the current in the line by introducing an additional EMF and changing the voltage drop across a network choke with known electrical parameters. A vector diagram of voltages and currents is given, explaining the principles of forming parameters of the current of the network choke. The Vector In and Vector Out virtual instruments for controlling the SSVR input and output voltage converters respectively are developed in the LabVIEW. Virtual instruments regulate the parameters of the vectors and implement the control of electrical potentials on the network choke. The test results of the developed control system confirmed the effectiveness of vector regulation.

1. Introduction
The radial scheme has been used traditionally in distribution networks of medium (6-20 kV) and low (up to 1000 V) voltage. The network configuration has become more complex, closed areas have emerged due to the introduction of smart grids technologies [1], the development of distributed generation with renewable sources [2, 3] and the emergence of microgrids and virtual power plants [4, 5]. In this regard, the problem of power flows regulation has become urgent in medium voltage networks [6].

This problem in high-voltage networks (110 kV and above) is solved by installing Flexible Alternative Current Transmission System (FACTS) devices, providing automatic regulation of the electrical network parameters. An example of universal FACTS devices that simultaneously control active and reactive power flows are Unified Power Flow Controller (UPFC) [7] or Hybrid Flow Controller (HFC) [8]. Vector voltage regulation [9] is a promising way to control semiconductor converters.

There are no effective technical solutions in medium voltage networks. It is proposed to use a smart transformer [10, 11] or power flow control device [12, 13] to regulate the power flows. Despite the positive simulation results [14, 15], these devices are still at the prototype stage.

The article discusses a method of vector control of power flows in medium voltage networks with distributed generation and consumers using a solid-state voltage regulator (SSVR) [16] and its control system. SSVR relates to second generation FACTS devices and their functionality exceeds that of UPFC.
2. Vector regulation

The method of vector regulation is considered on the example of the electrical network section with SSVR (Figure 1). It is necessary to control the amplitude and phase angle of the current vector in the line W to regulate the active and reactive power flows between the networks S1 and S2. As the network S1 can be an autonomous energy source or a microgrid, and as S2 – a centralized electrical network or another microgrid. SSVR is connected in shunt-series scheme in the transmission line [17].

Figure 1. Section of power line W between two electrical networks S1 and S2 with SSVR: T1 – three phase shunt transformer; T2 – group of single-phase serial transformers; AC/DC – active rectifier; C – capacitive storage; DC/AC – autonomous voltage inverter; L – network choke.

The principle of SSVR operation is based on AC/DC/AC conversion. The active rectifier AC/DC is fed by shunt transformer T1 and maintains a constant charge level of the capacitive storage C. The energy from the DC link is fed to a standalone inverter DC/AC [18]. The inverter is connected to the series transformer T2 primary winding and introduces an additional EMF to the power line, thereby changing the potential difference (a, b) at the network choke L. The initial state of the SSVR converters is idling when a zero voltage is formed at the network choke and, accordingly, no current is consumed and no current is generated. The SSVR control system calculates the parameters of the voltage vector generated by the converters according to the vector regulation algorithm, forming the required value of the phase angle and the magnitude of the choke current.

Regulation of the magnitude and phase angle of the voltage drop across the network choke with known parameters (resistance, reactance, quality factor) allows generating a line current with a given magnitude and phasing angle, and therefore control the power flows in the network.

The vector diagram of voltages and currents (Figure 2) explains the principle of the forming the specified parameters of the current of the network choke. Parameters (magnitude and phase angle) of the line current vector (network choke current) I_L directly depends on the parameters of the voltage drop vector U_L [19]:

\[ \vec{U}_L = \vec{S} - \vec{U}_{s1} = \vec{U}_{s2} + \vec{A}_1 - \vec{U}_{s1} \]  \hspace{1cm} (1)

Therefore, if one knows the required parameters of the line current vector (voltage drop across the network choke) and the voltage values of the networks S1 and S2, one can calculate the parameters of the additional EMF vector \( \vec{A}_1 \). This vector will be a control signal for the inverter PWM generator.

The considered principle of the formation of the required current is valid for both SSVR converters. It is used in the active rectifier AC/DC to consume the current of the required value and character (active, inductive, capacitive) for power supply the SSVR capacitive storage. And it is used in a DC/AC inverter to generate current with the required parameters into the network S2.

3. Control system

SSVR control system implemented on cRIO controller. The software components that control the cRIO are developed in visual programming language LabVIEW and are called virtual instruments.
SSVR control system includes 2 virtual instruments (VI):
- Vector In – implements vector control of the SSVR active rectifier (input converter). It forms the parameters of the phase voltages vectors of the input converter based on the current values of the network voltage and the specified magnitude and phase angle values of the current required to maintain the voltage within the operating limits on the capacitive storage.
- Vector Out – implements vector control of the SSVR inverter (output converter), connected to the primary windings of series transformers. It is based on similar principles for constructing the required voltage vector, as the Vector In.

The principle of VI operation is to form a coordinate plane where the current and voltage vectors are displayed (Figure 3). The obtained vectors coordinates are converted into the parameters of the magnitudes and phase angles of the voltages formed by the converters by means of blocks that perform the inverse transformation from a rectangular coordinate system into a polar one.

**Figure 2.** The vector diagram of voltages and currents at vector regulation of line current: $U_{S1}$ and $U_{S2}$ – voltage vectors of networks S1 and S2, respectively; $\bar{U}_L$ and $\bar{I}_L$ – voltage and current vectors of network choke; $\vec{S}$ – auxiliary vector; $A_0, \alpha_0$ and $A_1, \alpha_1$ – voltage vectors of the series transformer T2 and their phase angles corresponding to zero and specified current consumption from the network S1 (network choke current), respectively; $\phi_{12}$ – phase shift between the voltage vectors of the networks S1 and S2; $\varphi$ – phase angle of network choke; $\varphi_{S1}$ and $\varphi_{S2}$ – phase angles between the vector $\vec{S}$ and the voltage vectors of the networks S1 and S2, respectively.

**Figure 3.** Vector diagrams of input (a) and output (b) converter: 1, 2 – network S1 and S2 voltages respectively; 3 and 3’ – network choke current; 4 – voltage of the network choke; 5 – calculated converter voltage; 6 – compensation of the phase angle of the shift between the networks S1 and S2 voltages; 7 – voltage of the winding of the series transformer.
The parameters of the Vector In panel are a set of local variables, some of which enter the control system from sensors, for example, the network S1 voltage (vector 1 on Figure 3, a), and some are set by the operator and the algorithms of SSVR operation: network choke parameters, phase angle of the network choke current. Calculation results: the magnitude of the formed voltage (vector 4) and current (vectors 3 and 3’) of the network choke; the magnitude and phase angle of the voltage generated by the converter (vector 5) relative to the network S1 voltage; are transmitted to the converter control system, where they are used to form a real voltage vector.

The virtual panel of the output converter is received the results of measurements of the networks S1 and S2 voltages (vectors 1 and 2 on Figure 3, b) and the phase angle of the shift between them. The calculation results are the magnitude of the voltage formed on the network choke (vector 4), the magnitude and phase angle of the voltage compensating for the difference between the networks S1 and S2 (vector 6), the amplitude and phase angle of the serial transformer voltage generated by the output converter (vector 7) for a given value and the character of the network choke current (vector 3).

Vector Out takes into account the possible phase angle of shift between the network S1 operating at idle and the network S2, as well as the difference in the magnitude of their phase voltages. The lagging nature of the vector of the phase voltages of the network S1 regarding the network S2 by 30° is shown on Figure 3, b for clarity.

4. Results

The developed VI of the SSVR input and output converters were tested to verify the proposed method of vector regulation. The following assumptions were made for all modes: input voltage magnitude 10 V corresponds to the magnitude of the network phase voltage; inductance and resistance of the network choke 3 mH and 0.2 Ω, respectively; magnitude of the choke current 5 A.

The results of the simulation of the input converter operation at the value 135° of the phase angle of the current consumed from the network are presented on Figure 4, a. This mode corresponds to the vector diagram presented on Figure 3, a.

![Figure 4](image-url)

Figure 4. Oscillograms of voltages and currents of the input converter for the mode of consumption current with an angle of 135° from the network S1 (a) and the output converter for the mode of formation of the network choke current with an angle 0° (b): 1 – phase voltage of the network S1; 2 – input voltage of the SSVR converter; 3 – network choke current with respect to S1 voltage; 4 – network choke current with respect to converter voltage.

The calculated parameters of the voltage vector at the converter input (vector 5), which provide the specified phase angle of the current network choke are summarized in Table 1.

Studies have shown that the any mode (generation or consumption) of current of any character (active, inductive, capacitive) can be carried out by rotating the current vector relative to the network voltage vector. SSVR input converter begins to generate current in the supply network S1 while...
forming the current vector with phase angle of more than 90°. SSVR generates a leading current in the network when the value of the angle is 135°. Active current is generated at 180°.

Table 1. The results of the simulation of the input converter operation.

| The specified phase angle between the network choke current and the network S1 voltage, ° | 0 | 45 | 90 | 135 | 180 |
|---|---|---|---|---|---|
| Voltage magnitude at the converter input, V | 10.6 | 13.5 | 14.7 | 14 | 11.5 |
| The phase angle of the voltage at the converter input relative to the network S1 voltage, ° | -26.4° | -15.8° | -1.95° | 12.3° | 24.2° |

*The minus sign corresponds to the lag of the voltage at the converter input from the network voltage.*

Tests for different values of the phase angles of the network choke current relative to the vector of the network voltage were carried out to verify the output converter algorithms. In addition to the previously assumptions, the vector of the phase voltage of the network S1 is set lagging by 30° relative to the network S2. Figure 4, b shows oscillograms of network voltage and network choke current. This mode corresponds to the vector diagram presented on Figure 3, b.

The calculated parameters of the voltage vector of the serial transformer (vector 7) formed by the output converter to set the required phase angle of the network choke current are shown in table 2.

Table 2. The results of the simulation of the output converter operation.

| The specified phase angle between the network choke current and the network S1 voltage, ° | 0 | 45 | 90 | 135 | 180 |
|---|---|---|---|---|---|
| Magnitude of the serial transformer voltage formed by the output converter, V | -1.86 | -2.1 | -5.62 | -8 | -9.5 |
| The phase angle of the voltage of the serial transformer relative to the network S2 voltage, ° | -39° | -171° | -157° | -141.95° | -119.65° |

The current vector can be rotated up to 180° with the same value of the initial phase shift between the voltages of the networks S1 and S2 by changing in the magnitude and phase angle of the voltage vector of the winding of a serial transformer. It means that it is possible to ensure the consumption/generation of a current of any character from the network S1, and to control the power flows in the line.

5. Conclusions

The method of vector regulation of power flows due to the control of the magnitude and phase angle of the voltage drop vector across the network choke is proposed. This requires the installation of SSVR in the power line. SSVR introduces an additional EMF with given parameters of the magnitude and phase angle relative to the voltage at the installation point.

Virtual instruments for calculating the formed parameters of voltage vectors of the SSVR input and output converters are developed in LabVIEW. The results of the simulation of the SSVR converters operation made it possible to determine the parameters of the vectors required for controlling the phase angle of the network choke current. It is established that the control system provides the modes of consumption and generation of current of any character to the power line.
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