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# Power Flow Control in a Virtual Power Plant LV Network

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**Abstract-** The article studies the power flow control in a Virtual Power Plant (VPP) Low Voltage (LV) Network by controlling a voltage vector. The authors have developed an experimental device to control the voltage phase angle (0.4 kV) - Power Flow Control Device (PFCD). The experimental research is conducted with both PFCD and a physical VPP LV network model. The researchers analyze the power flow control made in the VPP LV network which is carried out by the PFCD under the voltage phase angle regulation in the range from 0 to 360 electric degrees. The results show that the electric parameters of the VPP LV Network depend on the value of variable voltage phase angle.

**Keywords** Distributed Generation Sources, Virtual Power Plant, Voltage Phase Angle, Power Flow Control Device, Semiconductor Voltage Converter.

**Nomenclature**

| | |
|---|---|
| BT | Booster Transformer |
| DEN | Distribution Electric Networks |
| D-FACTS | Distributed Flexible Alternative Current Transmission System |
| DG | Distributed Generator |
| EMF | Electromotive Force |
| FACTS | Flexible Alternative Current Transmission Systems |
| LV | Low Voltage |
| NNSTU | Nizhny Novgorod State Technical University n.a. R.E. Alekseev |
| PFCD | Power Flow Control Device |
| PSD | Phase Shifting Device |
| SVC | Semiconductor Voltage Converter |
| VPP | Virtual Power Plant |

## 1. Introduction

The use of LV networks with distributed generation (wind and solar power plants, mini-CHP and other) expands in all developed countries [1-3]. However, the growing number of LV distributed generation sources is not appealing to unified energy systems, as individual sources don't have enough power to synchronize their work with the system [4].

VPP can guarantee efficiency of LV distributed generation. VPP is an intelligent system that facilitates combination of technology and information in distributed generation sources, energy storage devices and controllable loads [5]. VPP network deals with the high-level electricity networks. The VPP allows releasing part of the unified power system's power.

It is necessary to solve two problems during designing a VPP: the first one is how to control information flows, the second one is how to control power flows between connected objects.

Many scientific researchers are studying the task of power flow control in electrical networks.

For electric networks of medium and high voltage the problem of power flow control is solved by means of Flexible Alternative Current Transmission System (FACTS) and Distributed Flexible Alternative Current Transmission System (D-FACTS) technologies [6]. The principle of power flow control is based on the regulation of electrical network interrelated parameters (voltage, resistance, current) using semiconductor voltage converters. Scientific research shows that incorporation of renewable energy sources and FACTS devices improves the performance of existing power transmission networks [7]. The newest advanced technologies of the power flow control in the electrical network are associated with voltage vector control when voltage vector's magnitude and phase angle are adjustable. The examples of this principle are as follows: Phase Shifting Transformers, Thyristor Controlled Phase Angle Regulator, and Unified power flow controller [8-10].

The regulation in the amount of transmitted power to consumers in LV electrical networks (0.4 kV) is achieved through the network physical reconfiguration and generated power amount changing. This is the reason why LV distributed generation sources are being used inefficiently.

According to the latest global research, breakthrough technologies in the field of electricity exchange systems in LV networks are associated with the development of the universal device such as Solid State Transformer (SST). SST technology can increase or decrease AC voltage levels, provide two-way power flow, actively change power characteristics, improve power quality and many other things [11-13]. The SST technologies are developing in the USA, Japan and a number of European countries [14-15]. However, the industrial production of SST is limited due to the absence of required quality semiconductor and magnetic materials [16-17].

The goal of our research is to study ways of possible PFCD application for the power flow control in the VPP LV network [18]. Technical implementation of PFCD is simpler and cheaper than SST.

The highlights of the study:

- Mathematical background of the method of vector voltage regulation for power flow control in VPP LV network.
- Design of experimental PFCD that implements the vector voltage regulation principle.
- Creation of physical model of the VPP LV network, which simulates power sources, a load and transmission lines for research of the experimental PFCD.
- Research of the power flow control in the VPP by the PFCD through the voltage phase angle regulation between 0 and 360 electrical degrees.

The rest of the paper is organized as follows: Section 2 describes the method of vector voltage regulation for power flow control in VPP LV network. Section 3 describes the experimental PFCD and its operation principle. Section 4 presents the results of study of the experimental PFCD using the VPP LV network physical model.

## 2. Problem Formulation

Figure 1 explains the principle of voltage vector regulation.

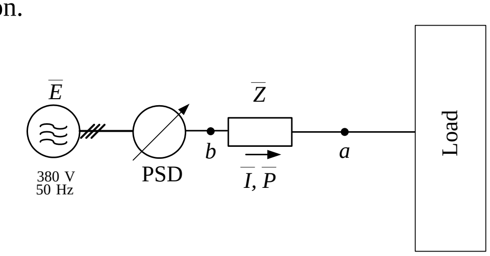



**Fig. 1.** Simplified scheme of power transmission line with phase shifting device for longitudinal-transverse voltage regulation.

A phase shifting device (PSD) for longitudinal-transverse voltage regulation that allows to change the voltage parameters at point B has been installed in line with the power supply *E* and the load. Booster transformer is a component of the PSD.

The power flow (*P*) control is carried out by changing the current magnitude (*I*) by force-changing the magnitude and direction of the voltage deviation vector in a line with impedance (*Z*) [19]. The change in the magnitude and nature of the current depends on the voltage parameters in the points *A* and *B*:

$$\bar{I} = \frac{\overline{U_a} - \overline{U_b}}{\bar{Z}} \quad (1)$$

Where $U_b$ is the vector sum of voltages on the power supply *E* and PSD booster transformer. The voltage phase regulation on the booster transformer leads to change of the $U_b$ phase relatively to $U_a$ and, as a consequence, to current and power flow changing:

$$P = \frac{|U_a| \cdot |U_b|}{|Z|} \cdot \sin(\varphi + \delta) \tag{2}$$

Where δ is the angle between the power supply voltage vector and the voltage vector at the end of the line, φ is the phase angle of the $U_b$ vector rotation.

Thus, the active power flow is proportional to the sine of the phase angle between the power supply voltage vector at the beginning of the line and the voltage vector at the end of the line. By changing the angle φ, it is possible to control the amount of active power transmitted through the line. The proposed approach can be used in electrical networks with numerous generation sources and consumers. This is explained by a simplified diagram of an electrical network containing power sources $E_1$, $E_2$ and a load (Fig.2).

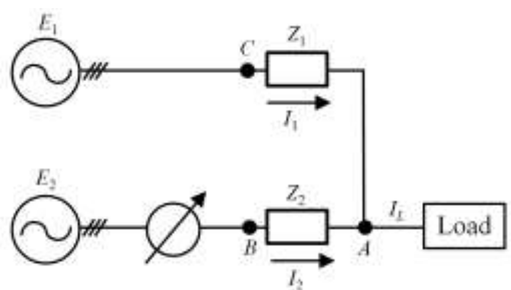



**Fig. 2.** Simplified diagram of an electrical network.

The principle of regulating the currents magnitude and, as a consequence, the power flows in this circuit is similar to the method described earlier.

The values of the currents and power flows in the network lines are given by the equation below:

$$\overline{I_1} = \frac{\overline{U_a} - \overline{U_c}}{\overline{Z_1}}; \quad \overline{I_2} = \frac{\overline{U_a} - \overline{U_b}}{\overline{Z_2}} \tag{3}$$

$$P_1 = \frac{|U_a| \cdot |U_c|}{|Z_1|} \cdot \sin(\delta); \; P_2 = \frac{|U_a| \cdot |U_b|}{|Z_2|} \cdot \sin(\varphi + \delta) \tag{4}$$

The required line current with $E_1$ can be obtained by regulating the line current with $E_2$ in accordance to the first Kirchhoff law.

For example, in order for the transmitted power along the line with $E_1$ to be greater than the transmitted power along the line from $E_2$, then the use of a PSD is necessary to set a certain angle φ. The value of the angle φ can be determined from the equations system (4). The function of the angle φ depending on the network parameters and the required power flow values is given by the formula below:

$$\varphi = \sin^{-1} \frac{P_2 \cdot |Z_2|}{|U_a| \cdot |U_b|} - \sin^{-1} \frac{P_1 \cdot |Z_1|}{|U_a| \cdot |U_c|} \tag{5}$$

The method for regulating the magnitude and phase angle $I_2$ is illustrated by a vector diagram (Fig.3), constructed with known ratios of active and reactive components $Z_2$.

In Fig. 3 legends are: $U_a$ - root-mean-square network voltage; $U_b$ - root-mean-square converter input voltage for the current values; $U_R$ - resistive drop of network inductor; $U_L$ - voltage drop across the inductive resistance of network inductor; $U_Z$ - root-mean-square of voltage drop across the network inductor resistance; $i_S$ - inductor current; $\varphi_L$ - given phase angle of input/output current; α – phase angle between the voltage vectors $U_a$ and $U_b$.

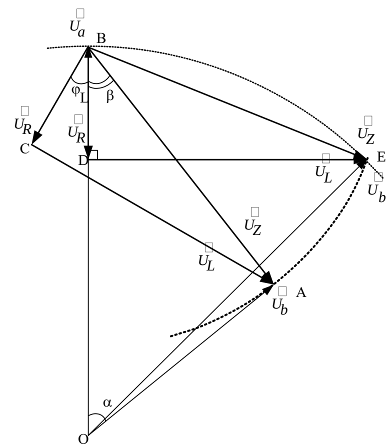



**Fig. 3.** Vectorial composition of given current formation.

Current magnitude is controlled by setting the location of the end point of vector $U_b$ on the hypotenuse of triangle ABC (the legs' lengths ratio is the same in such triangles). The phase angle of current $\varphi_L$ is controlled by triangle-turning. As a result, vector $U_b$ forms and it has the end in peak *A* on the segment of a described circle.

For the triangle *ABC* the below holds true:

$$\angle ABC = \beta + \varphi_L \tag{6}$$

Using the cosine theorem, we can conclude:

$$\angle ABC = \arccos \frac{U_Z}{2 \cdot U_S} = \arccos \frac{I_{S1} \cdot \sqrt{R^2 \cdot (1 + Q^2)}}{2 \cdot U_S} \tag{7}$$

Where *R* and *Q* are the reactor's reactance and *Q*-factor respectively.

Thus, if given the parameters of a particular device, you can calculate the parameters of the stress vectors and determine the phase angle.

The authors have developed a device based on the principle of voltage vector regulation which controls power flows in low voltage electrical networks with a complex structure.

## 3. Power Flow Control Device for Virtual Power Plant Low Voltage Network

An experimental 30 kVA PFCD, which allows for regulation of the phase angle of 0.4 kV voltage, has been created.

The main elements of the PFCD include semiconductor voltage converter (SVC), booster transformers (BT1-BT3) and a control system. SVC generates AC by means of amplitude and a phase angle. It's the same as a voltage converter with a common connecting element of DC. A detailed description of the SVC is given in [18]. Booster transformers are designed for existing additional EMF with adjustable parameters (Fig. 4).

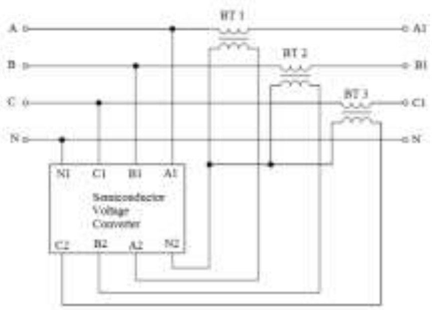



**Fig. 4.** SVC and booster transformers diagram.

Two-level control system forms the basis of PFCD. A low-level control system is for semiconductor elements of PFCD. The information about network parameters (current, voltage, phase angle) is transmitted from the measuring devices (current sensors and voltage) to controller MY RIO-1900 according to IEC 60870-5-104 Protocol. The controller analyzes the data and forms control influence SVC. A control strategy is based on the principle of power balance and described in detail in [18]. A high-level control system is designed to control the active elements of VPP network and exchange information with other PFCD.

Figure 5 shows the application of voltage vector control to regulate power flows in VPP LV network.

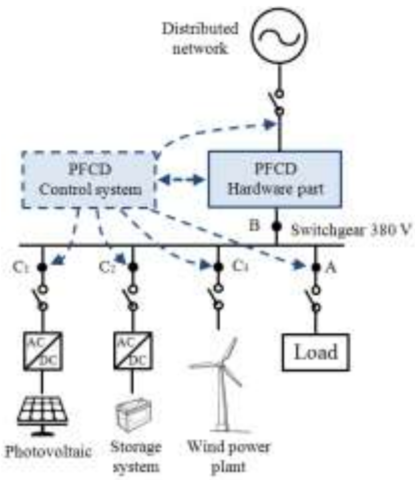



**Fig. 5.** PFCD application for VPP LV network.

PFCD force-changes voltage magnitude and voltage phase angle which redistribute power flows from DEN and distributed generation sources.

## 4. Test Results

### *4.1 Physical model of VPP LV network with experimental PFCD*

A physical model of VPP network is built to research the experimental PFCD that implements the voltage vector regulation principle (Fig. 6). It consists of DEN simulator (DN simulator), simulators of distributed generation sources DG-1, DG-2. A load module 0-140 kVA was used for variable load with the control step 5 kW and 5 kVAr.

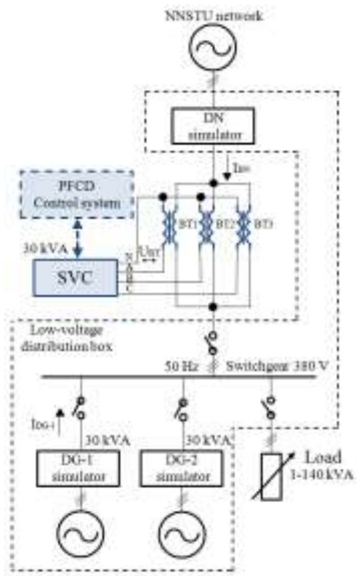



**Fig. 6.** Physical VPP LV network model scheme with experimental PFCD.

PFCD experimental model that controls output voltage magnitude and phase angle in the line is connected to DEN simulator.

The physical VPP LV network model with experimental PFCD is shown in Fig. 7.

**Fig. 7.** Physical VPP LV network model photo with experimental PFCD.

*4.2 Power flow analysis*

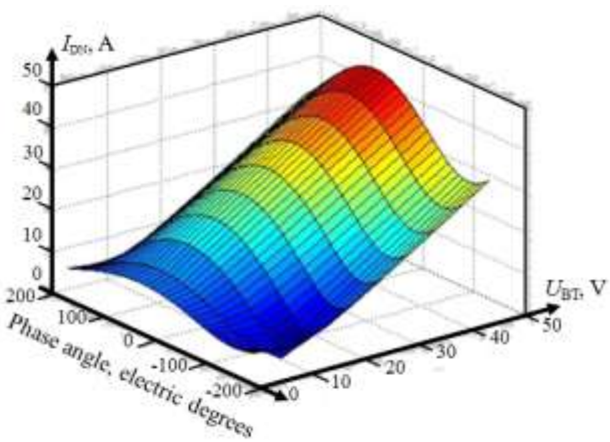
The goal of the research process was to identify how a changeable phase angle magnitude in the line DN simulator in the range from 0 to 360 electric degrees can control DN and DG power flows.

A study of the experimental PFCD was carried out for three scenarios:

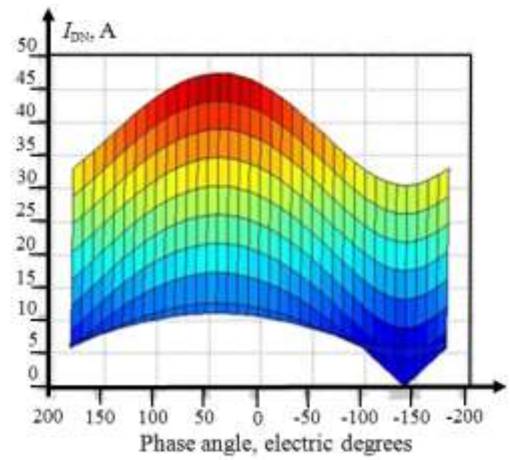
- Scenario 1 - VPP with one power source (DN simulator). The PFCD controls the power flow from the DN simulator to the load.
- Scenario 2 - VPP with two power sources (DN simulator and DG-1 simulator). The PFCD controls the distribution of power flows in the lines with DN simulator and DG-1 simulator.
- Scenario 3 - VPP with two power sources (DN simulator and DG-1 simulator) and then one source was disconnected (DG-1 simulator). PFCD automatically transfers the load power from the disconnected source to the DN simulator.

The article shows the results of scenario 2. It was necessary to determine the voltage phase angle values in the electrical line DN simulator, in which currents in the lines DN and DG-1 would alternatively become maximum and approach zero.

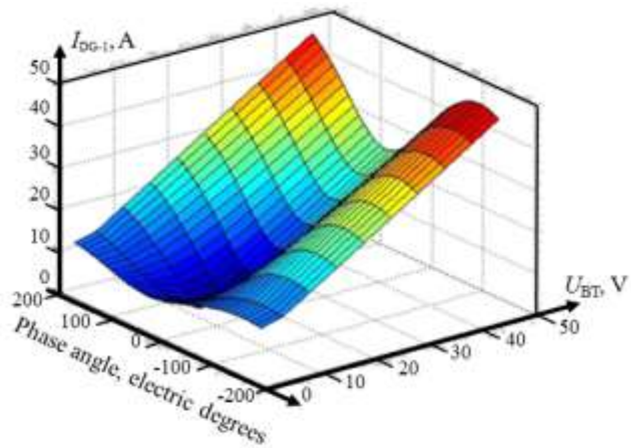
The research results are shown in Fig. 8.



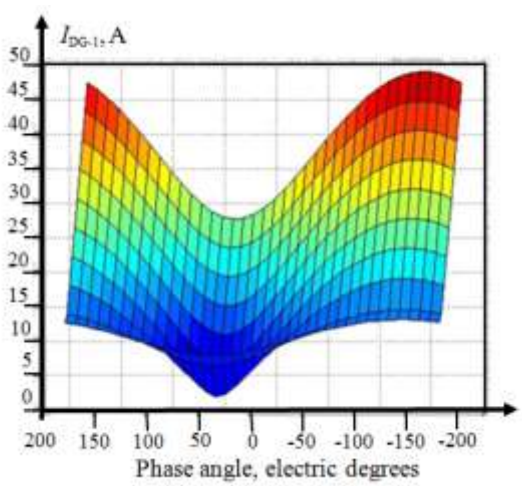

(a) Current in the line DN simulator dependence on output PFCD voltage




(b) Current amplitude in the line DN simulator dependence on voltage phase angle




(c) Current in the line DN simulator dependence on output PFCD voltage




(d) Current amplitude in the line DG-1 simulator dependence on voltage phase angle in the line DN simulator

**Fig. 8.** Currents of VPP LV network dependence on voltage phase angle.

Figure 8 showcases three-dimensional nomograms which allow to predict the relationship between the magnitudes and the phase angles of the currents of power transmission lines in any of the three scenarios with the most common scenario being 2 while scenarios 1 and 3 being special cases.

On the graphs (Fig. 8 a, c) the y-axes show the current magnitudes in the line; the x-axes indicate voltage phase angle values as well as voltage amplitude of a booster transformer.

As we can see from the graphs (Fig. 8), voltage phase angle changes from -180 to 180 electric degrees, power flows in the lines DN/DG-1 simulator redistribute.

If voltage phase angle equals to 25 electric degrees, the current in the line DN simulator becomes maximum (Fig. 8 a, b) while the current in the line DG-1 simulator approaches zero (Fig. 8 c, d). The load is from DN simulator. The power flow in the line DG-1 simulator is sort of locked but the electricity supply isn't switched off.

If voltage phase angle is about -150 electric degrees, there is a reverse situation. If the current in the line DN simulator decreases to 0 (Fig. 8, a, b) then the current in the line DG-1 simulator increases to a maximum (Fig. 8 c, d). In other words, the load is from DG-1 simulator.

If the values of voltage phase angle are intermediate, the load is supplied from the DN simulator and DG-1 simulator. However, if the values of voltage phase angle are different, the power flow of one of the electricity supplies prevails.

For all scenarios when controlling the voltage phase angle at all range, there was a permitted deviation at ±5% of the nominal value by controlling voltage amplitude. The transition time of electrical network in steady state after changing a voltage phase angle made up about four periods of mains voltage. Thus, the obtained effects for PFCD fully correlate with the expected results.

**5. Discussion**

The suggested way of the power flow regulation allows to bypass direct measurements of the currents of power lines and go to the vector control of voltages at the node points.

To implement this method, preliminary determination of several constants is required: $k = U_C / U_S$ - the ratio of the voltage of one arm of the capacitive storage device to the amplitude value of the phase voltage of the supply network; $k_F$ - the shape of the voltage; $R$ - resistance of the network choke or the network section; $Q$ is the $Q$-factor of the network choke or the network section; $R_C$ - equivalent resistance of the circuit of power consumption of the capacitive storage by direct current.

The use of the given constant parameters for the developed PFCD made it possible to derive an expression for determining the constant converter:

$$C_C = k^2 \cdot k_F^2 \cdot R \cdot \sqrt{(1+Q^2)}/3R_C \tag{8}$$

With the help of a constant converter, the parameters of the voltage vectors and the phase angle can be determined:

$$\angle ABC = \arccos(C_C^2) \tag{9}$$

The results showed that the experimental PFCD provides voltage phase angle vector control. Due to the voltage phase angle vector control there is a power flow control. Power flows are supplied by DEN and distributed generation sources.

The use of load-bearing semiconductor elements for PFCD allows to achieve the mass-dimensional characteristics of the device. At the same time, the use of PFCD does not worsen electric power quality. With the annual cost reduction of semiconductor technology the approach to control the power flow in VPP LV network and its proposed technical implementation can be considered promising.

At the same time the results are intermediate. Further research should prove the most efficient method to study unbalanced situations as well as assess the voltage and power losses. It is also necessary to improve some hardware components for manufacturing effective industrial PFCDs as they need improved circuitry. Moreover, it's important to develop new magnetic materials for electromagnetic devices and high-tech production of high-frequency capacitors.

The methods of PFCD application in VPP network can be stated separately.

VPP LV network can connect a large number of different distributed generation sources including renewable energy. Electrotransmission from energy supplies can be based on AC or DC. VPP LV network can have a closed topology. As a result, the choice of optimal connection points PFCD to VPP LV network is vital to have the most efficiency from power flow distribution perspective.

The strategy how to choose optimal connection points PFCD can be based on finding the most efficient ways to transmit electricity that are cost-efficient and allow only for relative to minimal energy losses. The strategy should eliminate at early states all inefficient ways to transmit electricity in which most power is lost and a fairly low power is transmitted for long distances.

Analyzing the selected ways of electrotransmission it is possible to determine previous connection points PFCD to VPP network and list the possible alternatives of connecting distributed generation sources to PFCD.

For each connection it's necessary to analyze the operation mode parameters of VPP network in order to determine power balance, test voltage levels and to assess system stability.

The analysis results show the optimal connection point PFCD to VPP LV network and required parameters of vector control.

## 6. Conclusion

This paper focuses on the problem of power flow control in VPP LV network. The authors create an experimental device PFCD to control the voltage phase angle (0,4 kV) in the range from 0 to 360 electric degrees. The researchers investigate the adjusting characteristics of the PFCD as well as prove out ways of possible PFCD application for the power flow control in the VPP LV network.

The research results indicate that:

- Power flows are redistributed in the lines of the VPP LV network physical model during the phase voltage angle regulation by PFCD
- The allowable voltage deviation (± 5% of the nominal value) on the load is maintained when the phase angle of the voltage is varied throughout the regulation range.

Developed scientific and technical findings of PFCD manufacturing can be of interest in research groups and companies developing technology for VPP and micro-grid.

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