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AUTOMATIC ADJUSTMENT OF REACTIVE POWER BY FACTS DEVICES UNDER CONDITIONS OF VOLTAGE INSTABILITY IN THE ELECTRIC NETWORK

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Abstract. *This article describes the problem of automatic regulation of reactive power using electronic devices FACTS (Flexible AC Transmission Systems): static synchronous compensator (STATCOM) and unified power flow controller (UPFC). With the help of a complex writing form, the following are determined: voltages at the installation nodes of the FACTS device and loads, currents of loads, power sources and electronic compensators in case of voltage instability at the load node of the electrical network. Voltages and currents are determined using the node-voltage method. The task of STATCOM is partial or full compensation of reactive power. During the reduction of the voltage at the load node, the reactive power generated by the power source decreases. The STATCOM should partially or fully compensate for the reactive power imbalance as quickly as possible. However, at the same time, it is not possible to fully compensate for the voltage reduction. A series-parallel or parallel-series UPFC can be used to solve this problem. As a result of using the UPFC, it is possible to automatically raise the voltage level to acceptable values with the help of the UPFC series compensator. The analysis shows that the parallel-serial UPFC is characterized by the stability of operation. In the case of using a series-parallel UPFC, there are restrictions on the ability to adjust the imaginary voltage component of the series compensator, since the angle of the voltage vector changes, which causes a failure in the operation of the regulator of the parallel compensator UPFC.*

Keywords: reactive power, static synchronous compensator, unified power flow regulator, voltage instability

AUTOMATYCZNA REGULACJA MOCY BIERNEJ PRZEZ URZĄDZENIA FACTS W WARUNKACH NIESTABILNOŚCI NAPIĘCIA W SIECI ELEKTRYCZNEJ

Streszczenie. *W artykule opisano problematykę automatycznej regulacji mocy biernej za pomocą urządzeń elektronicznych FACTS (Flexible AC Transmission Systems): statycznego kompensatora synchronicznego (STATCOM) oraz regulatora przepływu mocy (UPFC). Za pomocą złożonego formularza rejestracyjnego określane są: napięcia w węzłach instalacji urządzenia FACTS i obciążenia, prądy obciążenia, źródeł zasilania i kompensatorów elektronicznych w przypadku niestabilności napięcia w węźle obciążenia sieci elektrycznej. Napięcia i prądy są wyznaczane metodą napięć węzłowych. Zadaniem STATCOM jest częściowa lub pełna kompensacja mocy biernej. Podczas spadku napięcia w węźle obciążenia, moc bierna generowana przez źródło zasilania maleje. STATCOM powinien częściowo lub w pełni skompensować nierównowagę mocy biernej tak szybko, jak to możliwe. Jednocześnie jednak nie jest możliwe pełne skompensowanie spadku napięcia. W celu rozwiązania tego problemu można zastosować szeregowo-równoległy lub równoległo-szeregowy układ UPFC. W wyniku zastosowania UPFC możliwe jest automatyczne podniesienie poziomu napięcia do akceptowalnych wartości za pomocą kompensatora szeregowego UPFC. Analiza pokazuje, że równoległo-szeregowy UPFC charakteryzuje się stabilnością działania. W przypadku zastosowania szeregowo-równoległego UPFC istnieją ograniczenia w zakresie możliwości regulacji składowej urojonej napięcia kompensatora szeregowego, ponieważ zmienia się kąt wektora napięcia, co powoduje awarię działania regulatora kompensatora równoległego UPFC.*

Słowa kluczowe: moc bierna, statyczny kompensator synchroniczny, ujednolicony regulator przepływu mocy, niestabilność napięcia

Introduction

In modern conditions, there is a tendency to increase reactive power with a variable character, which is a problem for the effective use of alternating current power lines [7]. Conventional (not equipped with FACTS devices) power grids have the problem of low utilization of transmission line capacity, which reduces their efficiency due to limited possibilities of regulating reactive power flows [12].

FACTS devices are used to solve these problems: a static synchronous compensator (STATCOM) and a unified power flow controller (UPFC) [5]. The main advantage of STATCOM and UPFC is the automatic regulation of reactive power flows in electrical networks. The UPFC, in addition, provides an increase in the voltage level at the load. The UPFC adjustable parameters are line impedance, phase angle, and voltage. UPFC allows performing such an important function as ensuring voltage stability. The use of UPFC regulators ensures the improvement of the static and dynamic characteristics of power transmission lines [4, 5, 11].

UPFC is a combination of a Static Series Synchronous Compensator (SSSC) and Static Parallel Compensator (STATCOM) that share a DC capacitor (Fig. 1) [1, 11,15]. The series compensator improves the dynamic stability of the network load node in transient mode, the parallel compensator provides dynamic regulation of reactive power flows [8,13,14].

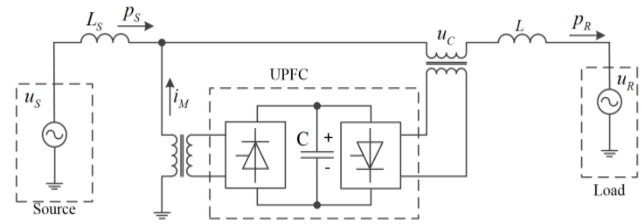

Fig. 1. Scheme UPFC

1. STATCOM simulation in static mode

The most widely used FACTS device for reactive power compensation is the STATCOM, which is designed for smooth regulation of reactive power within wide limits (±100%), has high speed in the modes of consumption and generation of reactive power, has relatively small dimensions, can be used in almost any electrical networks. The use of STATCOM allows not only to regulate reactive power, but also to increase network bandwidth, and optimize power flows and voltage levels. Its use in "weak" networks to reduce voltage deviations and fluctuations is particularly effective.

Fig. 2 shows the scheme of replacing a network node with a STATCOM.

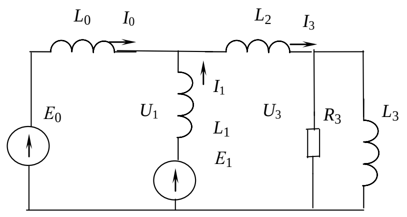

Fig. 2. Scheme of replacing a network node with STATCOM

The following values of network node parameters in relative units are stated as follows: $X_0 = 0.15$; $X_1 = 0.015$; $X_2 = 0.1$; $X_3 = 2$; $R_3 = 1$. Conductivity of branches

$$Y_0 = \frac{1}{jX_0};\ Y_1 = \frac{1}{jX_1};\ Y_2 = \frac{1}{jX_2};\ Y_3 = \frac{1}{R_3} + \frac{1}{jX_3} \qquad (1)$$

Voltages U_1 and U_3 are calculated according to the formula:

$$\begin{bmatrix} U_1 \\ U_3 \end{bmatrix} = \begin{bmatrix} Y_0 + Y_1 + Y_2 & -Y_2 \\ -Y_2 & Y_2 + Y_3 \end{bmatrix} \begin{bmatrix} Y_0 \cdot E_0 + Y_1 \cdot E_1 \\ 0 \end{bmatrix} \qquad (2)$$

The E_1 STATCOM parameter is selected in the adjustment process in such a way that the active power of the compensator is equal to zero, and the reactive power provides the optimal mode in the electrical network. For $E_0 = 1.05$, $E_1 = 1.0 - j0.13$ values of voltages: $U_1 = 0.995 - j0.129$ and $U_3 = 0.928 - j0.212$. The currents, accordingly, of the power source, the compensator and the load are equal:

$$I_0 = Y_0 \cdot (E_0 - U_1) = 0.863 - j0.364$$

$$I_1 = Y_1 \cdot (E_1 - U_1) = -0.041 - j0.311$$

$$I_3 = Y_3 \cdot U_3 = 0.822 - j0.675$$

The powers, accordingly, of the power source, the compensator and the load will be:

$$S_0 = E_0 \cdot \overline{I_0} = 0.906 + j0.383$$

$$S_1 = E_1 \cdot \overline{I_1} = 0.000 + j0.316$$

$$S_3 = E_3 \cdot \overline{I_3} = 0.906 + j0.453$$

The reactive power of the load and transmission lines is compensated by the power source and STATCOM.

Fig. 3 shows the amplitude-phase characteristics of currents I_0 and I_1 in the event of a decrease in the voltage at the power supply node in the range from $1.05 \cdot U_н$ to $0.9 \cdot U_н$. The arrow indicates the direction of change in the current components in case of a decrease in voltage.

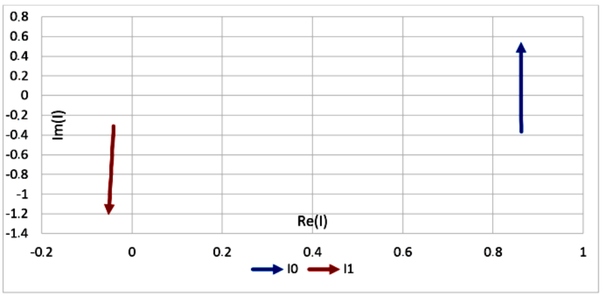

Fig. 3. Amplitude-phase characteristics of currents I_0 and I_1 in the event of a voltage drop in the power node with STATCOM

A decrease in the voltage of the power source leads to a decrease in the reactive component of the current I_0, and then to a change in its direction. The power supply reduces the generation of reactive power and then begins to consume it. In this case, the decrease in the reactive power of the power supply is compensated by the STATCOM.

To reduce the sharp decrease in reactive power consumption by the power source, it is necessary to reduce the effective EMF component of the compensator E_1 to the level of 0.95. However, as can be seen from Fig. 4, the active component of the current I_1 increases slightly, which characterizes the additional consumption of the active power of the STATCOM.

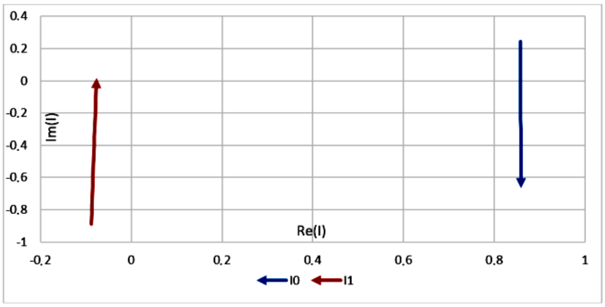

Fig. 4. Amplitude-phase characteristics of currents I_0 and I_1 in case of reduction of the real component E1 STATCOM

At the same time, the voltage level on the load remains insufficient. In the case of reducing the voltage of the power supply to the value $E_0 = 1.0$ the load voltage is $U_3 = 0.924 - j0.211$.

2. Simulation of parallel-serial UPFC in static mode

UPFC can be used to increase the load voltage. Fig. 5 shows the scheme of replacing a network node with a parallel-serial UPFC [6, 11].

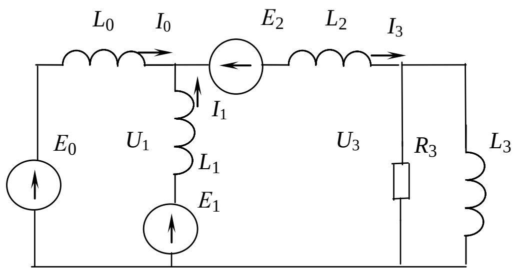

Fig. 5. Scheme of replacing a network node with a parallel-serial UPFC

Voltages U_1 and U_3 calculated according to the formula:

$$\begin{bmatrix} U_1 \\ U_3 \end{bmatrix} = \begin{bmatrix} Y_0 + Y_1 + Y_2 & -Y_2 \\ -Y_2 & Y_2 + Y_3 \end{bmatrix} \begin{bmatrix} Y_0 \cdot E_0 + Y_1 \cdot E_1 + Y_2 \cdot E_2 \\ -Y_2 \cdot E_2 \end{bmatrix} \qquad (3)$$

For $E_0 = 1.05$, $E_1 = 1.0 - j0.155$ and $E_2 = -0.1 - j0.15$ values of voltages:

$$U_1 = 0.996 - j0.154,\ U_3 = 1.034 - j0.103$$

currents:

$$I_0 = Y_0 \cdot (E_0 - U_1) = 1.029 - j0.359$$

$$I_1 = Y_1 \cdot (E_1 - U_1) = -0.046 - j0.260$$

$$I_3 = Y_3 \cdot U_3 = 0.983 - j0.620$$

powers:

$$S_0 = E_0 \cdot \overline{I_0} = 1.080 + j0.377$$

$$S_1 = E_1 \cdot \overline{I_1} = -0.006 + j0.267$$

$$S_2 = -E_2 \cdot \overline{I_3} = 0.005 + j0.209$$

$$S_3 = E_3 \cdot \overline{I_3} = 1.080 + j0.540$$

Reactive power is compensated by the power supply, parallel and series UPFC compensators [9, 10].

In the case of reducing the voltage of the power supply to the value $E_0 = 1.0$ voltage on the load $U_3 = 1.030 - j0.102$ practically does not change; the power of the series compensator does not change either $S_2 = 0.005 + j0.209$. In this case, the decrease in reactive power of the power source is compensated by a parallel compensator.

Fig. 6 shows the amplitude-phase characteristics of currents I_0 and I_1 in the event of a voltage drop in the power supply node in the range of $1.05 \ldots 0.9 \cdot U_n$.

A decrease in the voltage of the power source, as in the scheme with a STATCOM, leads to a decrease in the reactive component of the current I_0, and then to a change in the sign of the reactive component of the current I_0 (Fig. 7). The power source begins to consume reactive power, and the UPFC parallel compensator increases its generation, ensuring the balancing of reactive power at the load node.

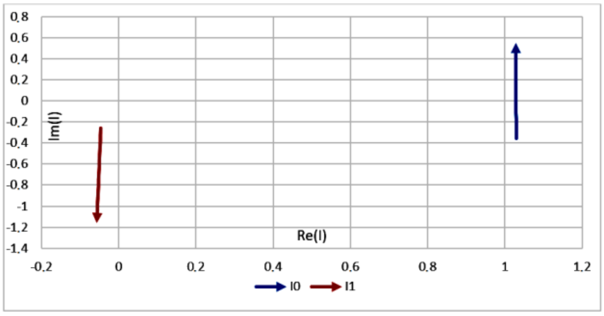

Fig. 6. Amplitude-phase characteristics of currents I_0 and I_1 in the event of a voltage drop in the power supply node with UPFC

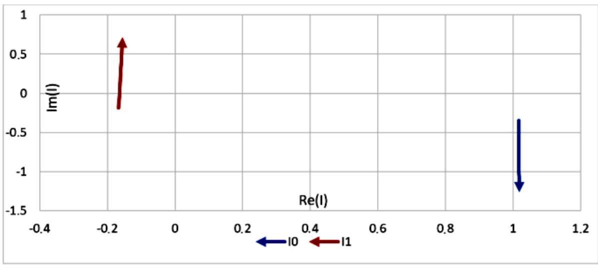

Fig. 7. Amplitude-phase characteristics of currents I_0 and I_1 in the event of a decrease in the real component E_1

To reduce the sharp decrease in reactive power consumption by the power source, it is necessary to reduce the effective EMF component of the parallel compensator E_1 to the level of 0.85. However, as can be seen from Fig. 7, the active component of current I_1 increases, which characterizes the additional consumption of active power by the compensator. The additional consumption of active power by the compensator can be compensated by simultaneously adjusting both EMF components without changing the phase angle, i.e. by adjusting the EMF module.

3. Modelling of series-parallel UPFC in static mode

Fig. 8 shows a substitution scheme with series-parallel UPFC. Voltages U_1 and U_3 are calculated according to the formula:

$$\begin{bmatrix} U_1 \\ U_3 \end{bmatrix} = \begin{bmatrix} Y_0 + Y_1 + Y_2 & -Y_2 \\ -Y_2 & Y_2 + Y_3 \end{bmatrix} \begin{bmatrix} Y_0 \left(E_0 - E_2 \right) + Y_1 E_1 \\ 0 \end{bmatrix} \tag{4}$$

For $E_1 = 1.0 - j0.145$, $E_2 = -0.1$ values of voltages:

$$U_1 = 1.094 - j0.144 \text{ and } U_3 = 1.02 - j0.234$$

currents:

$$I_0 = Y_0 \cdot (E_0 - E_2 - U_1) = 0.961 - j0.371$$

$$I_1 = Y_1 \cdot (E_1 - U_1) = -0.058 - j0.374$$

$$I_3 = Y_3 \cdot U_3 = 0.903 - j0.744$$

powers:

$$S_0 = E_0 \cdot \overline{I_0} = 0.961 + j0.371$$

$$S_1 = E_1 \cdot \overline{I_1} = -0.010 + j0.419$$

$$S_2 = -E_2 \cdot \overline{I_1} = -0.006 + j0.037$$

$$S_3 = E_3 \cdot \overline{I_3} = 1.095 + j0.548$$

Reactive power is compensated by a power supply and a parallel compensator.

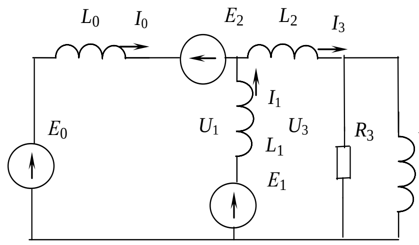

Fig. 8. Scheme of substitution of a network node with a series-parallel UPFC

In the case of reducing the voltage of the power supply to the value $E_0 = 1.0$ voltages $U_1 = 1.090 - j0.144$ and $U_3 = 1.016 - j0.234$ practically do not change.

However, in the case of a slight change in the imaginary voltage component of the series compensator $E_2 = -0.1 - j0.05$ the consumption of the active power of the parallel compensator increases sharply $I_1 = -0.362 - j0.671$, and in the case of changing the sign of the imaginary component $E_2 = -0.1 + j0.05$ the generation of active power increases sharply $I_1 = 0.239 - j0.678$.

Such instability limits the use of the series-parallel UPFC scheme.

4. UPFC modeling in dynamic mode

Fig. 9 shows the functional diagram of the control system [2], which is proposed to be used to control the UPFC.

A model with a three-phase non-linear load was used to simulate UPFC operation [3]. Characteristics of the elements of the experimental model: resistance of the power supply system 18.4+j17.1 mΩ, resistance on the direct current side of the non-linear load (three-phase rectifier) – $12 + j1.256$ Ω, resistance of a symmetrical three-phase load – $10 + j10$ Ω. An inductance connected in series with SSSC $L_{se} = 0.5$ mH, with STATCOM $L_{sh} = 0.4$ mH. Two capacitors connected in series: capacitance $C = 2500$ μF, voltage $u_{dc} = 325$ V, $u_{dcref} = 650$ V. Filter parameters that are enabled in parallel to each of the blocks $C_{se} = 47$ μF, $C_{sh} = 10$ μF. Power of transformers $T_{se} = 2.5$ kV·A, $T_{sh} = 2.5$ kV·A.

Fig. 10,a shows graphs of the rms value of the supply voltage, which varies with the coefficient $k = 1.1, 1.09 \ldots 0.9$. Source voltage 400 V (230 V – RMS voltage of one phase). Researches are carried out using three-phase series-parallel UPFC and parallel-series UPFC. After the research, it was found that both regulators behaved identically and the voltage change graphs coincided. The behavior of SSSC (Fig. 10,b) has a slight offset (230.7 V) relative to the actual voltage value of 231 V when the power supply voltage deviates. An increase in the voltage of the power supply practically does not affect the operation of the SSSC.

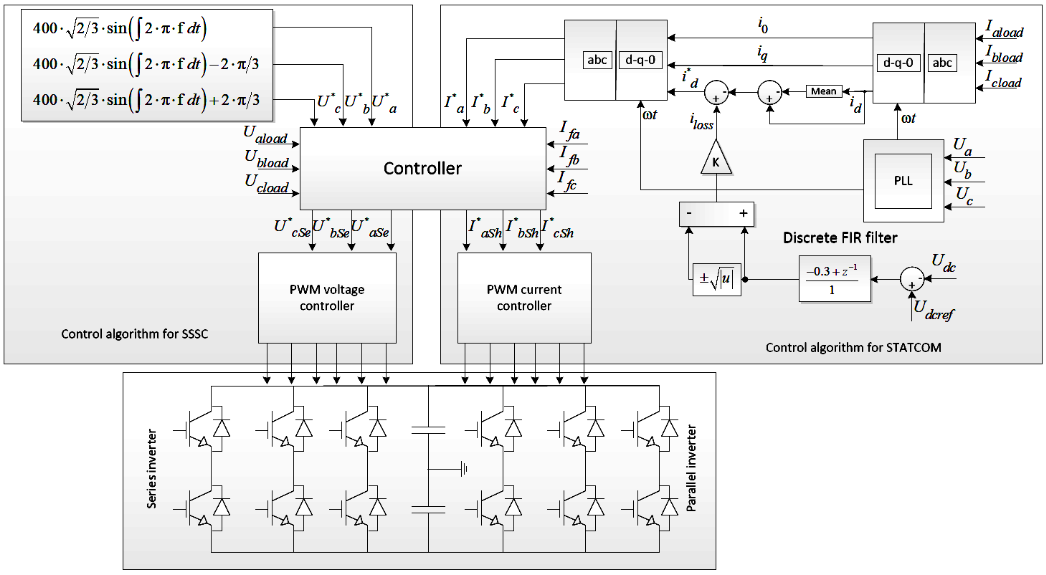

Fig. 9. Functional scheme of the UPFC control system

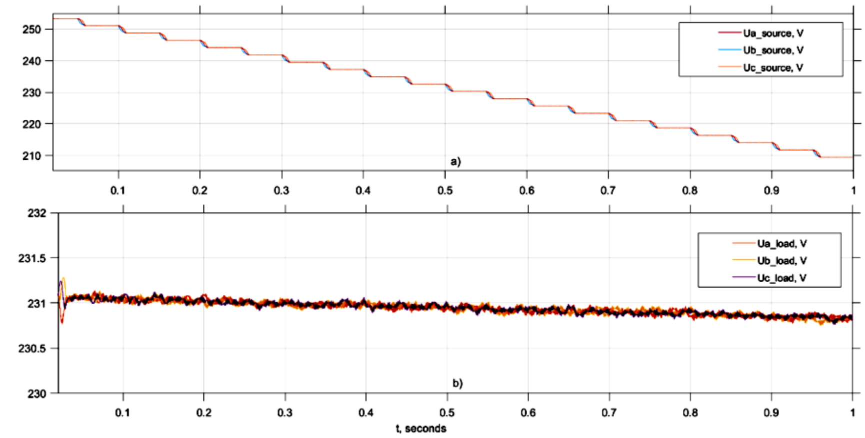

Fig. 10. The graph of the change in the rms value of the voltage: a) networks; b) loads

The graphs shown in Fig. 11a, b, c characterize, accordingly, the active P and reactive Q power of the power source, load and parallel compensator UPFC.

From these graphs, it is possible to determine: speed, power overshoot and the ability to compensate reactive power with UPFC.

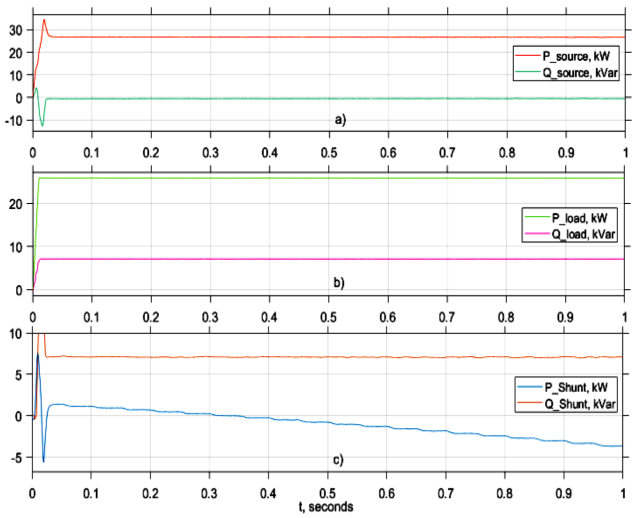

Fig. 11. The graph of the change in the rms value of the power: a) network; b) load; c) parallel compensator UPFC

The linearity of the power graphs depends on the power of the parallel transformer and the capacity of the DC storage capacitor. In case of an inappropriate setting, reactive power pulsation may occur.

The graph of the active power of the UPFC parallel compensator (Fig. 11c) shows the consumption of active power by the device at the coefficient $k = 1.1,\ 1.09 \ldots 1$ and its generation after reducing the input voltage coefficient to $k = 0.99,\ 0.98 \ldots 0.9$.

5. Conclusions

The behavior of STATCOM and UPFC has been demonstrated and the proposed control model has been verified under significant voltage disturbances at the load node of the electric network. STATCOM provides the fastest possible partial or full compensation of reactive power imbalance. However, at the same time, it is not possible to fully compensate for the reduction in voltage. A series-parallel or parallel-series UPFC can be used to solve this problem. As a result of using the UPFC, it is possible to automatically raise the voltage level to acceptable values with the help of the UPFC series compensator. The analysis shows that the parallel-serial UPFC is characterized by the stability of operation. In the case of using a series-parallel UPFC, there are restrictions on the ability to adjust the imaginary voltage component of the series compensator, since the angle of the voltage vector changes, which causes a failure in the operation of the regulator of the parallel compensator UPFC.

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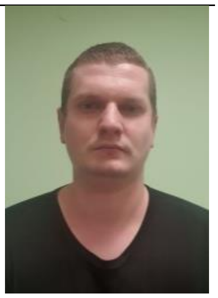

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