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Research of UPFC Influence on Control of Power System with Renewable Energy Sources

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***Abstract* – Power systems nowadays are becoming more complex, also with constantly growing electricity consumption. A new phenomenon of renewable energy sources connection into power system is also influencing the power system complexity. This paper deals with the possibilities of usage of software tools for power system studies in more complex way. The modeling of supplementary services in 39-bus of New England system is presented at the beginning of this paper. Also, the mutual interaction of renewable energy sources – offshore wind farm and UPFC was the subject of research. Advantages and disadvantages of such combination are presented in this paper.**

***Keywords* – UPFC, wind park, renewable energy sources, supplementary services, power system, PSLF.**

I. Introduction

Worldwide electricity consumption is constantly growing, and this fact is caused either by population or technology growth. During the last few years, due to technology efficiency improvements, and due to economic crisis, this growth is not so significant, but still, the worldwide consumption is growing. This enforces growth also on side of electricity production. Requirements on electricity transmission are therefore growing, but on the other side, standard way of building the new transmission lines is encountering some problems due to legislative or economic issues. This induces appearance of so-called bottlenecks in power system. Lines overloading and high risk of their cascading outages is appearing more and more often in such places in power system. Black-out is a word, which nowadays is very often mentioned together with all of these problems.

Interconnection of power systems and their mutual cooperation brings many advantages, from which the main is the mutual assistance during any outages, whether on the side of production or consumption. In the present time, some issues of such interconnection appeared, one example can be a liberalised electricity market, where we can see great differences between physical and market scheduled power flows. Such physical flows cause usage of free transmission capacities in certain areas, which have not induced such flows on the side of either consumption or production. Unplanned power flows are the main reason for bottlenecks appearance, in which transmission capacity is often exceeded. This is often happening on cross-border transmission lines, which were built mainly for mutual cooperation of neighbouring power systems during some outages. [2]

Also the topic of new renewable electricity source connection to the power system is very topical. Mainly large-scale wind parks and their connection are considered very problematic. It is caused mainly due to their unpredictability and sudden changes in produced power. Problems have appeared also due to their large installed power with central point of interconnection and rapid growth of their installed power. This induces problems with control of power system with such renewable sources implemented.

Such control problems can be detected and properly solved using a long term stability assessment. Supplementary services fall into the category of long-term stability. These services are purchased by transmission system operator (TSO) to fulfil system services in the power system, which serves to keep power system operation in limits of safe and reliable operation. To the group of most state-of-art methods of long-term stability improvement, belong specialized systems based on power electronics, so called FACTS devices. With their proper placement and regulation, high level of safety, reliability and quality of power system operation can be achieved.

These problems caused our motivation for long-term stability studies of power system with implemented renewable energy sources together with UPFC, the results of which are presented in this paper. This paper describes the possibilities of usage of such device for power flow regulation and therefore for improvement of supplementary and system services behaviour.[10]

II. Facts Devices

During the last few years, the new specialized devices based on power electronics and other passive and active elements (capacitors, reactors, or transformers), which provide the regulation of one or more parameters, such as current, voltage, impedance or phase shift, were developed. These specialized systems are known under abbreviation FACTS – Flexible AC transmission system.

These devices bring many advantages and possibilities for TSO. For example:

1. Power flow regulation, loop flows reduction,
2. Reliable interconnection of neighbouring power systems, and decreasing of needed electricity production on both sides,
3. Transmission capacity increase for existing lines to their limits without any other compensating devices,

4. Power system stability improvement, increasing static and transient stability limits, damping of generator electromechanical oscillations and decreasing of short circuit currents,
5. Reduction of a big shunt reactors and series capacitors and therefore reduction of space in power stations,
6. Compactness and modality of new FACTS systems allow their installation everywhere.

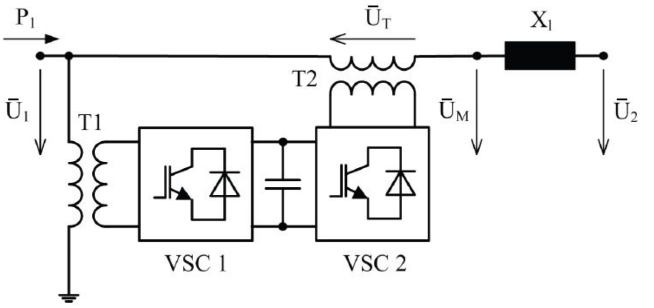


Fig. 1. UPFC schematic diagram [4].

These devices can be divided into four basic categories [7]:

1. Parallel regulators,
2. Serial regulators,
3. Combined serial-serial regulators,
4. Combined serial-parallel regulators.

According to these categories, different kinds of FACTS devices are known, such as, STATCOM (Static synchronous compensator), PST (Phase Shifting Transformer), SVC (Static VAR compensator), TCSC (Thyristor Controlled Series Capacitor), SSSC (Static Synchronous Series Compensator), UPFC (Universal Power Flow Controller), and we can also mention HVDC (High Voltage Direct Current) transmission system having also possibility of controlling real and reactive power, and is used to provide asynchronous connection between two power systems with e.g. different frequency. According to that which power can be regulated using such devices, we can divide them into three categories:

1. Reactive power regulation (SVC, STATCOM),
2. Real power regulation (TCSC, PST, SSSC),
3. Real and reactive power (HVDC, UPFC).

UPFC consists of parallel (excitation) and serial (auxiliary) transformer. Both transformers are connected through two VSC converters which are interconnected through mutual DC intermediate circuit with condenser. Serial converter injects AC voltage U_T (voltage on serial transformer) which can be according to the input voltage U_1 (on left side) freely rotated and can have amplitude freely set in the range from $0 \leq U_T \leq U_T$ max. Serial converter can therefore act in all four quadrants and independently control real and reactive power of line. Parallel converter can generate reactive current in way to keep voltage U_1 on set value. In this case, converter acts in voltage control mode. Parallel reactive current can also correspond to required inductive or capacitive reactive power, and therefore converter acts in reactive power control mode. Control parameters of UPFC are therefore amplitude and phase shift of injected voltage U_T and amplitude of reactive current Iq of parallel branch. This regulation possibility makes from UPFC most universal transmission device for both – real and reactive power regulation and control.[1]

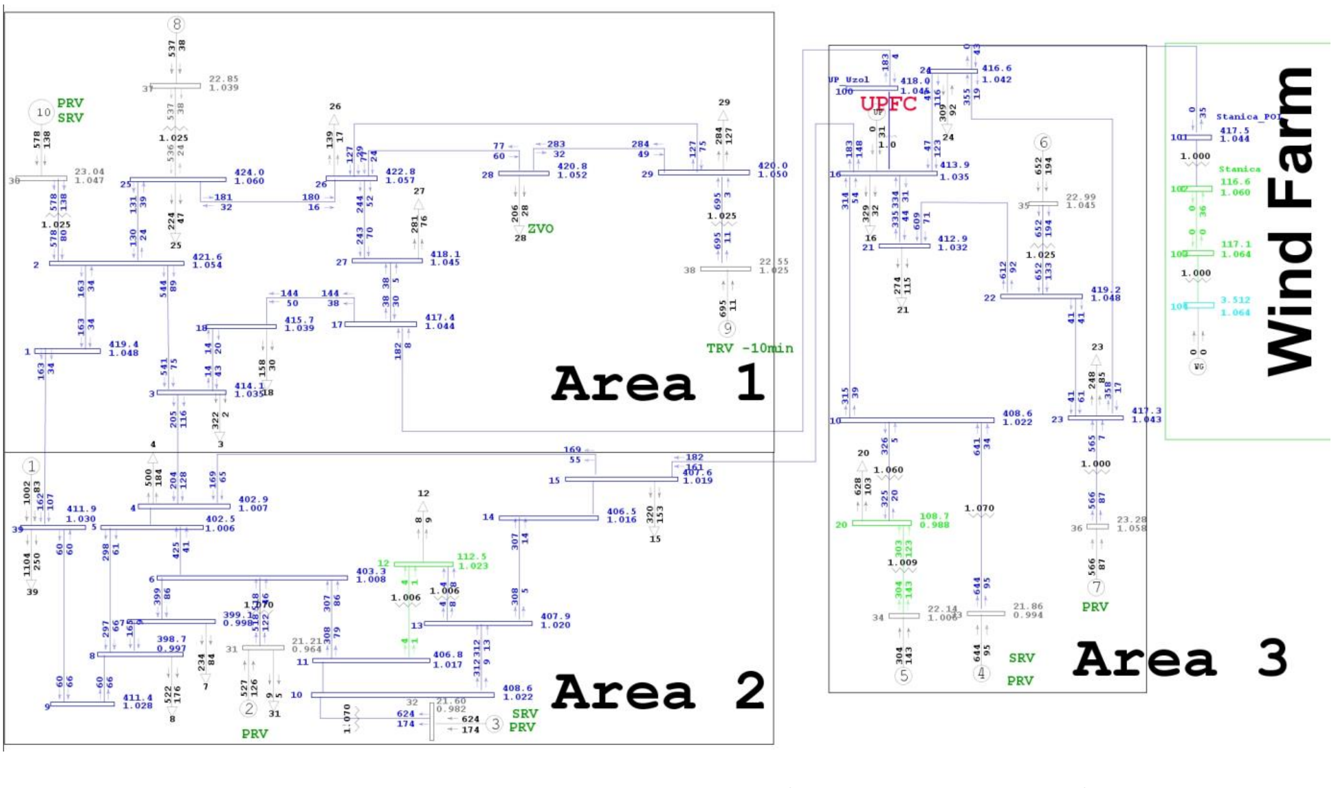


Fig. 2. 39-bus power system splitted to three areas with marked place of UPFC implementation and wind farm [5].

III. Modelled Power System

For the investigation of UPFC influence on power system, the 39-bus of New England power system was selected. This power system was divided into three areas, with generation and consumption almost in balance, mainly for possibility of primary and secondary power regulation investigation. All devices, like exciter, exciter regulation, power system stabilizer (PSS) and turbine with governor were modelled for all generators, presented in power system.

For purpose of power system modeling, a Positive Sequence Load Flow (PSLF) software was used, provided for authors by Slovak TSO – Slovenská elektrizačná a prenosová sústava (SEPS) in version 17.05.

In PSLF, the UPFC device is in load flow modelled by a transformer with variable tap ratio and phase shift and by a generator at the bus of line input, which supplies the reactive power for both the shunt and series converters, and also using „gcd" model, which presents power electronics device. For dynamic simulations, the UPFC is simulated script which acts as UPFC regulator, and controls series voltage injection and shunt MVAr injection into the network using current injections at input and output bus of UPFC. [6] [11]

As an addition to default 39-bus power system, an off-shore wind farm was modelled, using a single wind turbine with equivalent power as whole wind farm of 200 MVA, and it is equal to 50 machines with installed power of 4 MVA. The DFAG configuration of wind generator was chosen. Produced power from this wind park has to be transported using 30 km submarine cable. Cable parameters were selected according to a real cable, produced by ABB. Voltage level of connected generator was 3,3 kV, then the power was transformed to 110 kV voltage level, and on shore, power was again transformed to voltage level 400 kV and connected into the bus 24.

IV. Dynamic Models and Regulators

In addition to models, which are essential for short-term transient stability modeling, also other models which are representing primary and secondary power/frequency regulation are used. In the process of creating of the model, such models were added for some generators in each control area. For primary power/frequency control were selected these machines:

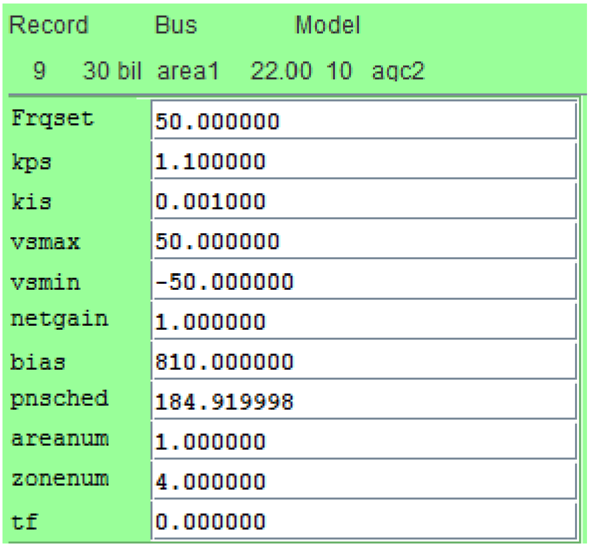
- Area 1 – Generator 10,
- Area 2 – Generator 2, Generator 3,
- Area 3 – Generator 4, Generator 7.

The size of primary power reserve has to be in each area at least equal to installed power of generator with higher installed power, which is in the generator 1 MW – 1 000 MW. Used turbine model of such generators has implemented primary power/frequency regulator. For machines, which are not connected to this control, part of model has to be switched off. Proper functionality of such regulation was tested using simulation, during which the load connected to the bus No. 3 with consumption of $S = (322 + j2.4)$ MVA was disconnected after 20 seconds of simulation. After disconnecting of this load, the frequency began to rise, but after proper regulatory intervention the frequency was stabilised on the value of transient deviation Δf_D = 145.7 mHz after 25 seconds. This is shown in smaller image in Fig. 5. From value of such deviation, and real power deviation, an area frequency response characteristic for whole 39-bus system can be calculated using formula (1):

$$\lambda_{PS} = \frac{\Delta P}{\Delta f} = \frac{322\ \text{MW}}{0.1457\ \text{Hz}} = 2210\,\frac{\text{MW}}{\text{Hz}}, \qquad (1).$$

Secondary power frequency control is in PSLF implemented through two models in pair. Central regulator for each control area was implemented through model "agc2". Then, the "uclp" model was added for each generator, which was supposed to be connected in secondary power frequency control. In each control area, one of the generators was selected to supply the secondary power reserve:

- Area 1 – Generator 10,
- Area 2 – Generator 3,
- Area 3 – Generator 4.


Record Bus Model

9 30 bil area1 22.00 10 agc2

Frqset	50.000000
kps	1.100000
kis	0.001000
vsmax	50.000000
vsmin	-50.000000
netgain	1.000000
bias	810.000000
pnsched	184.919998
areanum	1.000000
zonenum	4.000000
tf	0.000000

Fig. 3. Area 1 central regulator settings.

After selecting the proper models, there was such an issue to set up secondary regulators properly. After the number of simulations, finally proper settings were obtained. First value for regulator setting was a *frequency*, which was set to default 50 Hz. Value of *netgain* was set to 1. Using *areanum* and *zonenum*, regulated generators were selected. Value of *pnsched* was set according to power flow results. Values of *vsmin* and *vsmax* are representing limits for output of scheduled change of real power, and were set to ± 50 MW. Most important, and also harder to obtain were the values of proportional and integral gain of PI regulator. After such simulations, the best behaviour of PI regulator was obtained using $kps = 1.1$ and $kis = 0.001$. The last value, which has to be set, was the value of *bias*, which represents the gain of frequency deviation. This value according to [9] has to be set according to the frequency response characteristic. This value for the whole 39-bus system is given with formula (1). By simplification we can consider, that for each area (since we divided areas in the way that each would have almost the same generation and consumption value) the value of frequency response characteristic will be one third of frequency response characteristic for 39-bus power system. Bias value is then given by:

$$bias = \frac{1.1\lambda_{PS}}{3} = \frac{1.1 \cdot 2210\ \text{MW/Hz}}{3} = 810, \qquad (2).$$

Output control value of regulator is given with the next formula:

$$\Delta P_D = -kps.ACE - kis\int ACE.dt, \qquad (3).$$

After the proper tuning of regulator, the simulation was performed to verify regulator settings. Simulation time was set to 15 minutes, because until that time, secondary power frequency control has to finish its regulatory intervention until 15 minutes. Like in previous simulation, after 20 seconds, the load in bus No. 3 was disconnected, with the same value as mentioned above. After the frequency stabilization by the action of a primary power frequency control, a secondary power frequency control corrected the frequency to almost pre-fault value f = 49.994 Hz. Also, power flows through the lines has reached their pre-fault values, and power balance has reached pre-fault value at about the 3rd minute of simulation.

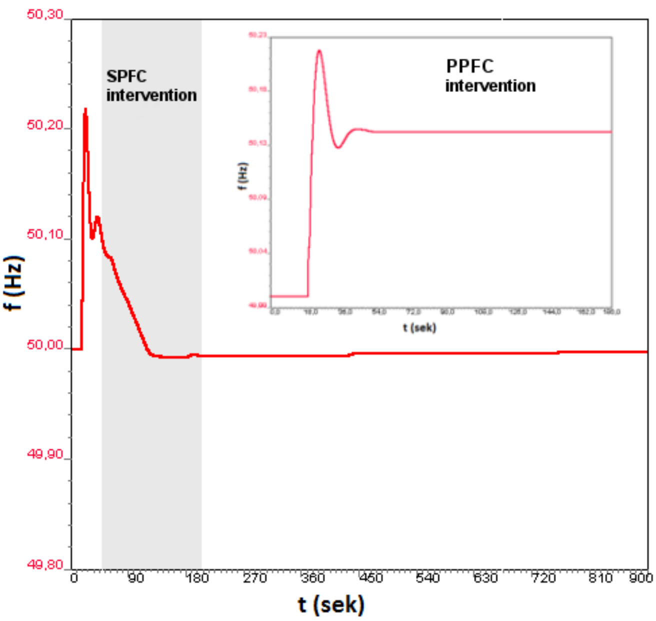


Fig. 4. Simulation results from testing of primary and secondary power frequency control behaviour (smaller image – primary power frequency control behaviour).

Since these regulations were working properly, UPFC (which consists of five models, as shown in TABLE I) with regulator was then implemented into the power system.

TABLE I

UPFC MODELS USED IN PSLF

UPFC	**Basic models**	GEN (generator)
		TR (transformer)
		GCD
	Dynamic models	UPFC
		EPCmod

Due to a great complexity of setting of all of these models, we will not provide all details about settings, which are given in [8].

Together with the UPFC, the wind farm was also added to the power system, together with its dynamic models, which are displayed in TABLE II.

TABLE II

WIND GENERATOR MODELS USED IN PSLF

WG	**Basic models**	GEN (generator)
	Dynamic models	gewtg
		exwtge
		wndtge

After taking all of these steps, a simulation of wind farm and UPFC influence on power system control was performed, results of which will be presented in the next chapter.

V. SIMULATION OF UPFC AND WIND FARM INTERACTION

Simulation of wind farm connection into the power system was performed during 8 minutes (480 seconds). Produced power of wind farm at the moment of connection was set to 180 MW. Produced power depends on wind speed, so using initial conditions table in PSLF, several times during the simulation, sudden change of wind speed was simulated, by changing value of Glimv parameter, which represents the wind speed in ms^{-1}. The minimal wind speed, on which a minimal power was produced, was 3 ms^{-1} which corresponds to 8 MW. The maximal wind speed, exceeding which the wind farm was considered to be disconnected was set to 25 ms^{-1}. The maximal power of wind farm was 200 MW. After the 450 seconds of simulation, a wind has exceeded the maximum speed and the wind farm was disconnected. The wind speed and produced power of wind farm during the simulation is shown in Fig. 5.

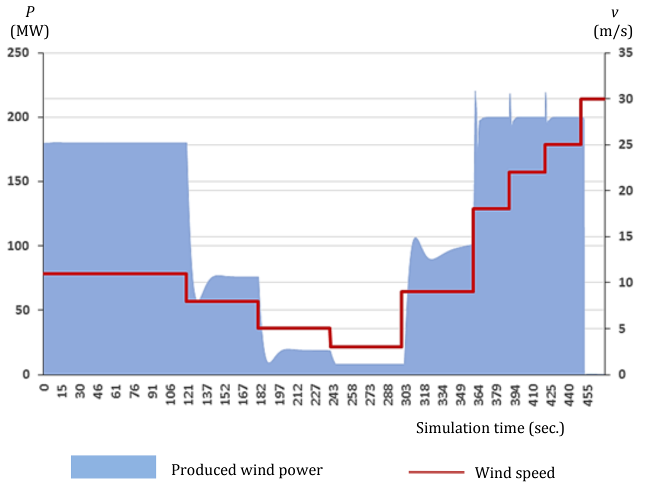


Fig. 5. Produced wind power dependence according wind speed.

The primary and secondary power/frequency control reacted on changes of produced power by the wind farm. Especially, generator No. 4 was supposed to react on these changes, by decreasing its produced active power to keep the balance of produced and consumed active power in control area, as it can be observed in Fig. 6.

On the cross-border line between area No. 1 and 3 the UPFC device was installed. This device was keeping transferred active power on set value of 183 MW. As it can be observed from Fig. 7, this power flow has not changed even during connecting of wind farm or during changes of wind produced power. Such changes in power balance induced a few oscillations, the largest one during disconnecting of wind farm caused by high wind speed. This has shown that UPFC has positive influence on power system stability and reliability. It is improving the transfer capability of power line, and balancing the power transmission between other transmission lines, so no cross-border line is overloaded. In [8], also the UPFC influence on active power losses in power system is presented; where positive, but also negative influence of such regulation is shown – by inserting of higher impedance into transmission line, amount of active power loses are growing.

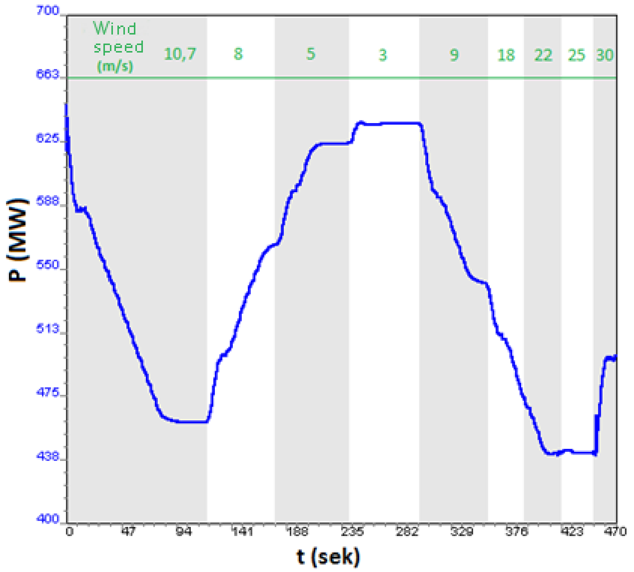


Fig. 6. Produced active power of wind generator No. 4 in area No. 3.

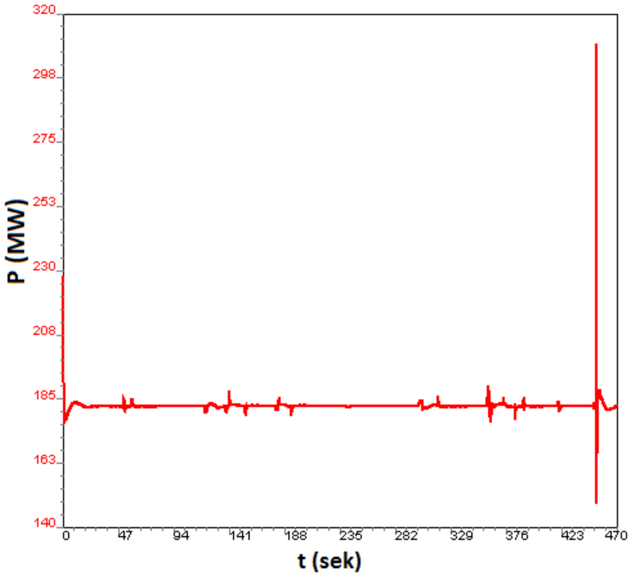


Fig. 7. Active power flow through UPFC device during simulation.

VI. Conclusion

1. Current state of interconnected power system induces need for effective analysis and search for new solutions. Simulation software is providing best solution for research of interconnected power systems. There are few types of simulation software, which are able to provide simulations of large-scale power systems with many elements. This paper has shown possibilities of usage of such software – PSLF.

2. Modeling of supplementary and system services is also an important task, which can help to detect and solve such issues in power system. Their study is very important in connection with renewable energy sources in different scenarios of prediction of their share on installed or produced power, during different weather conditions, and in various configuration of power system during outages, fault in different places in power system. In this paper such example of primary and secondary power/frequency control implementation into model and simulation of their behaviour is shown. [12]

3. Simulation of mutual interaction of wind farm and UPFC has shown that a power system can handle connection of new source with installed power of 200 MVA, but instability and unpredictability of wind farm have a negative influence on power system stability. Sources, which are providing primary and secondary power frequency control has to react on sudden and large changes of wind farm produced power. That means that such power system should have large power reserves. On the other hand, simulation has proven that using the UPFC device; scheduled power flow can be easily kept on cross-border line. Only few oscillations were observed on power flow through the UPFC, due to sudden changes of wind farm produced power. Sizes of oscillations were proportional to size of wind farm produced power. If the UPFC device will be implemented on both cross-border lines from area No. 3, any change of produced power will influence only the area No. 3. This can have positive, but also negative influence – quick mutual cooperation during faults can become more complicated. But this problem can be solved by using a proper control algorithm of the UPFC. [3]

4. As mentioned above, the UPFC is the most universal transmission device for both – active and reactive power regulation and control. But on the other hand this has large disadvantage – complexity of UPFC is reflected in the price of such device, which consists of price of two large transformers, and two high power AC/DC converters. Price of such device is the main reason for such a few installations in the whole world. But large advantages of UPFC are significant.[13]

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