FLEXIBLE CONTROL OF THE EXPORT POWER FLOWS BY USING DC LINK

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The functional possibilities of modern direct current (DC) links for a power system control have been considered. The organization structure of the load frequency control in the interconnected power system of Ukraine is proposed in case of DC link construction near Khmelnitskaya nuclear power plant. The simulation results are shown in the event of the generating unit disconnection at Burshtyn thermal power plant. It is established that DC link connection to the active power controller of "Burshtyn island" allows providing the flexible control of the export power flows in alternating and direct current networks. References 10, table 1, figures 5.
Key words: frequency, power flow, direct current link, automatic generation control, interconnected power system, simulation.

Widespread implementation of the modern technologies such as flexible alternating current transmission systems and direct current (DC) links in the power systems creates new opportunities in power system control [1-3]. Alongside with providing the active power transmission, the modern DC links enable the oscillations damping [3], a participation in the automatic load-frequency control [4], power system restoration after the blackout [5]. In recent years the installed capacity of offshore wind farms (e.g. in Northern Europe countries) has been significantly increased. In order to provide evacuation of the generation power from these windfarms, the multi-terminal DC links may be used in the future. They will provide the flexible power flow control in DC and alternating current (AC) networks [6]. Besides, the multi-terminal hybrid network interconnection will be used as a component of the future SuperGrid that will allow transmitting the electricity from the remote renewables to the consuming centers and expanding European energy market [7].

Taking into account the DC technologies development and SuperGrid formation, the research of the interconnected power system (IPS) of Ukraine operation considering increase of the export power flows is important. Nowadays, the electricity from IPS of Ukraine to European Network of Transmission System Operators for Electricity (ENTSO-E) is exported from so named "Burshtyn island" and Dobrotvorskaya thermal power plant (TPP).

In Ukraine, the activities are held to provide the synchronous operation of IPS with ENTSO-E [8]. One of the cases of the export power flow control is a DC link application. The electricity exporters in Ukraine are also interested in DC link construction. Compared to the old-fashioned 800 kV DC link Volga hydroelectric power plant (HPP) – "Mikhailovskaya" substation, the modern DC links provide the flexible control of IPS operation. In particular, including a DC link in the "Burshtyn island" interface in most cases will provide a reliable schedule implementation to ENTSO-E and will increase the reserve capacity at Burshtyn TPP.

The aim of the paper is to research the DC link operation in the event of the generation decreasing in "Burshtyn island" (e.g. generating unit disconnection). To implement it the detailed model has been developed, which includes the automatic power controller at Burshtyn TPP, border areas of IPS and ENTSO-E as well as the automatic generation control (AGC) in IPS of Ukraine.

Let us consider one of the cases of the frequency control organization in IPS of Ukraine (Fig. 1). Nowadays IPS of Ukraine is divided in two control areas. One of them operates synchronously with unified power system (UPS) of Russia while the second one ("Burshtyn island") is connected to ENTSO-E. The planning DC link with the rated capacity 600 MW may be installed nearby Khmelnitskaya nuclear power plant (NPP).

In Fig. 1, the following notations are indicated: DbTPP is Dobrotvorskaya TPP; KhmNPP is Khmelnitskaya NPP; BuTPP is Burshtyn TPP; DnHPP-1 is Dneprovskaya HPP-1; ZU is 750 kV "Zapadnoukrainskaya" substation; AGC IPS is the automatic generation control of IPS of Ukraine; APC is the automatic power controller of «Burshtyn island».

The input signals of the national AGC are the frequency in IPS of Ukraine f_{IPS} and tie line interchanges $P_{f,i}^{IPS}$ with UPS of Russia and IPS of Belarus. The AGC controls the net interchange power and the frequency. Based on these signals the proportional integral (PI) controller generates the control signal $P_{ref}^{DnHPP-1}$ transmitted to the regulating units of Dneprovskaya HPP-1. The automatic frequency control organization in IPS operating synchronously with UPS of Russia and IPS of Belarus as well as the operation algorithm and mathematical models of the national AGC (at the system, power plant and aggregate control levels) are considered in detail in [9]. It should be noted that AGC of Russia, which generates a control signal to the regulating Volga HPP, is also considered in the model but not shown in Fig. 1.
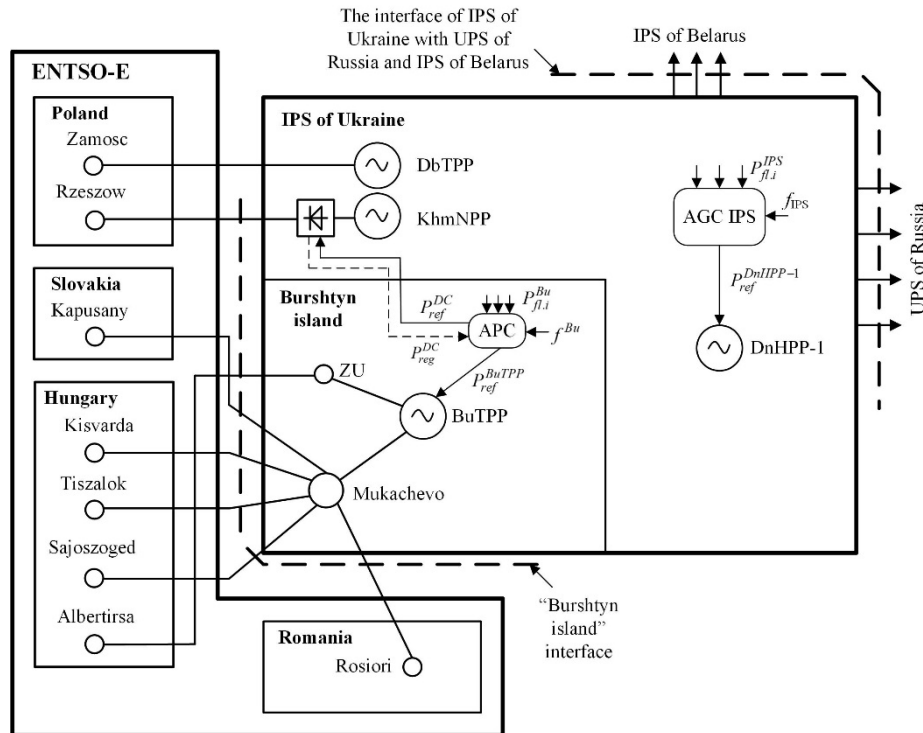

Fig. 1

The automatic power controller of "Burshtyn island" also regulates the export net interchange power with the frequency correction. The input singals of the controller are the current frequency f^{Bu} and tie line interchanges $P_{f,i}^{Bu}$ at "Burshtyn island" interface including: DC link Khmelnitskaya NPP – Rzeszow; OHL 750 kV ZU – Albertirsa; OHL 400 kV Mukachevo – Sajoszoged, Mukachevo – Kapusany; Mukachevo – Rosiori; OHL 220 kV Mukachevo – Kisvarda, Mukachevo – Tiszalok. The island control error (ICE) calculated in APC is defined as follows

$$ICE = \left(P_{net}^{Bu} - P_{net\,ref}^{Bu} \right) + K_{bias} \left(f^{Bu} - f_{ref}^{Bu} \right),$$

where P_{net}^{Bu} is the current net interchange power of "Burshtyn island", $P_{net}^{Bu} = \sum P_{f,i}^{Bu}$; $P_{net\,ref}^{Bu}$ is the reference net interchange power setpoint; K_{bias} is the frequency bias; f^{Bu} is the current frequency in «Burshtyn island»; f_{ref}^{Bu} is the reference frequency setpoint.

On basis of *ICE* the control signal P_{ref}^{APC} is calculated in APC as well as its components transmitted to Burshtyn TPP P_{ref}^{BuTPP} and control system of DC link P_{ref}^{DC} (Fig. 1). The components of the signal P_{ref}^{APC} are distributed in such a way that

$$P_{ref}^{APC} = P_{ref}^{BuTPP} + P_{ref}^{DC}.$$

It should be noted that the distribution of these components depends on relation of the control signal P_{ref}^{APC} and control range of DC link P_{reg}^{DC}:

If $P_{reg}^{DC} = P_{nom}^{do} - P_{ref}^{DC} > P_{ref}^{APC}$ **then** $P_{ref}^{DC} = P_{ref}^{APC}$

otherwise $P_{ref}^{DC} = P_{reg}^{DC}$,

$$P_{ref}^{BuTPP} = P_{ref}^{APC} - P_{reg}^{DC}, \qquad\qquad P_{Gi}^{BuTPP} = \alpha_i P_{ref}^{BuTPP},$$

where P_{nom}^{dc} is the rated capacity of DC link; P_{ref}^{DC} is the reference active power setpoint of DC link defining the current power flow; P_{Gi}^{BuTPP} is a control signal transmitted to the governor of the *i*-regulating unit of Burshtyn TPP, *i*=1,…,6; α_i is the participation factor of *i*-generator in the secondary frequency control, *i*=1,…,6.

The proposed approach provides the following active power transfers. If the current control range of DC link allows transmitting all unscheduled power calculated in APC of "Burshtyn island" then DC link power flow is changed by P_{ref}^{APC}. Otherwise, the DC link power flow will be changed partially (considering the current control range) and the remaining part of P_{ref}^{APC} signal will be distributed among the regulating units of Burshtyn TPP. It should be noted that the proposed algorithm is one of the possible ones. For example, the regulating units of Burshtyn TPP can be used to compensate small active power fluctuations caused by the load variations. Besides, in the APC operation algorithm the export net interchange power also must be considered. Taking into account that at present time the active power is mainly exported to Hungary, the increase of the DC link power flow will increase the loading of the border area networks in Poland and Slovakia. Thus, the dynamic characteristics of DC link, the regulating units of Burshtyn TPP as well as the export schedule must be considered in the APC operation algorithm.

The developed model also includes the 750-220 kV border area network models of Central European countries: Poland, Slovakia, Hungary and Romania that allows researching the DC link impact on the network operation. Besides, in the model the control system of DC link is considered, shown in Fig. 2 [10].
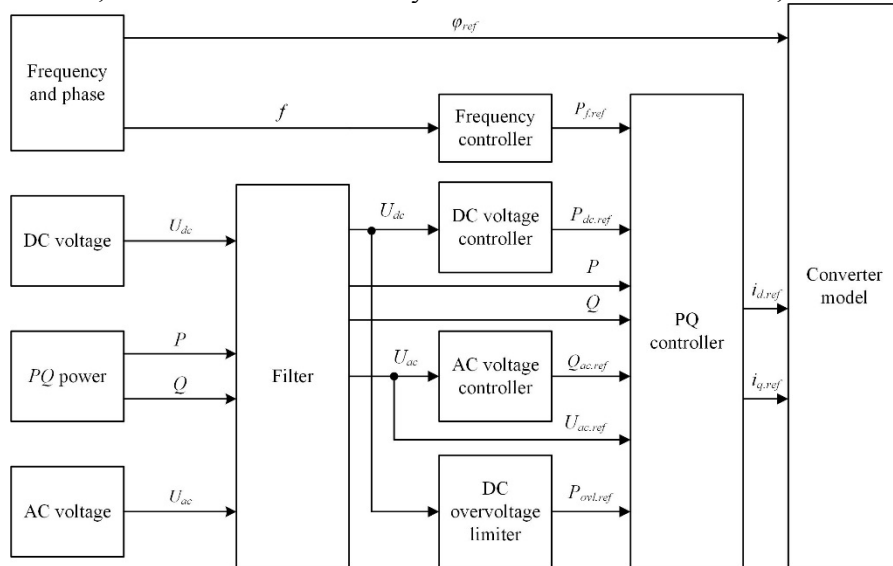

Fig. 2

The input signals of the DC link control system model are the current frequency *f* in the power system, the angle φ_{ref} at the reference busbar, the direct U_{dc} and alternating current U_{ac} voltages as well as the active *P* and reactive *Q* powers (Fig. 2). As seen in Fig. 2, the input signals of the filter used to smooth the signals are U_{dc}, U_{ac}, *P* and *Q*. The output signal of the frequency controller is the active power reference value $P_{f.ref}$ proportional to the frequency deviation of the current frequency *f* from its reference value f_{ref}:

$$P_{f.ref} = K_f(f - f_{ref}),$$

where K_f is the gain factor of the frequency channel.

The DC voltage controller generates the active power setpoint $P_{dc.ref}$ in DC circuit which is calculated as follows:

$$P_{dc.ref} = K_{U_{dc}}(U_{dc} - U_{dc.ref}),$$

where $K_{U_{dc}}$ is the gain factor in DC voltage channel.

The reactive power control in AC circuit is performed by the AC voltage controller, which generates the reactive power reference set point $Q_{ac.ref}$:

$$Q_{ac.ref} = K_{U_{ac}}(U_{ac} - U_{ac.ref}),$$

where $K_{U_{ac}}$ is the gain factor in AC voltage channel; $U_{ac.ref}$ is the AC voltage reference set point.

In order to prevent the overvoltage in DC network, the overvoltage limiter model is also used. The output signal of the PI controller of the limiter is the signal $P_{ovl.ref}$:

$$\Delta U_{dc} = U_{dc.ref}^{max} - U_{dc},$$

$$P_{ovl.ref} = K_P^{out} \Delta U_{dc} + K_I^{out} \int_{t_1}^{t_2} \Delta U_{dc} dt,$$

where ΔU_{dc} is the deviation of the current DC voltage U_{dc} from the maximum voltage set point $U_{dc.ref}^{max}$; K_P^{out}, K_I^{out} are the gains of the proportional and integral links of the overvoltage limiter controller; t_1, t_2 are the integration limits.

As seen in Fig. 2, the *PQ* controller generates the reference currents $i_{d.ref}$ and $i_{q.ref}$ in *dq*-components proportional to the active and reactive power. Further, the reference signals $i_{d.ref}$, $i_{q.ref}$ as well as φ_{ref} are transmitted to the current controller of the converter.

Thus, the detailed model has been developed including the automatic power controller of "Burshtyn island", AGCs of IPS of Ukraine and UPS of Russia [9], DC link control system [10] and ENTSO-E border area models as well.

The frequency control simulation is performed in the event of generating unit disconnection (at the moment *t*=15 sec) with the loading 176,7 MW at Burshtyn TPP. The simulation results are presented in Fig. 3−5. In the initial load flow, the total generation power of Burshtyn TPP is 1570,2 MW. The DC link and six generators of Burshtyn TPS are connected to APC of "Burshtyn island". The reference setpoint of the DC link power flow is 300 MW (Fig. 4, *a*).
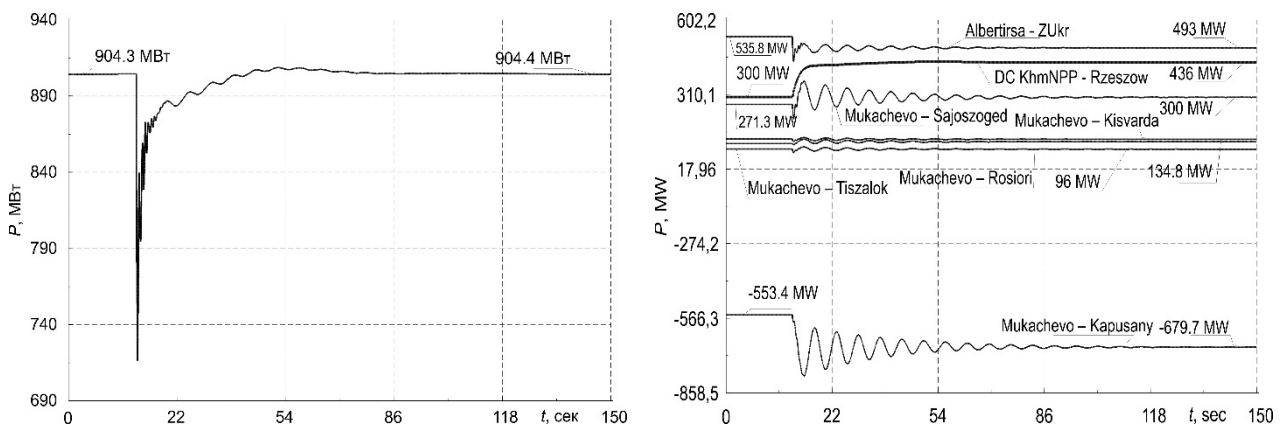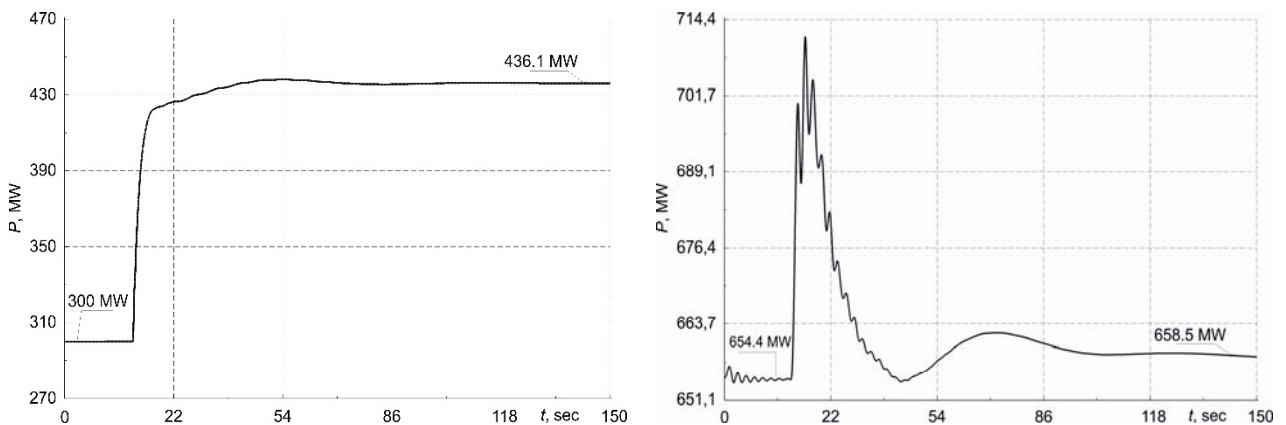

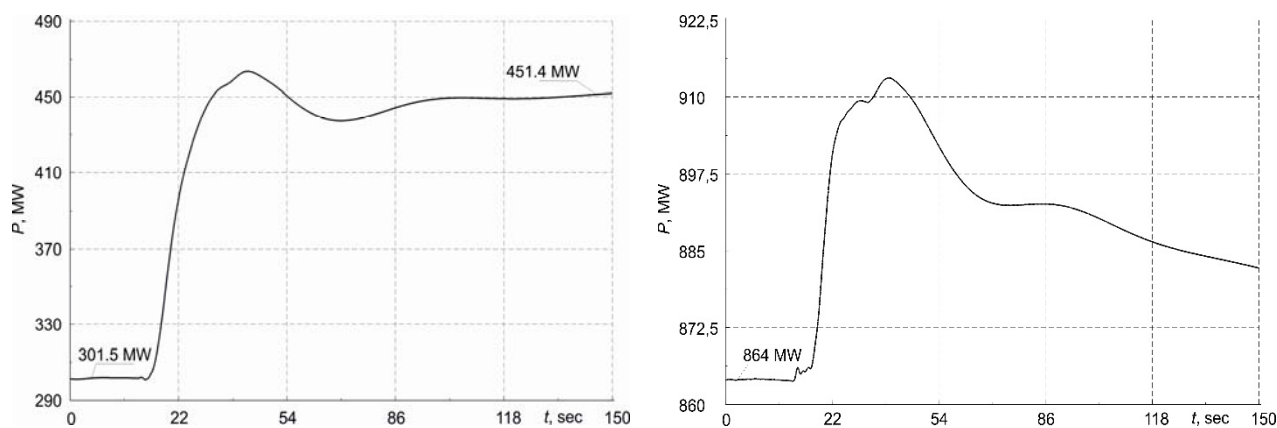**Fig. 3,** *a, b*

Fig. 4, *a, b*

Fig. 5, *a, b*

At the initial time the generating unit disconnection results to the net interchange power deviation at "Burshtyn island" interface from its reference value (Fig. 3, *a*). As the control range of DC link P_{reg}^{DC} (300 MW) is sufficient to transmit the additional power (Fig. 4, *a*), the APC controller generates the signal P_{ref}^{APC} transmitted to DC link control system. In this case, during the secondary frequency control the generation power of the units at Burshtyn TPP must not be deviated. As shown in Fig. 3, *a*, the increasing of DC link power flow allows restoring the net interchange power at "Burshtyn island" interface. Besides, the DC link power flow change also affects the power transfer of other OHLs (Fig. 3, *b*). For example, the increasing of the DC link power flow results to the loading increase of 440 kV OHL Mukachevo – Kapusany. The further development of detailed ENTSO-E border area models will allow researching the DC link impact on European network operation.

At the same time, in IPS of Ukraine operating synchronously with UPS of Russia and IPS of Belarus, the change of the DC link power flow results to the deviation of the net interchange power of IPS of Ukraine (Fig. 4, *b*). As the net interchange power has deviated from its set point value, AGC of IPS generates a signal $P_{ref}^{DnHPP-1}$ transmitted to the regulating Dneprovskaya HPP-1 (Fig. 5, *a*). Besides, Volga HPP also reacts on the frequency deviation (Fig. 5, *b*). As the generation power of Dneprovskaya HPP-1 increases during the secondary control, the generation power of Volga HPP decreases to its initial value.

As seen in Fig. 3, *a*, after the secondary frequency control the net interchange power at "Burshtyn island" interface is restored at its reference value. The power flow of DC link has changed by 136,1 MW meanwhile the generation power of Dniprovskaya HPP-1 is increased by 149,9 MW (Table).

Element	Active power, MW		
	The initial load flow	The load flow after the secondary control	Power change
Generation			
Burshtyn TPP	1570,2	1405,9	-164,3
Dniprovskaya HPP-1	301,5	451,4	149,9
Power flows			
DC link KhmNPP - Rzeszow	300	436,1	136,1
Net interchange power of "Burshtyn island"	904,3	904,4	0,1
Net interchange power of IPS of Ukraine with UPS of Russia and IPS of Belarus	654,4	658,5	4,1

Thus, modern DC link application allows providing a flexible control of the export power flows in AC/DC hybrid power systems to control the reserve capacity of Burshtyn TPP. Due to the active power flexible control by modern DC link, it becomes possible to use the secondary reserves controlled by the national AGC for "Burshtyn island".

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ГНУЧКЕ КЕРУВАННЯ ЕКСПОРТНИМИ ПЕРЕТОКАМИ З ВИКОРИСТАННЯМ ВСТАВКИ ПОСТІЙНОГО СТРУМУ

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Розглянуто функціональні можливості сучасних вставок постійного струму (ВПС). Запропоновано структурну схему організації автоматичного регулювання частоти в об'єднаній енергосистемі України у разі спорудження ВПС біля Хмельницької атомної електростанції. Наведено результати моделювання для випадку відключення енергоблоку на Бурштинській тепловій електростанції. Встановлено, що підключення ВПС до автоматичного регулятора потужності «Бурштинського острова» дозволяє забезпечити гнучке керування експортними перетоками в мережах змінного та постійного струмів. Бібл. 10, табл. 1, рис. 5.
Ключові слова: частота, переток потужності, вставка постійного струму, система автоматичного регулювання частоти потужності, об'єднана енергосистема, моделювання.

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ГИБКОЕ УПРАВЛЕНИЕ ЭКСПОРТНЫМИ ПЕРЕТОКАМИ С ИСПОЛЬЗОВАНИЕМ ВСТАВКИ ПОСТОЯННОГО ТОКА

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Рассмотрены функциональные возможности современных вставок постоянного тока (ВПТ). Предложена структурная схема организации автоматического регулирования частоты в объединенной энергосистеме Украины для сооружения ВПТ возле Хмельницкой атомной электростанции. Приведены результаты моделирования при отключении энергоблока на Бурштынской тепловой электростанции. Установлено, что подключение ВПТ к автоматическому регулятору мощности «Бурштынского острова» позволяет обеспечить гибкое регулирование экспортными перетоками в сетях переменного и постоянного токов. Библ. 10, табл. 1, рис. 5.
Ключевые слова: частота, переток мощности, вставка постоянного тока, система автоматического регулирования частоты и мощности, объединенная энергосистема, моделирование.