Assessment of the Primary Load-Frequency Control Operation by Considering the Effect of Photovoltaic Power Plants

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Abstract — **In this paper, the influence of different volume of power installed in the Photovoltaic Power Plant on the support service activity is simulated on the power system mathematical models and it analyses the impacts on their quality and reliability.**

Keywords: component; formatting; style; styling; insert (key words)

I. Introduction

To ensure stable operation of the power system, Transmission system operator (TSO) regulates power on sources according to instantaneous consumption in a system that is partly predictable but enters the control as unknown. The current rapid development of renewable energy sources, and particularly of photovoltaic power plants (PPP), has caused the system to increase the proportion of installed power whose entire capacity must be redeemed and delivered to the grid. The problem of the increase in RES is the lack of electricity supply compared to conventional energy sources. PPPs energy supply is partly predictable (past year statistics from the same period, weather forecasts, etc.) but due to variable weather, the performance of PPP is changing considerably, causing a disruption to the power balance of electricity generation. This phenomenon has a detrimental effect on network management capabilities and increases the demand for support services and reserves held on conventional sources. In this paper, the influence of different volume of power installed in the PPP on the support service activity is simulated on the power system mathematical models and it analyses the impacts on their quality and reliability. In this paper, the influence of different volume of power installed in the PPP on the support service activity is simulated on the power system mathematical models and it analyses the impacts on their quality and reliability.

Support for the development of renewable energy sources brought an increased in the share of PPP in the total installed capacity, which currently (September 2018) accounts for about 4.0% of the total installed capacity of the SR. This value is about 660 MW of installed power in solar panels.

Specifically, the characteristic feature of PP is their daily production of electricity, which, when neglected by mechanical contamination of the panels, is directly proportional to the intensity of the solar radiation. On bright summer sunny days, when PPP output is maximal, the power-delivery curve has a characteristic course with an exponential increase from about 5:00 in the morning, with a peak at around 13 o'clock and an exponential drop to zero at around 22 o'clock (Fig. 1). The power output curve is smooth with no sharp changes. In case of variable weather conditions (cloud transition over the PPP area), the power delivered varies in the order of tens of percent of installed power. These weather conditions are applied in MODES as different sets of block parameter type parameters - power source for the PPP model. The analysis of the output power of the two PPP systems on clear and cloudy days is according to [49] in Fig. 1. This is the performance of the 24-hour performance on the two PPP systems installed on different places in Slovakia. The installed PPP performance was, according to [49], 550 MW for PPP1 and 150 MW for PPP2. The performance of the PPP has been chosen to represent the relative share of the PPP in the installed power equivalent to the actual share of the PPP in the power system of Slovakia. The source type parameters were set for the summer day for sunny and cloudy day.

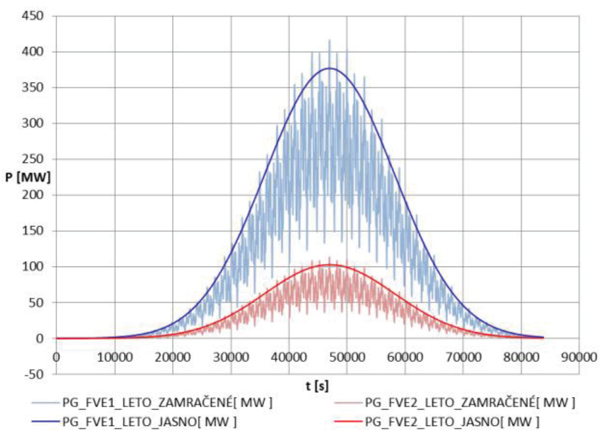

Figure 1 The generation during a clear and cloudy day [2]

Comparing the two power source models for PPP, there is a significant fluctuation in the delivered power from the PPP over time on a cloudy day. These changes are caused by the transition of the cloud, which changes the intensity of the solar radiation and consequently the delivered power from the PPP. The change in the delivered power causes a change in the frequency variation and the transmitted power in the system that activates the Primary frequency reserve PFR and thus changes the deviation of the cross-border profile. The high share of PPP in the power system thus imposes increased demands on support services and on the power reserves that need to be maintained for the proper functioning of these frequency restoration reserves.

The content of the following part of paper will examine the impact of RES (in this case, we will only talk about PPP for their characteristic dependence on electricity production and the high share of RES. Wind power plant can be neglected in this case for their minimum production share in Slovak power system).

II. Impact of RES on the dynamics of Power system of SlovakiA

The aim of the paper is to analyze the process of activation and activity of the PFR on the power system of Slovakia. For the purposes of modeling, the system was modified and supplemented by other lines and nodes in the surrounding TSOs to ensure the maximum possible value of the output data from the model based on available input data.

The system is monitored by PFR activity, which is activated during modeling of long-term dynamics (24h). The impact of PPP is modeled on several levels. The primary task is to compare the quality of PFR in case of favorable and unfavorable weather conditions. Subsequently, the share of production from PPP will be increased in an effort to model the impact of PPP on the system and PFR according to the forecasted development of renewable energy sources and to determine the anticipated boundary of the PPP share for reliable operation and quality of PFR in the power system.

A. Modificated model of Slovak power system

The PS SR system model was created in MODES program. All parameters of the main network elements as well as the dynamic parameters of the control elements use approximated data. From the available data, the selected parameters of the main transmission system elements were imported into the MODES program

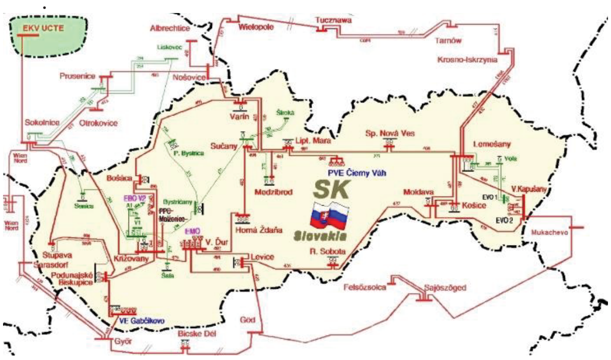

Figure 2. Modified model of Slovak power system

In order to achieve the most accurate dynamic results, the system model was supplemented with nodes and branches of neighboring countries (the so-called first loop) - modeled as separate ROs. Fig. 2 represents a single-pole scheme of a model network created in MODES.

Surrounding TSOs interconnected systems are modeled without resources with set balance value. The equivalent ENTSO-E node represents a part of the continental European interconnected system (SZKE). A ENTSO-E node operates a single block with an installed capacity of 241.366 GW representing conventional sources within the modeled interconnected area. The installed power and consumption of the equivalent system does not represent the entire continental European synchronous zone, only part of it as equivalent to the PPP involved in the modeled system. The block type parameters are set to represent a similar dynamic to the interconnected SZKE system (PFR, activation rate, etc.). The block is connected to the modeled SR system by an equivalent line at the 400 kV voltage level to the Kriz400 node.

B. Influence of Slovak PPP on P / f stability in system

The share of production from PPP on consumption in the Slovak republic power system during the day (24h) is shown in Fig. 3. The proportion of production in this case is set according to [5]. The DDZ is set at the sampling nodes for the average daily load during the summer day. The source of the PPP block (which represents the change in sunlight intensity during the day)

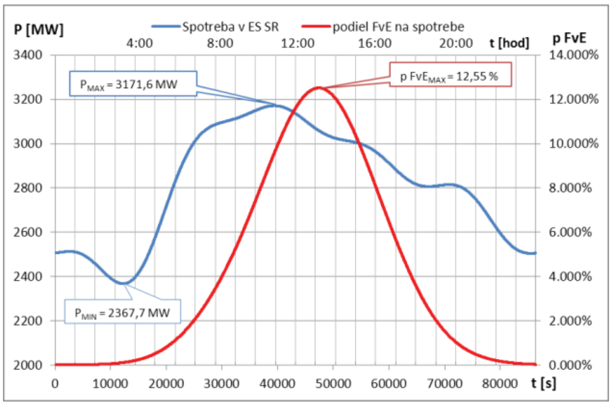

Figure 3. Share of production from PPP to consumption in SR PS

Consumption model during the day - DDZ was designed according to [5]. The difference between minimum and maximum consumption is ΔPS = 803.9 MW. The maximum share of PPP production in consumption reached 12.55% at 13:10. The outputs from the MODES program correspond to the real values in the PS of SR during the day when the minimum consumption was measured in the system (29 July 2017).

The effect of PPP on the system is more pronounced, resulting in a more significant system frequency deviation compared to active PRV in SRV assessment.

Thus, the time interval from 11:00 am to 3:00 pm was chosen, the average July day when, according to [5], system consumption is in its annual lows, production from PPP is at its highest level in the year, and the share of PPP in consumption is in the system at said time interval in the range of 10 to 12%. The course of the frequency variation during the conditions described above for the case of cloudy and clear day is shown in Fig. 4. The effect of cloudiness is particularly evident on frequency variations. In the case of a clear day when the performance of the PPP power supply is easily predictable, the frequency deviation is in the order of mHz (Fig. 4 shown in blue). The red curve represents the frequency deviation for the cloud day. The maximum frequency deviation value is Δf_{MAXobl} = 86.18 mHz. The black dashed line indicates the frequency deviation limit (± 70 mHz), when according to [1], the APS quality assessment is performed.

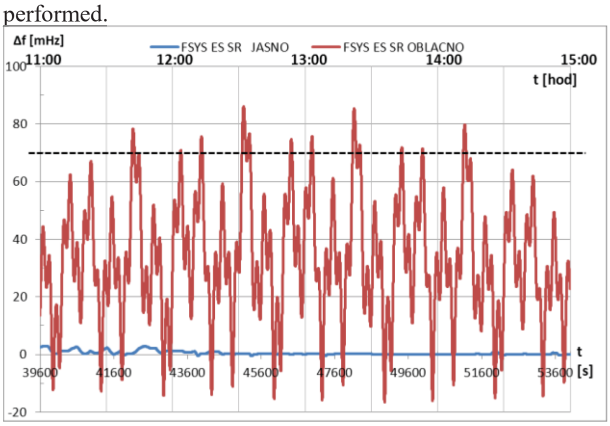

Figure 4. Frequency deviation course during cloudy and clear day

C. Primary Freguency Reserve Quality Assessment

The PFR Quality Assessment was conducted at the PS SR during the 24-hour dynamics modeling. Several scenarios have been modeled for this. The basic prerequisite for the evaluation of PFR quality on the blocks that are involved in this Support services (SS) is the transition of cloud through PPP, which causes fluctuation of the delivered power, which in relatively short time cycles (due to modeling of long-term dynamics of the day) disturbs the power balance in the system and causing deviation of the frequency and the agreed balance value [9]. These conditions place higher demands on the quality of block management and thus on the provision of PFR. Frequency deviation due to PPP under adverse weather conditions increases with the proportion of PPP production per consumption (Figure 3). Therefore, for the sake of clarity, only the time period of the day when the PPP impact is most significant will be monitored.

The RDP quality assessment was carried out on all RDP blocks. There are 21 blocks in total. An extract from the analysis of PFR program MODES of individual blocks providing PFR is in table Table 1.

Table 1. Analysis of PFR on resources in PS of SR

Blok	PRR+ [MW]	PRR- [MW]	N_{tMIN} [MW]	N_t [MW]	N_{tMAX} [MW]
TG31	20	-20	99	115	219
TG32	20	-20	99	115	219
TG41	20	-20	99	115	219
TG42	20	-20	99	115	219
1MKZ1	20	-20	99	169	219
1MKZ2	20	-20	99	169	219
2MKZ1	20	-20	99	169	219
2MKZ2	20	-20	99	169	219
TG1	4	-4	40	54	110
TG2	4	-4	40	54	110
TG5	4	-4	40	54	110
TG6	4	-4	40	54	110
TG21	5	-5	40	95	110
TG22	5	-5	40	95	110
TG23	5	-5	40	95	110
TG24	5	-5	40	95	110
ENOB1	5	-5	40	62	110
ENOB2	5	-5	40	62	110
ENOB3	5	-5	40	62	110
ENOB4	5	-5	40	62	110
OST	57	-57	100	401	600
Total	**273**	**-273**	**1372**	**2381**	**3672**

D. Quality assessment of RDP during normal operation of the EC SR

The analysis of system dynamics modeling on a cloudy day is based on the time interval from 11:00 to 15:00. At this time, the effect of the PPP is most pronounced and the frequency variation is greatest. The evaluation takes place for 15 minute intervals in which the frequency deviation is at least 0.07 Hz. The list of PFR quality evaluation is shown in Tab. 2 [10]. Analysis of RDP quality assessment was performed for model 24h cloud summer day on the system according to Figure 2. with PPP with total installed capacity = 660 MW.

Table. 2 Results of PFR Quality Assessment

Blok	B12	B13	B14	B15	P_{vyp}
TG31	**219.182**	**125.864**	**119.975**	**159.380**	25.000
TG32	**54.779**	**125.837**	**119.957**	**159.317**	25.000
TG41	**54.779**	**125.837**	**119.957**	**159.317**	25.000
TG42	**54.779**	**125.837**	**119.957**	**159.317**	25.000
1MKZ1	**34.312**	**104.348**	**120.589**	**143.073**	25.000
1MKZ2	**34.313**	**104.364**	**120.606**	**143.047**	25.000
2MKZ1	**34.312**	**104.348**	**120.589**	**143.073**	25.000
2MKZ2	**34.313**	**104.364**	**120.606**	**143.047**	25.000
TG1	**20.698**	**47.896**	**57.718**	**68.278**	10.000
TG2	**20.698**	**47.896**	**57.718**	**68.278**	10.000
TG5	**20.698**	**47.896**	**57.718**	**68.278**	10.000
TG6	**20.698**	**47.896**	**57.718**	**68.278**	10.000
TG21	**14.282**	**37.059**	**45.669**	**63.298**	12.500
TG22	**14.282**	**37.059**	**45.669**	**63.298**	12.500
TG23	**14.282**	**37.059**	**45.669**	**63.298**	12.500
TG24	**14.282**	**37.059**	**45.669**	**63.298**	12.500
ENOB1	**17.225**	**21.177**	**35.082**	**47.420**	12.500
ENOB2	**17.225**	**21.177**	**35.082**	**47.420**	12.500
ENOB3	**17.225**	**21.177**	**35.082**	**47.420**	12.500
ENOB4	**17.225**	**21.177**	**35.082**	**47.420**	12.500
OST	**133.328**	**331.654**	**375.730**	**494.180**	142.500

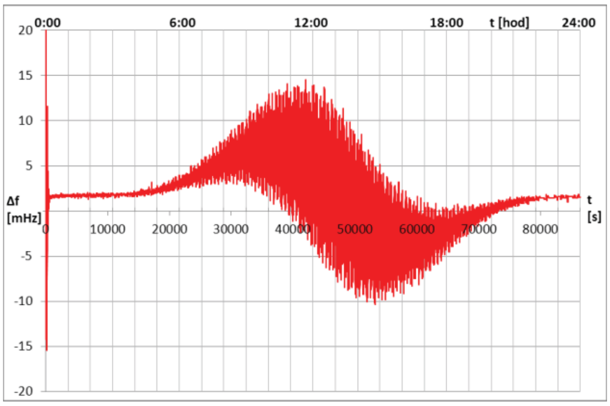

Figure 5. Deviation of system SVK PS frequency during cloudy day

PPPs operating in a system with installed capacity in the order of hundreds of MW do not have a significant impact on the stability of the system in the case of a cloudy day when the production prediction is difficult to achieve. The PFR is activated throughout the interconnected system and thus substantially compensates for the disruption of the power balance in the system due to the variable production of PPP [8]. The following chapters will be devoted to analyzing the impact of PPP installed in the surrounding TSOs on the quality provided by the Support Services. The total installed power of the PPP in the interconnected system moves in the order of tens of GW (see Table 3).

E. *Influence of Slovak PPP on P / f stability in system*

It follows from the definition of the principle of PFR activity that the primary regulation of active power in the whole interconnected system operates at the frequency stabilization. Therefore, the influence of PPP on surrounding TSOs is compared in this section.

The installed performance in PPP varies across EU countries. The EU as a whole has committed itself to raising the share of renewable energy to 20% of final electricity consumption by 2020, while the share of renewable energy in transport should reach 10% [12]. Most countries, including Slovakia, have the development of renewable energy sources in their national action plans. The installed capacities of individual countries whose TSOs belong to the ENTSO-E (TSO are part of the interconnected system) are shown in Tab. 3. The installed capacity of the blocks is according to [2].

According to [4], the total installed PPP power in the modeled system is set to PPPP = 18.8 GW. It is an PPP in the northern part of continental Europe (Poland, Germany, Belgium, Czech Republic, Slovakia, Hungary). PPP in Poland and Hungary have been neglected for small installed power. The total installed power in PPP is thus equivalent to the modeled system in terms of consumption, which is in the modeled system PODB = 190 GW[7]. The maximum PPP production share during a clear summer day of consumption thus constitutes approximately 7% of the PPP surrounding TSOs.

Table 3. List of PPPs operating in a modeled system

Country	Block name	Node name	S_N [MW]	Nt_{MIN} [MW]	Nt_{MAX} [MW]
Česká rep.	FV_CZ	FV_SZKE	1200	0	950
Germany	FV_DE	FV_SZKE	4000	0	4000
	FV_50H	FV_SZKE	2000	0	2000
	FV_TNT	FV_SZKE	8000	0	8000
Belgie	FV_BE	FV_SZKE	1000	0	600
France	FV_FR	FV_SZKE	2000	0	1600
Slovakia	FV_V	FV_Leme	115	0	144
	FV_S	FV_Medz	252	0	315
	FV_Z	FV_PodBi	144	0	180
Total			**18711**		**17789**

Where:

S_N - installed PPP power.

N_{tMIN} - Minimum Power of the Power Supply

N_{tMAX} - the power of the power supply (maximum power of the block)

The power output from the PPP in the surrounding TSOs of the interconnected system was in this case taken into account by adding equivalent blocks representing the production from the PPP in each country. PPPs are connected to an equivalent node representing SZKE. The dynamic parameters of the individual components of the blocks representing the PPP are according to [2]. The course of the balance on a clear day (24 h) is shown in Figure. 6. In this case, the balance has a minimum deviation. The performance of the power designated as SFR (secondary frequency reserve) represents the power activated by the equivalent block (UC1REG) representing SFR in the equivalent area of the SZKE. The SFR value was calculated according to [3] to 2% of the installed power in the modeled system. The total PFR in SZKE is approximately 3000 MW. TFR (therciary frequency reserve) is also involved. The automatics representing TFR changes the entered turbine power of the EKVIV block in case of SFR on the UC1REG control block. The course of the PS of SR and SZKE balance and the performance of the UC1REG block (SFR activated power) is shown in Figure. 6

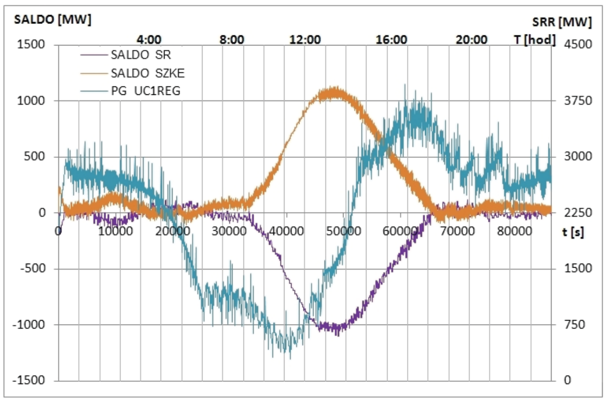

Figure 6. Performance of activated PFR in SZKE

The delivery of power from the PPP from the entire interconnected area does not have a more pronounced impact on the modeled system in terms of the rate of activation of the regulatory reserve on interconnected systems during the cloudless day [11]. For comparison, Figure. 7 shows the frequency and power deviation of the sources (including the production from the PPP) in the control area of the SR modeled system over a 24 h clear day. Since the frequency deviation has not reached a value of at least ± 0.07 Hz for the entire period under review, the quality of the PSS quality assessment is not being performed according to [1], [19].

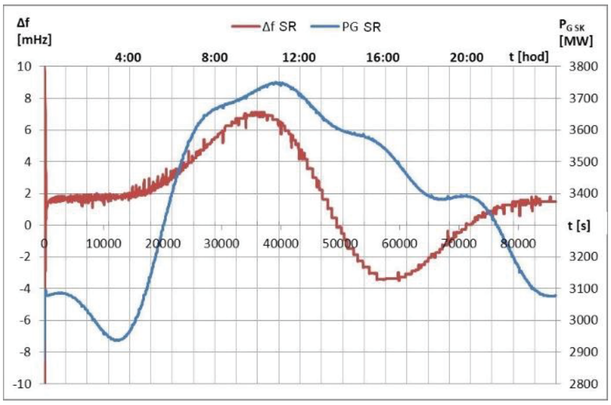

Figure 7. Course of deviation of frequency and power on blocks in PS of SVK

III. PFR Quality Assessment

The assessment of the performance of the primary power control activity taking into account the influence of the PPP in the surrounding TSO is described in this section of the article. The set parameters simulate cloud transition over the PPP and thus change the delivered power [12]. This phenomenon causes a disruption of the power balance in the interconnected system and consequently a frequency and balance deviation. The PFR responds to this change in the entire interconnected area. The P / f regulation is represented in the system by blocks in PS SVK and RO SZKE. Resources in these areas compensate for excess energy at a time when PPP production is the largest and thus reduces the power on blocks that are involved in it within the block control band [13]. The frequency deviation course between 10:00 and 16:00 is shown in Figure. 8. At this time interval, the frequency deviation exceeds 100 mHz. The PFR quality assessment is performed at 15 minute intervals when the frequency deviation exceeds ± 0.1 Hz (in the graph, the deviation limit is indicated by a horizontal dashed line). The course of the frequency deviation in the system is without the intervention of TFR and SFR for the purposes of PFR evaluation.

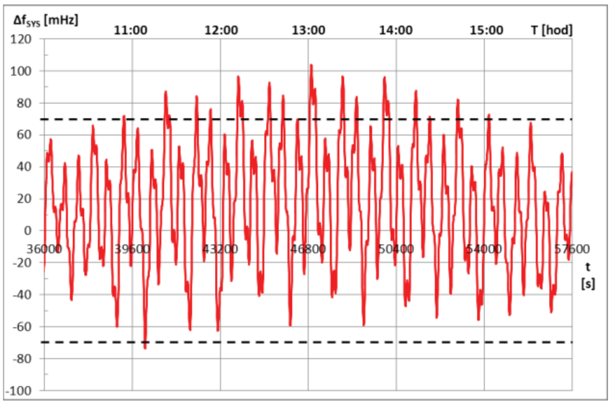

Figure 8. Frequency deviation in TSO SVK in the period from 10:00 to 16:00 – cloudy

The PFR quality assessment was carried out in a total of five business hours when the frequency deviation exceeded ± 0.07 Hz (see Figure 8). The evaluation was carried out at power plant units as a whole. The results of the PFR quality assessment are shown in Table 4. All blocks meet the quality criterion of [1] in all business hours monitored.

Table 4. Evaluation of Quality of RDP Resources in the Extended PS SR Model

Block	B11	B12	B13	B14	B15	P_{out} [MW]
TG31	29,607	25,907	28,958	29,016	25,906	25
1MK Z1	33,614	30,389	33,013	32,438	31,233	25
TG1	29,105	26,101	27,004	29,201	27,479	10
TG21	20,053	20,256	20,032	19,064	21,521	12.5
ENO B1	21,840	19,773	21,956	21,784	20,142	12.5
Other	166,749	151,730	165,301	160,689	155,804	142,5

Where:

b - Linear regression line directive evaluated at 15 minute intervals after G2 failure

| B | - the average of the straight line linear regression line direction values for a given business hour of the day.

P_{out} - 50% five times the PFR offered

Quality assessment was performed only in the case of a cloud day modeled throughout the interconnected system, where the impact of PPP is most pronounced. In other cases, the condition of minimum frequency variation according to [1] has not been fulfilled throughout the period under review. The PFR quality assessment is shown in Table 5.

Table 5. Evaluation of PFR quality in case of EMO failure

Blok	B11	B12	B13	B14	B15	B16	P_{VYP}	PRR+
TG31	29,656	31,068	28,556	34,279	28,728	26,412	25	10
TG1	29,334	30,050	27,352	28,077	28,109	27,182	10	4
TG21	16,443	18,294	17,734	18,841	17,681	17,355	12,5	5
ENO B1	20,471	20,158	19,380	20,325	19,214	19,839	12,5	5

The average of the absolute values of the directions calculated for each business hour of the day from 15 minute intervals when the absolute value of the frequency deviation exceeded 0.1 Hz that meet the quality criterion is shown in green.

Conclusion

The role of modeling dynamics was to analyze the impact of Photovoliatic power plants (PPP) on long-term, resp. medium-term dynamic behavior of the interconnected system, special resources working in TSO of Slovakia. For this purpose, the condition of quality assessment under [1] has been used. The quality of regulation of the power of the systems working in the system depending on the changes in the frequency in the system and the balance in TSO (evaluation of the quality of support services in the real system) is evaluated for various transients in the system. In the first step, the normal operation of the system is analyzed throughout the day with the consideration of Day-ahead load diagram. The aim was to compare the current day for different weather conditions. Above all, the comparison for clear day (the production prediction of the PPP is quite accurate and the dispatcher can provide sufficient SFR) and the cloud day when the change of generation from the PPP is relatively fast and difficult to predict. The latter case occurs under specific conditions in the system when passing a dense cloud over a territory with a high installed power density in PPP.

The principle of PFR quality assessment is to ensure the required performance value with respect to the frequency change in the interconnected system. In this case, all modeled blocks satisfy the condition defined in [1]. It should be noted here that any failure to comply with the condition does not necessarily imply an error in the power control process on the block or any part of it. As introduced in the individual dynamic simulations, the system's power control functioned correctly and at the required time interval according to the control principle.

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