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THE INFLUENCE OF COMPENSATORY REGIME OF OPERATION OF PUMP HYDROPOWER PLANT CAPLJINA ON VOLTAGE CONDITIONS IN ELECTRIC POWER SYSTEM OF BOSNIA AND HERZEGOVINA

UTICAJ KOMPENZATORSKOG REŽIMA RADA CRPNE HIDROELEKTRANE ČAPLJINA NA NAPONSKE PRILIKE U ELEKTROENERGETSKOM SISTEMU BOSNE I HERCEGOVINE

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Abstract: The paper presents the results of testing the operational capabilities of the pump hydropower plant (PHPP) Capljina in compensatory, under excited mode in real time, and answers the questions how, and to what extent, the operation of PHPP Capljina in the under excited mode affects the improvement of voltage conditions in the power system of B&H. The test was performed with one machine in compensatory under excited mode with the takeover of reactive power in the amount of 160 MVAr, in a period of 4 hours. During the test, thermal power plant (TPP) Gacko operated in the maximum under excited mode for a certain period of time.

Keywords: voltage, pump storage, work in under excitation, interconnection, reactive power

Sažetak: U radu su pokazani rezultati testiranja pogonskih mogućnosti crpne hidroelektrane (CHE) Čapljine u kompenzatorskom potpobuđenom režimu rada u realnom vremenu i odgovoreno je na pitanja kako i koliko rad CHE Čapljine u potpobuđenom režimu utiče na poboljšanje naponskih prilika u elektroenergetskom sistemu BiH. Testiranje je izvršeno sa jednom mašinom u kompenzatorskom potpobuđenom režimu rada sa preuzimanjem reaktivne snage u iznosu od 160 MVAr, u periodu od 4 sata. U toku testa je termoelektrana (TE) Gacko u određenom vremenu radilo u maksimalnom potpobuđenom režimu rada.

Ključne riječi: napon, crpna hidroelektrana, potpobuđeni režim rada, interkonekcija, reaktivna snaga

INTRODUCTION

For several years, the transmission system of Bosnia and Herzegovina (B&H) has had a pronounced problem of high voltages, mainly as a result of lightly loaded 400 kV and 220 kV transmission lines, especially in periods characterized by low load (spring, autumn, weekends, night, early morning periods).

At the same time, the entity responsible for system management (ISOB&H) has very limited possibilities for regulating reactive power and voltage, so it is not always able to bring the voltage situation within the permitted limits.

Reactive power and voltage regulation, i.e. Q/U regulation, is a set of activities and measures that actively influence the voltage amounts in individual nodes of the transmission network and the power system as a whole. With efficient and sufficiently fast Q/U regulation, it is possible to manage voltages, losses in the network, release the transmission capacities of individual lines, and generally actively influence the techno-economic parameters of the power system operation. Generators and various types of transmission equipment are used to maintain voltage throughout the transmission system.

The occurrence of impermissibly high voltages at an operating frequency, higher than the allowed values (420 kV, 245 kV, 123 kV) is present and occurs in the power system of B&H and in the power system of neighbouring countries [1]. In addition to the problem of lightly loaded transmission lines in B&H, the other problem is the reception of reactive power throughout the year on interconnection transmission lines 400 kV and 220 kV from Croatia. The solution to the problem of high voltages in the region is possible only through a regional approach, but in such a way that everyone solves their problem of reactive power surplus in their system, not to overflow reactive power from systems with excess reactive power and high voltages to systems with lower voltages. In the Republic of Croatia, the implementation of the SINKRO GRID

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project is underway [2], according to which the installation of a device for reactive power compensation with a total power of 550 MVAr is planned. Two variable reactors connected to 220 kV busbars in SS Mraclin (power 100 MVAr) and 220 kV busbars in SS Melina (power 200 MVAr) have already been put into operation. The connection of static VAR compensator (SVC) devices with a power of 250 MVAr inductively and 70 MVAr capacitively to the 220 kV bus in SS Konjsko is in progress.

The Independent System Operator in Bosnia and Herzegovina (ISOB&H) prepared a study: "Impact of the compensatory regime of the Capljina pump storage hydropower plant on the voltage conditions in the power system of Bosnia and Herzegovina", in December 2020 [3], with the main goal of, based on testing PHPP Capljina's operating capabilities in compensatory real-time mode, offering answers to questions about how and to what extent PHPP Capljina's operation in the described mode affects the improvement of voltage conditions in the B&H power system, and showing the impact and importance of other production resources on voltage regulation in the power system of B&H.

In order to maintain the voltages within the limits, and in accordance with the Grid Code [4], the Independent System Operator in B&H implements the following measures:

- issues orders to power plants for maximum takeover of reactive power, i.e. engagement of production units in the capacitive area of the capability curve,
- regulates voltages by changing the position of the tap changer of the transformer,
- switches off transmission lines, taking into account the safety of the system, i.e. avoiding unilateral power supply of individual substations.

Since there are no installed high-voltage reactors, which consume reactive power and thus directly contribute to voltage reduction at the connection point, in the B&H power system, as an additional measure to reduce voltage, work of PHPP Capljina plant is in synchronous compensatory under excited mode until the installation of compensating devices.

As it is known, the electromechanical and control characteristics of the PHPP Capljina generator-motor enable compensatory (over-excited or under-excited operation, +/- 160 MVAr per machine) in all four quadrants of the capability curve, whereby during asynchronous start-up up to 100 s, consumption on 220 kV network is about 20 MW, while in stationary compensating operation consumption is about 4 MW.

As the work in the compensating regime is not financially valorised by appropriate methodologies, as well as the auxiliary service of Q / V regulation of other production facilities that regulate voltage, the regulation resources of PHPP Capljina are not used in voltage regulation.

In any case, if the service of reactive power compensation and synchronous compensation would be paid to PHPP Capljina and other production facilities, which are able to regulate voltage conditions in the network, it is necessary to do an economic analysis to see whether a more cost-effective solution is installation of compensation devices [5] than payment of the auxiliary service of reactive power compensation and synchronous compensation.

1. THE VOLTAGES IN CHARACTERISTIC SUBSTATIONS AT MINIMUM LOAD REGIME IN 2020

In order to estimate the voltage conditions in the transmission system of Bosnia and Herzegovina, Figure 1 shows a daily diagram with measured mean hourly values of 400 kV voltage at the busbars in substations SS Mostar 4, SS Sarajevo 10, SS Banja Luka 6, SS Tuzla 4 and SS Trebinje, for the day 25.5.2020. At four o'clock in the morning, the minimum consumption in B&H was realized in the amount of 605 MWh / h. The picture shows that the voltages during the whole day in all characteristic SS were above the allowed value of 420 kV and that they increased with the decrease of consumption, in order to reach the maximum in the early morning hours.

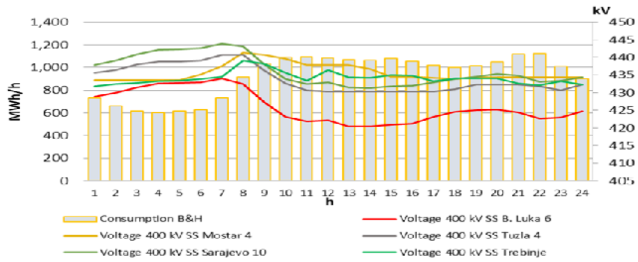

Figure 1. Daily diagram of 400 kV voltage in selected SS for the minimum load regime of B&H achieved on 25.5.2020.

Looking at the year-round data shown in [6], the duration of 400 kV overvoltages during 2020 exceeded 90% in these SSs, except for SS Banja Luka, which worked 39% of hours per year at impermissibly high voltages. High voltages generally affect the insulation of equipment (transformers, switches, etc.), endangering the equipment itself and reducing its service life, and there is a problem of possible activation of overvoltage protection which at extremely high voltages could disconnect certain network units.

2. PHPP CAPLJINA TEST WORK IN COMPENSATORY MODE

The real-time testing of PHPP Capljina, as well as the impact of other production facilities and network elements was conducted from the dispatch center (DC) of ISOB&H, with previously agreed manipulations of network facilities and elements with the Croatian Transmission System Operator (HOPS), Elektroprivreda Hrvatske zajednice Herceg Bosne (EP HZ HB), Elektroprivreda Republike Srpske (ERS) and Elektroprenos B&H.

Since the problem of high voltages in the B&H power system is most pronounced during the night [7] and [8], in order to get a more realistic picture, testing of PHPP Capljina was performed at night, from 01:00 to 05:00 (h).

Initially, it was planned to hold two tests in two days, so that one machine (generator G2) would work on the first day, and the next day two machines in compensatory under excited mode (reactive power takeover in the amount of 2x160MVAr) for a minimum of 4 hours.

However, due to a failure of the G1 generator, it was not possible to perform testing of both machines in the compensating mode. For this reason, only one unit was tested as follows:

- Test 1. Work with one machine in compensatory under excited mode (reactive power takeover in the amount of 160 MVAr), in a period of 4 hours (from 01:00 to 05:00 h), 17.11.2020.
    - o With the generator G2 in PHPP Capljina in the maximum compensatory mode of operation, TPP Gacko adjusted the work so that it worked with cos φ = 1, i.e. the reactive power consumption at the point of connection to the transmission network was zero, Q = 0.
    - o After one hour of compensatory mode of operation of PHPP Capljina, TPP Gacko switched to the maximum under excited mode of generator operation, taking over about 70 MVAr of reactive power from the transmission network.
    - o At the beginning of the third hour of the test, the interconnection OHL 400 kV Mostar 4 - Konjsko was disconnected.
    - o After the expiration of the fourth hour of the PHPP test, Capljina came out of the compensatory mode.

2.1. Test 1. Operation of PHPP Capljina in compensatory under excited mode of operation with one machine

The switching condition in the B&H power system was made in such a way that all elements of the network that the ISO B&H DC switches off were in operation in order to reduce the voltage in the B&H power system.

Due to monitoring the impact of other generators connected to the transmission network of B&H, i.e. due to the vicinity of PHPP Capljina, the operation of TPP Gacko was adjusted to work with cos φ = 1, i.e., the production of reactive power on the generator was zero (Q = 0).

2.1.1. Power system before the test

A detailed description of the operating condition of the B&H power system for the first hour of operation (period from 00:00 to 01:00 h), before the test of compensatory operation of PHPP Capljina, was made based on a calculation of power flows and voltage conditions in the B&H power system. The switching state, power flows and voltage conditions on the 400 kV and 220 kV transmission network of the B&H power system are shown in Figure 2.

These calculations enable the presentation of relevant data: balances of active and reactive power, power flows on interconnection transmission lines, loads of system elements, node voltages. In this sense, a broader model has been formed that includes the B&H power system and the power systems of neighbouring countries: Croatia, Serbia and Montenegro [9].

Regarding the B&H power system, a complete model is used at voltage levels of 400 kV, 220 kV and 110 kV. The switching state, production and consumption are formed in accordance with the daily report, for the first hour of operation on November 17th, 2020. The SCADA / EMS (Supervisory Control And Data Acquisition / Energy Management System) system also provides snapshot data of the Croatian and Serbian power system models, for the period of operation, at voltage levels of 400 kV, 220 kV and 110 kV, with accurate data on switching state, production, consumption and node voltages, in addition to the Transmission Operator System of Montenegro (CGES) sending the relevant data on exchange by interconnection OHLs and certain node voltages.

The calculated values of power flows on interconnection OHLs correspond to actual flows, and the calculated values of voltages in system nodes are almost identical to the values of voltages in data from SCADA system of ISOB&H, which confirms the validity of the model and results.

From the data shown in Figure 2, a low load on the transmission line can be observed. The most loaded 400 kV transmission line is the 400 kV transmission line Trebinje - Lastva, in the amount of 42%. At the 220 kV voltage level, the most loaded transmission line is the 220 kV transmission line Trebinje - Perucica, in the amount of 60.8%. The situation is not better on the 110 kV network, as shown in [3], except for the 110 kV connection Visoko - Dobrinje, where the load was 42.4%, all other 110 kV OHLs were loaded below 40%. The result of low load of OHL and impermissibly high voltage values (higher than the allowed values of 420 kV, 245 kV, 123 kV) is a large amount of capacitive charging power in the transmission network, of 964.6 MVAr. At rated voltages, the capacitive charging power would be slightly lower and would amount to 819.7 MVAr.

Under such operating conditions, the B&H power system injects reactive power into neighbouring systems in the total amount of 281.9 MVAr.

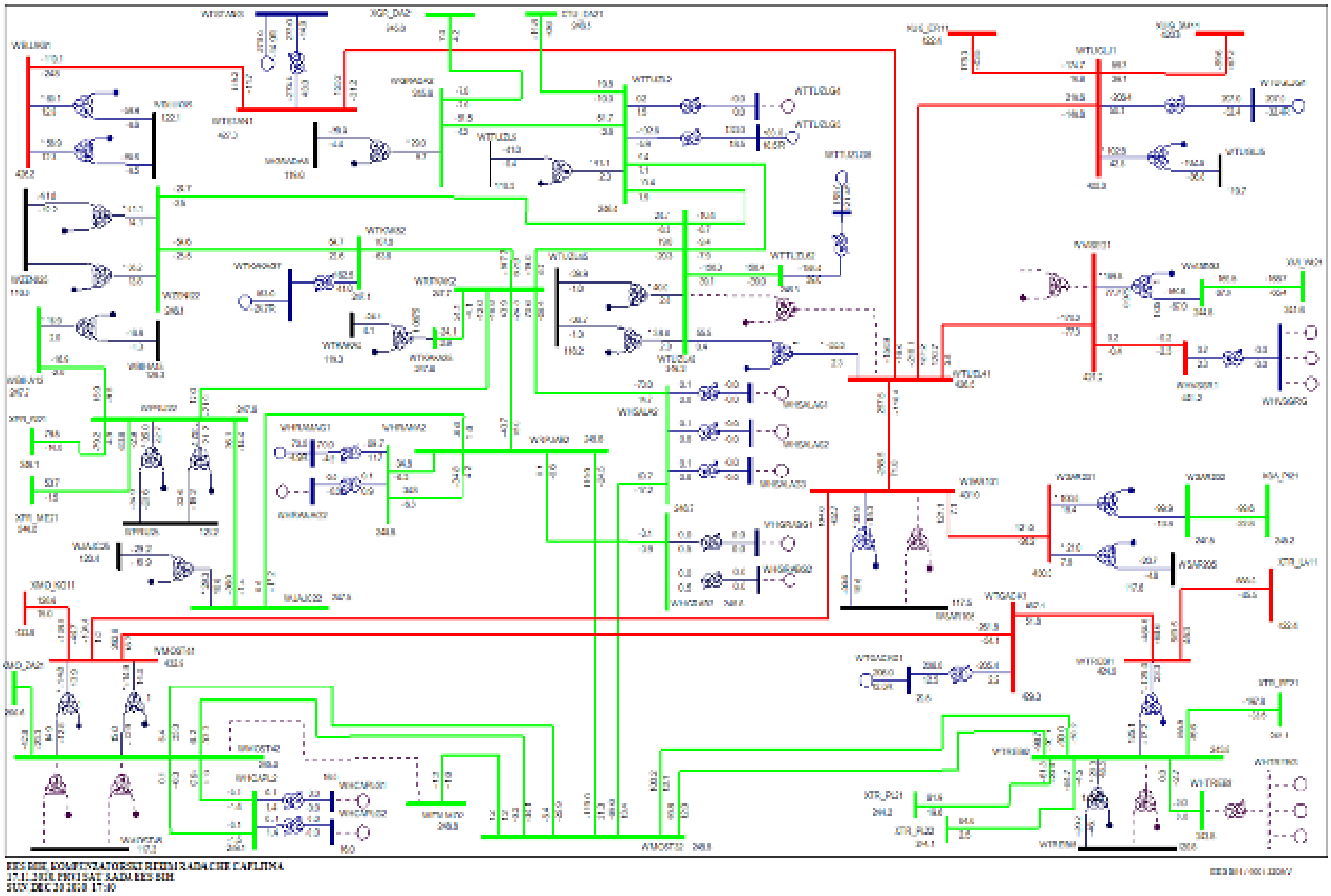

Figure 2. Switching state, power flows and voltage conditions in the B&H power system, 17.11.2020. from 00:00 to 01:00 h

2.1.2. Transmission network topology in B&H

Due to a permanent fault, transformer (TR) 3 220/110 kV and TR 4 220/110 kV in substation (SS) Mostar 4 are out of operation; as same as TR 3 220/110 kV in SS Trebinje and TR 400/110 kV in SS Visegrad.

TR 2 400/110 kV in SS Sarajevo 10, and TR 2 400/220 kV in SS Tuzla 4 are in reserve, while OHL 220 kV Mostar 4 - EAL is switched off due to termination of Aluminij d.d. Mostar.

Before the start of the test, i.e. in the first hour, the active power flow on the MONITA cable between Montenegro (Montenegro) and Italy (IT) had a direction from Montenegro to IT in the amount of about 400 MW. For the first hour of operation of the B&H power system, i.e. in the period from 00:00 h to 01:00 h, on the 400 kV and 220 kV network, the production facilities shown in Tables I and II were in operation. The tables present the average hourly production at the power plant threshold, i.e. on the transmission network. As can be seen, all generation units, except the G5 in TPP Tuzla, take over reactive power from the transmission network and thus help to improve the voltage conditions. The part of the reactive power taken from the transmission network is "spent" on the magnetization of block transformers, part is used to ensure the operation of self-consumption in thermal power plants, and part is taken over by production units to provide excitation in capacitive / under excited mode.

Table I. Production of plants on 400 kV network

Power plant	P	Q
	(MW)	(MVAr)
TPP Gacko	206	-2
TPP Ugljevik	207	-52
TPP Stanari	275	-42

Table II. Production of plants on 220 kV network

Power plant	P	Q
	(MW)	(MVAr)
TPP Tuzla G5	133	5
TPP Tuzla G6	159	-40
TPP Kakanj G7	163	-36
TPP Rama	70	-11

At the time of 00:54 h, before the start of test 1a, the B&H power system injected reactive power into neighbouring systems in the total amount of 152.25 MVAr, while reactive power was injected from the Croatian power system in the amount of 51.69 MVAr, and reactive power in the amount of 106.72 MVAr was injected from the B&H power system into the Montenegrin power system. The reactive power in the amount of 97.22 MVAr was injected into the Serbian power system from the B&H power system.

2.1.3. Test 1a. - Operation of PHPP Capljina in compensatory under excited mode

The compensatory under excited mode of operation of PHPP Capljina started at 01:00 h, while the maximum takeover of reactive power from the power system, in the amount of 160 MVAr, was reached at 01:08 h. During the asynchronous start-up lasting 100 seconds (s), the consumption of PHPP Capljina was about 20 MW, while in the steady state the consumption of active power was about 4 MW (average consumption of active power during the start-up in the time from 00:59:55 h to 01:01:55 h, it was 24.58 MW).

The Figure 3, shows the values of active and reactive power taken every 5 seconds from the high voltage 220 kV side of the block transformer of generator G2, for the period of its commissioning and transition to compensatory mode from 00:55 h to 1:09 h.

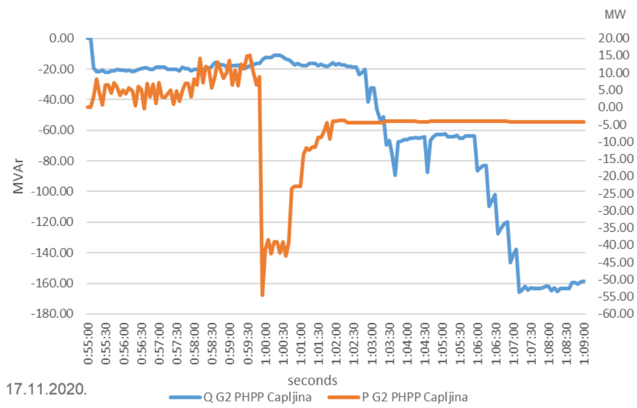

Figure 3. Active and reactive 5-second power when PHPP Capljina enters the compensatory under excited mode

By taking over 160 MVAr of reactive power from the network, as expected, the voltage reduction was mostly reflected on the substations that are closer to PHPP Capljina. Tables III and IV show the voltage conditions in the relevant nodes of the 400 kV and 220 kV network, at 00:54 h, before entering, and at 01:09 h, after entering PHPP Capljina in the compensatory under excited mode. With the entry of PHPP Capljina and the takeover of 161.87 MVAr from 01:09 h, there was a decrease in voltage in the southern and slightly in the central part of the B&H power system (400 kV substations), while in the rest of the system no significant voltage reduction was recorded. As expected, the largest voltage reduction occurred in the nearest substations such as SS Mostar 4 (reduction of 4.9 kV) and SS Gacko (reduction of 3.89 kV). In the northern part of B&H, there was no voltage reduction because the transport of large amounts of reactive power from surplus areas to more remote deficit areas is not possible. It is not possible due to large voltage drops caused by reactive power losses.

Table III. Voltages in 400 kV nodes before and after the entry of PHPP Capljina

SUBSTATION	VOLTAGE (kV)	VOLTAGE (kV)	ΔU (kV)
SS 400/xkV	00:54 h	01:09 h	
Mostar 4	434.65	429.75	-4.9
Gacko	429.71	425.82	-3.89
Trebinje	426.28	422.84	-3.44
Sarajevo 10	431.73	429.41	-2.32
Sarajevo 20	432.65	430.65	-2
Tuzla 4	429.03	429.2*	*
Stanari	428.72	428.13	-0.59
Banja Luka 6	427.21	426.84	-0.37
Ugljevik	423.15	422.68	-0.47
Visegrad	422.61	422.19	-0.42

* no changes in measured values ("frozen" measurements)

There is a significant voltage reduction in 220 kV substations located in the southern part of the B&H power system. The largest change, i.e. voltage reduction, occurred in the nearest substations, namely: SS Mostar 4 (reduction of 5.22 kV) and substation Trebinje (reduction of 2.83 kV).

Table IV. Voltages in 220 kV nodes before and after the entry of PHPP Capljina

SUBSTATION	VOLTAGE (kV)	VOLTAGE (kV)	ΔU (kV)
SS 220/xkV	00:54 h	01:09 h	
Mostar 4	251.31	246.09	-5.22
Mostar 3	249.11	244.91	-4.2
Trebinje	244.84	242.01	-2.83
RP Kakanj	246.97	246.97	*
Prijedor 2	247.74	247.2	-0.54
Jajce 2	249.96	248.83	-1.13

* no changes in measured values ("frozen" measurements)

Reactive power flows (mean minute values) on the interconnection OHL 400 and 220 kV voltage level of the B&H power system, in the time of 01:09 h, after the entry of PHPP Capljina into the compensatory under excited mode of operation, are shown in Tables V and VI. In this case, there is an increased injection of reactive power from the Croatian power system in the B&H power system, by 38.24 MVAr, and a reduced injection from the B&H power system into the power system of Montenegro, by 34.23 MVAr. The injection of reactive power in the Serbian power system was also reduced by 4.62 MVAr, and the

Table V. Reactive power flows Q on 400 kV transmission line

400 kV interconnection line	Q (MVAr)	Q (MVAr)	ΔQ (MVAr)	
	00:54 H	01:09 h	in B&H	from B&H
Mostar 4 - Konjsko	-47.12	-60.15	13.03	
Ugljevik - Ernestinovo	10.53	4.82		-5.71
Ugljevik - S. Mitrovica	53.56	51.26		-2.3
Trebinje - Lastva	37.72	17.23		-20.49

Table VI. Reactive power flows Q on 220 kV transmission line

220 kV interconnection line	Q (MVAr)	Q (MVAr)	∆Q (MVAr)	
	00:54 h	01:09 h	in B&H	from B&H
Mostar 4 - Zakucac	-22.13	-35.93	13.8	
Prijedor 2 - Medjuric	7.48	5.18		-2.3
Prijedor 2 - Sisak	19.08	16.92		-2.16
Gradacac - Djakovo	-9.36	-9.46	0.1	
TPP Tuzla - Djakovo	-11.71	-11.71	0	
Trebinje - Plat	1.54	0.4		-1.14
Trebinje - Perucica	49.73	40.26		-9.47
Sarajevo 20 - Piva	19.27	15		-4.27
Visegrad - Vardiste	43.66	41.34		-2.32

total export of reactive power from the B&H power system to neighbouring systems was reduced by 77.09 MVAr.

From the analysis of reactive power flows on interconnection OHL it can be concluded that after PHPP Capljina enters the compensatory under excited mode and voltage decrease in power nodes of B&H there is an additional increase in reactive power flows ("overflow") from system with higher voltages (power system Croatia) into a system with lower voltages (power system B&H). It is also noticed that by reducing the value of voltage in the nodes of the B&H power system, there is a decrease in the injection of reactive power to systems with lower voltage values - the power system of Montenegro and the power system of Serbia.

2.1.4. Test 1b. – Operation of PHPP Capljina in compensatory under excited mode and maximum under excited mode of TPP Gacko

The largest production facility in the southern part of the B&H power system, which can help reduce the voltage value, with the exception of PHPP Capljina, is TPP Gacko, which is connected to 400 kV network. The operation of this power plant in the under excited mode of operation significantly affects the voltage reduction in the power system of B&H, which is proven by the test.

The entry of TPP Gacko into the maximum under excited mode of operation was recorded at 02:09 h. At that time, the total takeover of the reactive power of this power plant from the transmission network was 72.86 MVAr.

In addition to the operation of PHPP Capljina in the compensatory under excited mode, during the period from 01:00 h to 02:00 h, the entry of TPP Gacko into the under excited mode additionally contributed to the improvement of voltage conditions in the B&H power system. Tables VII and VIII show the voltage conditions in the relevant nodes of 400 kV and 220 kV network at 01:09 h, before entering, and at 02:09 h, after entering TPP Gacko in the capacitive / under excited mode. The most significant voltage change occurs in the 400 kV voltage substations SS Mostar 4, SS Gacko and SS Trebinje.

Table VII. Voltages in 400 kV nodes

SUBSTATION	VOLTAGE (kV)	VOLTAGE (kV)	∆U (kV)
SS 400/xkV	01:09 h	02:09 h	
Mostar 4	429.75	427.76	-1.99
Gacko	425.82	421.5	-4.32
Trebinje	422.84	420.99	-1.85
Sarajevo 10	429.41	428.73	-0.68
Sarajevo 20	430.65	430.4	-0.25
Tuzla 4	429.2*	429.2*	*
Stanari	428.13	428.23	0.1
Banja Luka 6	426.84	426.88	0.04
Ugljevik	422.68	422.36	-0.32
Visegrad	422.19	421.45	-0.74

Table VIII. Voltages in 220 kV nodes

SUBSTATION	VOLTAGE (kV)	VOLTAGE (kV)	∆U (kV)
SS 220/xkV	01:09 h	02:09 h	
Mostar 4	246.09	245.47	-0.62
Mostar 3	244.91	243.66	-1.25
Trebinje	242.01	241.23	-0.78
RP Kakanj	246.97	246.97	*
Prijedor 2	247.2	247.39	0.19
Jajce 2	248.83	248.59	-0.24

The reactive power flows (mean minute values) on interconnecting OHLs 400 and 220 kV at the time of 01:09 h, after PHPP Capljina enters the compensatory under excited mode at 02:09 h, after TPP Gacko enters the capacitive/under excited mode of operation, are shown in Tables IX and X, respectively.

Table IX. Reactive power flows Q on 400 kV transmission line

400 kV interconnection line	Q (MVAr)	Q (MVAr)	∆Q (MVAr)	
	00:54 H	01:09 h	in B&H	from B&H
Mostar 4 - Konjsko	-60.15	-70.25	10.1	
Ugljevik - Ernestinovo	4.82	16.3		11.48
Ugljevik - S. Mitrovica	51.26	47.77		-3.49
Trebinje - Lastva	17.23	-23.5	-40.73	

Table X. Reactive power flows Q on 220 kV transmission line

220 kV interconnection line	Q (MVAr)	Q (MVAr)	∆Q (MVAr)	
	01:09 h	02:09 h	in B&H	from B&H
Mostar 4 - Zakucac	-35.93	-35.88	-0.05	
Prijedor 2 - Medjuric	5.18	5.68		0.5
Prijedor 2 - Sisak	16.92	16.97		0.05
Gradacac - Djakovo	-9.46	-14.38	4.92	
TPP Tuzla - Djakovo	-11.71	-11.71	0	
Trebinje - Plat	0.4	8.27		7.87
Trebinje - Perucica	40.26	38.73		-1.53
Sarajevo 20 - Piva	15	8.85		-6.15
Visegrad - Vardiste	41.34	34.58		-6.76

2.1.5. Test 1c. – Operation of PHPP Capljina in compensatory under excited mode of operation, maximum under excited mode of operation of TPP Gacko and disconnection of 400 kV OHL Mostar 4 - Konjsko

The disconnection of underloaded transmission lines, taking into account the safety criterion N-1, is one of the most common measures used by the ISOB&H DC in order to reduce the voltage in the B&H power system. The disconnection of the underloaded OHL 400 kV Mostar 4 - Konjsko, i.e. the reduction of the reactive power supply from the Croatian power system, would lead to an additional voltage reduction in the B&H power system. Tables XI and XII show the voltage conditions in the relevant nodes of 400 kV, i.e. 220 kV network at 02:09 h, before disconnection, and at 03:03 h, after disconnection of OHL 400 kV Mostar 4 - Konjsko. The disconnection of the lightly loaded 400 kV Mostar 4 - Konjsko transmission line led to a decrease in voltage in SS Mostar 4, by 5.62 kV, in SS Gacko, by 3.76 kV, while in SS Trebinje a lower voltage of 4.94 kV was recorded.

The disconnection of the mentioned transmission line was also reflected in the voltages in SS Sarajevo 10, where a voltage decrease of 2.92 kV was recorded, while in SS Sarajevo 20 a voltage decrease of 2.8 kV was recorded.

In addition to significant voltage changes in the 400 kV network, a decrease in voltage in the 220 kV network was also recorded. In SS Mostar 4 the voltage was reduced by 2.38 kV, and in SS Trebinje by 3.15 kV.

Table XI. Voltages in 400 kV nodes

SUBSTATION	VOLTAGE (kV)	VOLTAGE (kV)	∆U (kV)
SS 400/xkV	01:09 h	03:03 h	
Mostar 4	427.76	422.14	-5.62
Gacko	421.5	417.74	-3.76
Trebinje	420.99	416.05	-4.94
Sarajevo 10	428.73	425.81	-2.92
Sarajevo 20	430.4	427.6	-2.8
Tuzla 4	429.2*	427.19	*
Stanari	428.23	427.15	-1.08
Banja Luka 6	426.88	425.92	-0.96
Ugljevik	422.36	421.66	-0.7
Visegrad	421.45	421.19	-0.26

Table XII. Voltages in 220 kV nodes

SUBSTATION	VOLTAGE (kV)	VOLTAGE (kV)	∆U (kV)
SS 220/xkV	01:09 h	03:03 h	
Mostar 4	245.47	243.09	-2.38
Mostar 3	243.66	242.05	-1.61
Trebinje	241.23	238.08	-3.15
RP Kakanj	246.97	245.77	-1.2
Prijedor 2	247.39	247.02	-0.37
Jajce 2	248.59	247.55	-1.04

Tables XIII and XIV show the voltage conditions in the relevant nodes of the 400 and 220 kV transmission network, at 00:54 h, immediately before the start of the test, and at 03:03 h, after the disconnection of the 400 kV OHL Mostar 4 - Konjsko, when PHPP Capljina in the compensatory under excited mode, it takes over 130.35 MVAr from the transmission network (on the threshold of the power plant), and TPP Gacko operates in the capacitive mode and takes over 53.04 MVAr from the transmission network. The largest decrease was measured in these operating conditions of the B&H power system - the voltage difference in relation to the voltage conditions immediately before the start of the test. In SS Mostar 4 voltage decrease by 12.51 kV was recorded, in SS Gacko by 11.97 kV, in SS Trebinje by 10.23 kV, in SS Sarajevo 10 by 5.92 kV, while in SS Sarajevo 20 the voltage was reduced for 5.05 kV.

Table XIII. Voltages in 400 kV nodes

SUBSTATION	VOLTAGE (kV)	VOLTAGE (kV)	∆U (kV)
SS 400/xkV	00:54 h	03:03 h	
Mostar 4	434.65	422.14	-12.51
Gacko	429.71	417.74	-11.97
Trebinje	426.28	416.05	-10.23
Sarajevo 10	431.73	425.81	-5.92
Sarajevo 20	432.65	427.6	-5.05
Tuzla 4	429.03	427.19	*
Stanari	428.72	427.15	-1.57
Banja Luka 6	427.21	425.92	-1.29
Ugljevik	423.15	421.66	-1.49
Visegrad	422.61	421.19	-1.42

This was reflected in the reduction of voltage in the 220 kV network, so in SS Mostar 4 lower voltages were recorded by 8.22 kV, in SS Mostar 3 by 7.06 kV and in SS Trebinje by 6.76 kV.

Table XIV. Voltages in 220 kV nodes

SUBSTATION	VOLTAGE (kV)	VOLTAGE (kV)	∆U (kV)
SS 220/xkV	00:54 h	03:03 h	
Mostar 4	251.31	243.09	-8.22
Mostar 3	249.11	242.05	-7.06
Trebinje	244.84	238.08	-6.76
RP Kakanj	246.97	245.77	-1.2
Prijedor 2	247.74	247.02	-0.72
Jajce 2	249.96	247.55	-2.41

The reactive power flows (mean minute values) on interconnection transmission lines 400 kV and 220 kV voltage level of the B&H power system, at 02:09 h, after entering TPP Gacko in capacitive / under excited mode and at 03:03 h, after disconnection of OHL 400 kV Mostar 4 - Konjsko, are shown in Tables XV and XVI.

After disconnection of OHL 400 kV Mostar 4 - Konjsko at 03:03 h, power system of B&H injects reactive power into neighbouring systems, in the total amount of 65.69 MVAr, whereby reactive power is injected from the Croatian power system in the amount of 11.68 MVAr, while reactive power in the amount of 6.49 MVAr is injected from the B&H power system into the Montenegrin power system. At the same time, reactive power in the amount of 70.68 MVAr is injected from the B&H power system into the Serbian power system.

In this case, there is a significant reduction in the injection of reactive power from the Croatian power system into the B&H power system by 73.32 MVAr and a reduced injection from the B&H power system into the Montenegrin power system, by 17.59 MVAr. The reactive power injection in the Serbian power system was also reduced by 11.47 MVAr.

Table XV. Reactive power flows Q on 400 kV transmission line

400 kV interconnection line	Q (MVAr)	Q (MVAr)	ΔQ (MVAr)	
	02:09 h	03:03 h	in B&H	from B&H
Mostar 4 - Konjsko	-70.25	0	-70.25	
Ugljevik - Ernestinovo	16.3	16.33		0.03
Ugljevik - S. Mitrovica	47.77	41		-6.77
Trebinje - Lastva	-23.5	-25.49	1.99	

Table XVI. Reactive power flows Q on 220 kV transmission line

220 kV interconnection line	Q (MVAr)	Q (MVAr)	ΔQ (MVAr)	
	02:09 h	03:03 h	in B&H	from B&H
Mostar 4 - Zakucac	-35.88	-34.17	-1.77	
Prijedor 2 - Medjuric	5.68	4.34		-1.34
Prijedor 2 - Sisak	16.97	14.81		-2.16
Gradacac - Djakovo	-14.38	-14.21	-0.17	
TPP Tuzla - Djakovo	-11.71	-16.28	4.57	
Trebinje - Plat	8.27	17.5		9.23
Trebinje - Perucica	38.73	28.18		-10.55
Sarajevo 20 - Piva	8.85	3.8		-5.05
Visegrad - Vardiste	34.58	29.88		-4.7

2.1.6. Test 1d. – exit of PHPP Capljina and TPP Gacko from the under excited mode of operation

According to the program task, the test lasts for 4 hours, i.e. at 05:00 h, PHPP Capljina exits from the compensatory under-excited mode of operation, and TPP Gacko from the capacitive / under-excited mode of operation.

Tables XVII and XVIII show the voltage conditions at the relevant 400 kV nodes, i.e. 220 kV network at 05:01 h, in the operating conditions of the B&H Power System when the 400 kV Mostar 4 - Konjsko OHL is disconnected, and PHPP Capljina, in the compensatory under excited mode, takes over 171.77 MVAr from the transmission network, while TPP Gacko, in capacitive mode, takes over 68.30 MVAr, and at 05:16 h, after PHPP Capljina leaves the compensatory mode, when TPP Gacko takes over reactive power in the amount of 17 MVAr, which is mainly “spent” on the magnetization of the block transformer.

The largest voltage change occurred in SS Mostar 4 (voltage increase of 400 kV by 5.4 kV) and the largest change in the 220 kV network occurred in SS Mostar 3 (increase of 5.66 kV).

Table XVII. Voltages in 400 kV nodes

SUBSTATION	VOLTAGE (kV)	VOLTAGE (kV)	ΔU (kV)
SS 400/xkV	05:01 h	05:16 h	
Mostar 4	423.54	428.94	5.4
Gacko	419.33	424.44	5.11
Trebinje	419.17	421.57	2.4
Sarajevo 10	427.35	429.13	1.78
Sarajevo 20	428.88	429.61	0.73
Tuzla 4	427.19	427.19	*
Stanari	427.84	427.93	0.09
Banja Luka 6	426.31	425.97	-0.34
Ugljevik	422.65	421.8	-0.85
Visegrad	422.21	421.17	-1.04

Table XVIII. Voltages in 220 kV nodes

SUBSTATION	VOLTAGE (kV)	VOLTAGE (kV)	ΔU (kV)
SS 220/xkV	05:01 h	05:16 h	
Mostar 4	243.46	248.28	4.82
Mostar 3	241.28	246.94	5.66
Trebinje	240.48	241.87	1.39
RP Kakanj	245.77	247.06	1.29
Prijedor 2	246.95	246.95	0
Jajce 2	247.92	248.73	0.81

The complete cycle of compensatory operation of PHPP Capljina, 400 kV voltages in SS Mostar 4 and SS Trebinje, changes of mean minute reactive power of TPP Gacko and reactive power on OHL 400 kV Mostar 4 - Konjsko, OHL 400 kV Trebinje - Lastva, OHL 220 kV Mostar 4 - Zakucac, OHL 220 kV Trebinje - HPP Perucica, from 00:00 to 06:00, are shown in Figure 4.

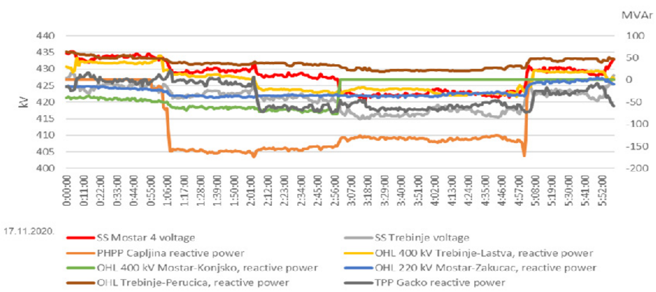

Figure 4. Change of 400 kV voltage and reactive power depending on the operation of PHPP Capljina, TPP Gacko and disconnection of 400 kV Mostar 4-Konjsko

3. CONCLUSION

1. The voltage values measured during the test show that the compensatory mode of operation of PHPP Capljina has an impact on voltage reduction in the part of the B&H power system, mostly in the southern and slightly less in the central part of the B&H power system, while in the northern part of the power system operating mode has no major effect on voltage conditions.
2. By analysing the test results of PHPP Capljina, we can see the significant contribution of TPP Gacko in the regulation of voltage conditions, which proves that the excitation mode of generators connected to the transmission network has a significant impact on voltage regulation, and that all generators, through the provision of ancillary service Q / V regulations, which according to the existing market rules, procedures and methodologies are not financially valorised, significantly contribute to better voltage conditions in the B&H power system.
3. The fastest and simplest solution for reducing excessive voltages to the allowable limits of available resources is the engagement of PHPP Capljina, with a previously developed methodology for cost valorisation for compensatory mode, as well as valorisation of Q / V voltage regulation that would be stimulating for additional engagement of production facilities in under excitation mode. This would enable greater absorption of reactive power from the transmission network and partial mitigation of voltage conditions.

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BIOGRAPHY

Senad Hadžić was born in 1965 in Visegrad. He graduated on the Faculty of Electrical Engineering in Sarajevo in 1993, where he also obtained a Master's degree in 2012. Employed at ISOB&H as an engineer for system and market development. From 2007 to 2015, he performed the duties of the Head of the real time operation department. In addition to operation control of the power system through SCADA / EMS, he performed the tasks of operational planning, accounting, and electricity exchange. Previously, he worked in JP EP B&H on the same jobs, wholesale electricity and calculations of losses in the transmission and distribution network.

Husnija Ferizović was born in 1958 in Drvar. He graduated on the Faculty of Electrical Engineering in Sarajevo in 1982, where he also obtained a Master's degree in 2003. Employed in ISOB&H in Sarajevo in strategic planning department. He works on analysing the operation of the EES in stationary and dynamic conditions, coordinating the settings of protection, using modern softwares PSS/E (PowerSymulator for Engineering, Siemens Power Technologies International), ASPEN (Advanced Systems for Power Engineering, Inc.). He previously worked in JP EP B&H, on the tasks of analysing and planning the development of the power system.

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