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SENSITIVITY ANALYSIS OF OPTIMAL ECONOMIC DISPATCH

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In this paper the optimal operation of a smart grid that is similar to a real power system located in Dobrogea area, Romania and the sensitivity of the objective function of the presented mathematical model is analyzed. The decrease of the maximum generation limit of the hydro plant after the occurrence of the drought in the Dobrogea area is considered. The presented mathematical model can be used by the national energy dispatcher in order to determine the optimal operation of a power system. The smart grid analyzed contains renewable energy sources, thermal plants, hydro plants, loads and energy storage systems.

Keywords: Energy storage systems, Li-Ion, Optimal operation, Renewable energy sources, Smart grid, Transmission network.

1. Introduction

A Smart Grid is a power system that can efficiently integrate the behavior and actions of all users connected to it (generators, consumers and prosumers) in order to ensure a sustainable power system that is economically efficient with high quality energy and supply security [1]. A smart grid allows the management of a large number of consumers, producers and energy storage units through an efficient management of the whole system as well as increased energy efficiency.

The increase of the CO_2 level, as an equivalent indicator of the increase of the environment pollution, imposes the necessity to develop solutions regarding the production of electricity that does not produce polluting substances beyond the admissible environment limits. In Europe, a 40% reduction in pollutant emissions compared to 1990 has to be reached by 2030. These greenhouse gas (GHG) emissions impose that some power plants that do not meet the requirements to not operate, thus the share of non-polluting sources increases [2].

The integration of renewable energy sources (RES) into power systems determines the possibilities of storing and developing energy storage systems to be considered. Energy storage systems (ESS) are needed because of the volatility of RES and due to the load variation. ESS can charge during off-peak load

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periods, and discharge during the peak load and also can be discharged during periods when the electricity is at a high price and charge when the electricity is at a low price [3].

In Romania, the transmission network is a natural monopoly (where competition does not make sense) and is used by all manufacturers and consumers to exchange electricity. Congestion impedes the energy transmission from some production areas to consumption areas, and interruptions in power supply can endanger the stability of the system as a whole. Therefore, the transmission network needs to optimally operate. In order to achieve this, it is necessary to invest in new elements or in reinforcements in order to increase operational safety, to ensure the power exchange and to maximize social welfare.

The national energy dispatcher must ensure a safe operation of the transmission network taking into account the electricity market. Unbalances can appear between what is generated and what is demanded, thus the energy dispatcher is economically dispatching the power produced in order to balance the consumption while taking into account the power system constraints [4], [5].

The mathematical model (MM) presented in this paper is determining the optimal economic dispatch of the transmission network presented that is similar to the one located in the southeastern area of Romania [6], [7]. The transmission network contains SRE, ESS, loads, hydro generating units and thermal generating units that are connected to the grid [8]. The sensitivity of the objective function (FOB) is analyzed considering the decreasing of the power produced by the hydro generating unit [9], [10].

Different types of batteries can be used such as flywheels, super capacitors, superconducting magnetic energy storage, reduction and oxidation, compressed air energy storage, etc. This paper uses Li-Ion batteries with a conversion efficiency of 0.9 and a lifetime of 10 years. The location of each storage system is presented in Fig. 1.

Li-Ion batteries are used for large ESSs although their price is relatively high. The functioning of a Li-Ion battery is ensured by the movement of the electric charges produced by the materials of which the anions and cations are made. The charging and discharging of the battery are determined by the movement of the electric charges and also through electrochemical reactions. Even if the price of the Li-Ion batteries is relatively high they present a reduced self-discharge than other ESSs [11].

In this paper it is considered that in 2030 the consumption can grow with 20% compared to the year 2018. The load is aggregated, and it is according to a reference day from 2018. Transelectrica published the demand forecast of the Romanian National Power System which is taken into account in this paper [12], [13]. In [4] the optimal operation of the smart grid in a reference day from 2030 when the hydro generating units is functioning at maximum is presented. In this paper the case where the hydro generating unit is not operating (case 10) is compared to the case when the hydro generating unit is operating at maximum power (case 0) from [4]. Also, the sensitivity of the FOB is analyzed.

The year 2018 was the third warmest year in Romania's history, and globally, the years 2015-2018 were the warmest in history and it is forecasted that next ones are even worse. The climate will destabilize which means that the atmosphere of the planet warms up from year to year and the local effects are different: in some areas, the climate can cool, in others it can get warmer, sometimes very quickly. Romania has been prevented so far from forest fires that have affected large areas of Europe in recent years, but this will change with the installation of long periods of drought, especially in Muntenia, Dobrogea and southern area of Moldova [14].

2. Mathematical Model

The FOB (1) of the MM (1) – (10) is minimizing the costs associated with the production of the thermal power plants, hydro power plants and wind power plants (total generation costs).

$$\min\left(\sum_{th}\sum_{t} c_{th}\cdot P_{th,t} + \sum_{h}\sum_{t} c_{h}\cdot P_{h,t} + \sum_{t} LWP\cdot P_{t}^{wpcr}\right) \quad (1)$$

$$P_{h}^{min} \le P_{h,t} \le P_{h}^{max}$$
$$P_{th}^{min} \le P_{th,t} \le P_{th}^{max} \quad (2)$$

$$P_{h,t} - P_{h,t-1} \le RU_{h}$$
$$P_{th,t} - P_{th,t-1} \le RU_{th} \quad (3)$$

$$P_{h,t-1} - P_{h,t} \le RD_{h}$$
$$P_{th,t-1} - P_{th,t} \le RD_{th} \quad (4)$$

$$SOCESS_{t} = SOCESS_{t-1} + \left(P_{t}^{ch}\cdot\eta_{ch} - \frac{P_{t}^{dch}}{\eta_{dch}}\right)\cdot\Delta_{t} \quad (5)$$

$$P_{min}^{ch} \le P_{t}^{ch} \le P_{max}^{ch} \quad (6)$$

$$P_{min}^{dch} \le P_{t}^{dch} \le P_{max}^{dch} \quad (7)$$

$$SOCESS_{min} \leq SOCESS_t \leq SOCESS_{max} \quad (8)$$

$$P_{wp,t} + \sum_{th} P_{th,t} + \sum_{h} P_{h,t} + P_t^{dch} \geq L_t - P_t^{ch} \quad (9)$$

$$P_{wp,t} + P_t^{wpcr} \leq \Lambda_t^{wp} \quad (10)$$

After solving the MM (1) – (10) the optimal operation of the smart grid is obtained. The MM is neglecting the losses of the grid.

In (1) the FOB of the MM is described, where c_{th} is the thermal generating unit production cost, $P_{th,t}$ is the power produced by the thermal generating units th at time t. The production cost of the hydro generating unit is c_h while $P_{h,t}$ is the power produced by the hydro generating unit h at time t. LWP is the value of loss of wind and P_t^{wpcr} is the curtailed power of the wind generating units at time t. The optimal power produced by the hydro power plant ($P_{h,t}$) and thermal power plants ($P_{th,t}$) is between the minimum and the maximum generation limit and it is represented by equation (2) where P_h^{min} and P_{th}^{min} are minimum generated power by the hydro power plant h at time t, respectively by the thermal power plant th at time t. P_h^{max} and P_{th}^{max} are the maximum power generated by the hydro power plant h at time t, respectively by the thermal power plant th at time t.

Equation (3) is determining the optimal power produced by the thermal and hydro power plants at successive hours limited by the rump up limit of the thermal power plant (RU_{th}) and hydro power plant (RU_h). Similar, equation (4) is determining the optimal power generated at successive hours but this time limited by the rump down limit of the thermal power plant (RD_{th}) and hydro power plant (RD_h). The state of charge of the ESSs ($SOCESS_t$) is influenced by the charging (η_{ch}) and discharging efficiency (η_{dch}) and it is represented by equation (5).

In equation (6) is described the charging power of the energy storage system (P_t^{ch}). The charging power is bounded by the minimum (P_{min}^{ch}) and maximum (P_{max}^{ch}) charging power limit. Similar, in equation (7), the discharging power of the ESSs (P_t^{dch}) is bounded by the minimum (P_{min}^{dch}) and maximum (P_{max}^{dch}) discharging power limit. In this case, the minimum limit is recommended not to be less than 20% of the total battery capacity so as not to affect the battery lifecycle. Sate of charge ($SOCESS_t$) is between the minimum ($SOCESS_{min}$) and maximum ($SOCESS_{max}$) limit as presented in equation (8). The balance that has to be maintained between the consumption and production, by the energy dispatcher, is represented by equation (9).

The power produced by the wind power plants ($P_{wp,t}$) takes into account also the curtailed power (P_t^{wpcr}) is bounded by the availability of the wind power plants (Λ_t^{wp}).

3. Case Study

The data for thermal generating plants are reported in Table 1.

In Table 2 the power of the hydro generating unit and the value of the FOB in each case considered are reported.

In Table 3 data for hydro plant are reported. For the hydro generating unit it is considered that the maximum power that can be generated is varying. The power decreases by 10% compared to the capacity of the generator ($P_{th}^{max} = 210$ [MW]) in each case considered.

Table 1

Data for Thermal Power Plants

Thermal unit	Bus	P_{th}^{min} $[MW]$	P_{th}^{max} $[MW]$	c_{th} [€/MWh]	RU_{th} [MW/h]	RD_{th} [MW/h]
T1	b5	0	155	40.88	40	40
T2	b5	0	155	55.55	40	40
T3	b5	0	155	78.51	40	40
T4	b5	0	155	54.81	40	40
T8	b8	0	160	40.88	35	35
T10	b10	0	200	42	45	45
T11	b11	0	420	42	50	50
T12	b12	0	50	40.88	30	30
T14	b14	0	100	40.88	35	35
T24	b24	0	50	55.55	30	30

Table 2

The Value of the Maximum Power Limit of the Hydro Generating Unit and FOB

Case	P_h^{max} $[MW]$	FOB [€]
0	210	1.156.748
1	189	1.164.893
2	168	1.173.169
3	147	1.181.666
4	126	1.190.754
5	105	1.200.599
6	84	1.211.766
7	63	1.223.240
8	42	1.236.320
9	21	1.252.210
10	0	1.268.855

Table 3

Data for Hydro Power Plants

Hydro unit	Bus	P_h^{min} $[MW]$	P_h^{max} $[MW]$	c_h $[€/MWh]$	RU_h [MW/h]	RD_h [MW/h]
H11	B11	0	210	32	45	45

Table 4

Load Profile in 2030

Time [h]	Aggregated Load [MW]	Time [h]	Aggregated Load [MW]
1	2649	13	2376
2	2625	14	2530
3	2545	15	2433
4	2434	16	2708
5	2469	17	2506
6	2556	18	2340
7	2384	19	2913
8	2409	20	2674
9	3056	21	2514
10	2954	22	2454
11	2890	23	2443
12	2535	24	2658

The load profile for a reference day in 2030 (aggregated loads) is presented in Table 4. In year 2030, the load is increasing with 20% compared to 2018 considering the forecast published by Transelectrica regarding the demand of the Romanian National Power System [12]. Aggregated wind generating is presented in Table 5.

Table 5

Aggregated Wind Power Plants Production

Time [h]	Aggregated Wind Generation [MW]	Time[h]	Aggregated Wind Generation [MW]
1	1474	13	1553
2	1279	14	1392
3	1244	15	1456
4	1276	16	1428
5	1359	17	1405
6	1459	18	1358
7	1536	19	1421
8	1289	20	1332
9	1426	21	1324
10	1512	22	1377
11	1377	23	1305
12	1532	24	1424

The place where the ESS are located can be seen in Fig. 1. The ESS have a conversion efficiency of 90% and the life cycle is 10 years. The capacity of the

Li-Ion batteries is 200MWh in the whole transmission network. The maximum state of charge in the whole system is 200 [MWh] while the minimum state of charge is 40 [MWh]. The charging and discharging efficiency are considered 90% and the value of loss of wind is considered 50 €/MWh.

The analyzed power system is a smart grid that contains: 11 generating units (10 thermal generating units and one hydro generating unit), 7 wind power plants, 28 transmission lines, 7 energy storage systems and 16 load demands.

In Table 6 the variation of the power produced by the hydro generating unit in 2030, in each case considered it is presented. The power produced decreases with 10% compared to the previous case.

Table 6

The Variation of Hydro Power Plant Generation Power in 2030

Time [h]	$P_{h,t}$ [MW]										
	Case 0	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**	**Case 9**	**Case 10**
1	210	189	168	147	126	105	84	63	42	21	0
2	210	189	168	147	126	105	84	63	42	21	0
3	210	189	168	147	126	105	84	63	42	21	0
4	210	189	168	147	126	105	84	63	42	21	0
5	210	189	168	147	126	105	84	63	42	21	0
6	210	189	168	147	126	105	84	63	42	21	0
7	191	149	123	102	81	60	39	18	0	0	0
8	165	144	123	102	81	60	39	18	0	0	0
9	210	189	168	147	126	105	84	63	42	21	0
10	210	189	168	147	126	105	84	63	42	21	0
11	210	189	168	147	126	105	84	63	42	21	0
12	165	144	123	102	81	60	39	18	0	0	0
13	182,6	161,6	140,6	108	96	72	39	18	0	0	0
14	210	189	168	147	126	105	84	63	42	21	0
15	210	189	168	147	126	105	84	63	42	21	0
16	210	189	168	147	126	105	84	63	42	21	0
17	210	189	168	147	126	105	84	63	42	21	0
18	165	144	123	102	81	60	39	18	0	0	0
19	210	189	168	147	126	105	84	63	42	21	0
20	210	189	168	147	126	105	84	63	42	21	0
21	210	189	168	147	126	105	84	63	42	21	0
22	210	189	168	147	126	105	84	63	42	21	0
23	210	189	168	147	126	105	84	63	42	21	0
24	210	189	168	147	126	105	84	63	42	21	0

4. Results

After solving the MM using the optimization software GAMS, the optimal economic dispatch of the smart grid resulted. In 2030 the consumption can grow with 20% compared to year 2018 and taking into account the global warming the evolution of the seasons is changing bringing droughts, fires or floods. Romania has been prevented so far from forest fires that have affected large areas of Europe in recent years, but this will change with the installation of long periods of drought, especially in Muntenia, Dobrogea and southern Moldova.

The analyzed grid (Fig. 1) is similar to the one that is located in the southeastern area of Romania (Dobrogea area) which leads to the possibility of drought occurring in this area, thus, the hydro power plant may have less power than the maximum power used. In Fig. 2 the location of the power system is presented. Thus, it is considered to determine the optimal operation of the smart grid by analyzing the sensitivity of the FOB when the power of the hydro generator is decreasing in case of drought.

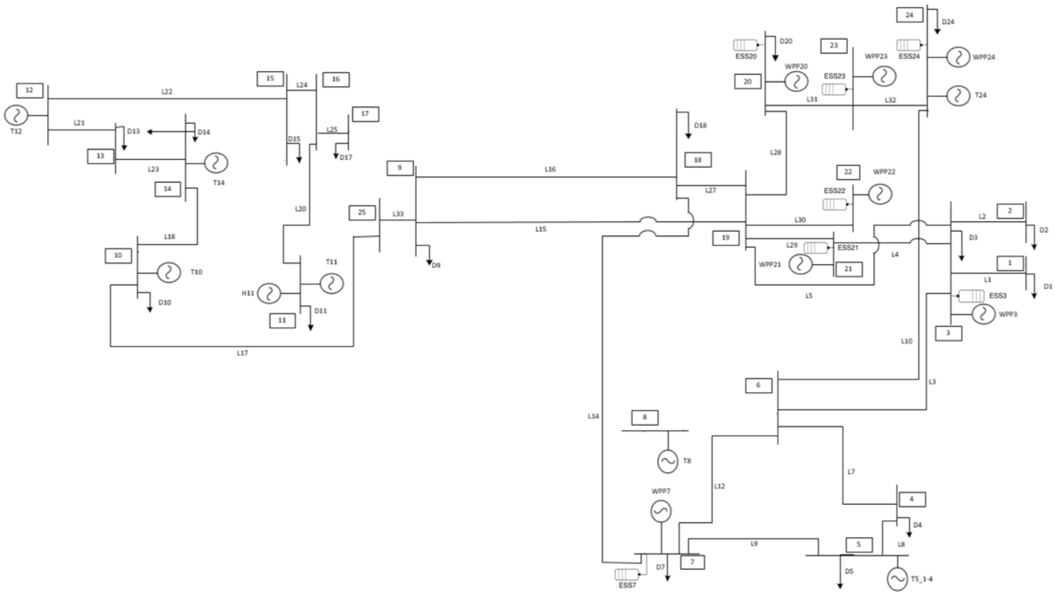

Fig. 1. The topology of the power system

The power of the hydro generating unit is decreasing with 10% compared to the normal operation power at which the hydro generator functions (210 MW). There are 11 cases considered, case 0 is the normal operation case where the maximum limit of the hydro generator is 210 MW and case 10 is the case where the hydro generating unit cannot supply the demands, thus the power produced is 0 MW.

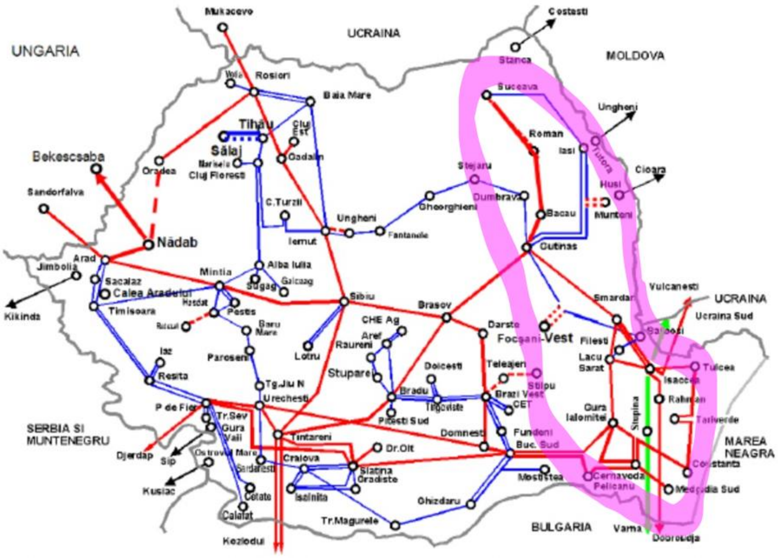

Fig. 2. The location of the power system

In Fig. 3 it is presented the variation of the FOB considering each case presented. It can be seen that: with the decrease of the power of the hydro generator, the value of the FOB increases, since the demands are supplied by thermal generating units that have a higher production cost.

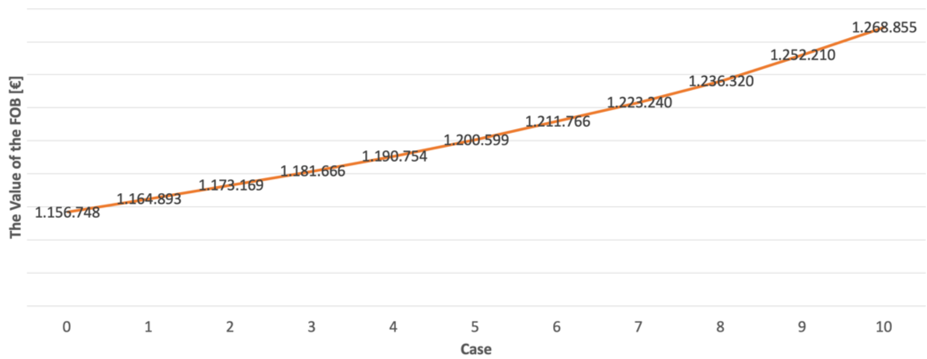

Fig. 3. The variation of the FOB taking into account the considered cases

In Fig. 4 the power produced by the thermal and hydro power plants in case 0 it is presented. It can be seen the optimal operation of the smart grid in 2030. In case 10 (Fig. 5), when the hydro generating unit is no longer producing, the power produced by the thermal power plants is increasing while respecting the system constraints (e.g. not exciding the capacity of the generators).

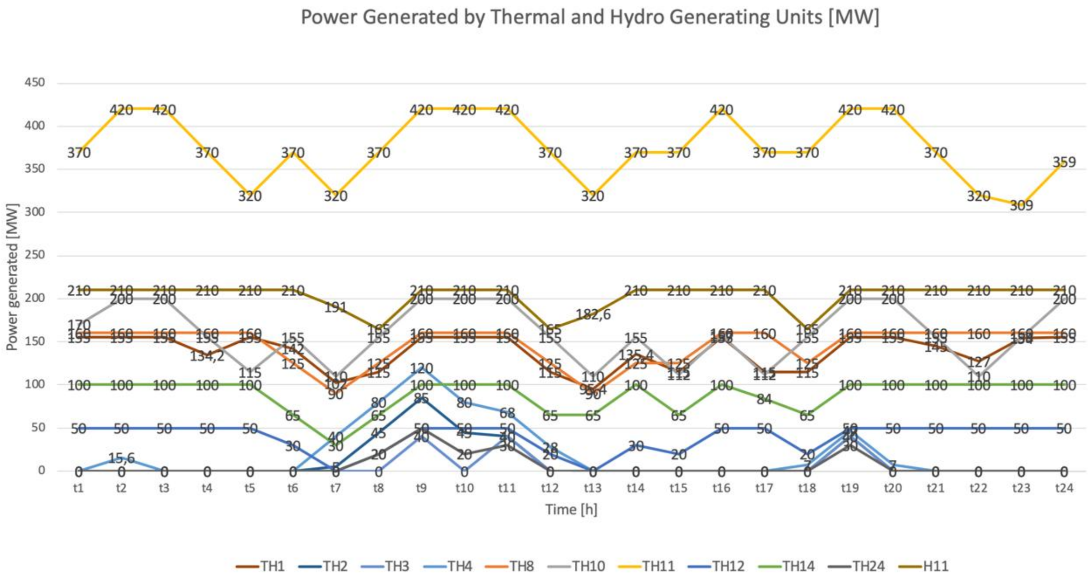

Fig. 4. The power generated by each hydro and thermal power plant for the case 0

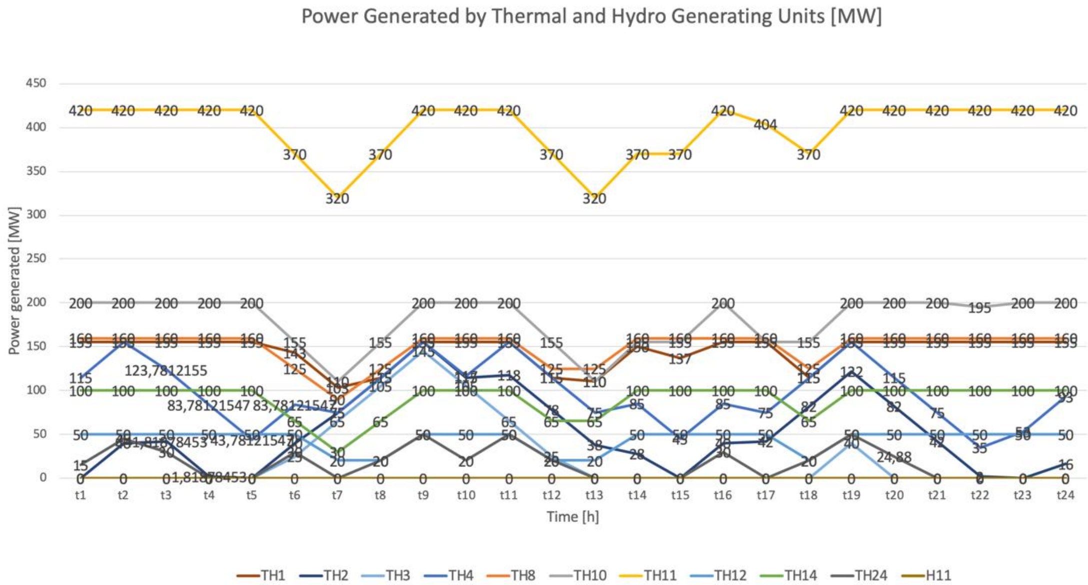

Fig. 5. The power produced by each hydro and thermal power plant for the case 10

In Fig. 6 charging and discharging of the ESSs in case 0, during the reference day of 2030 is represented and in Fig. 7 the charging and discharging of the energy storage systems in case 10.

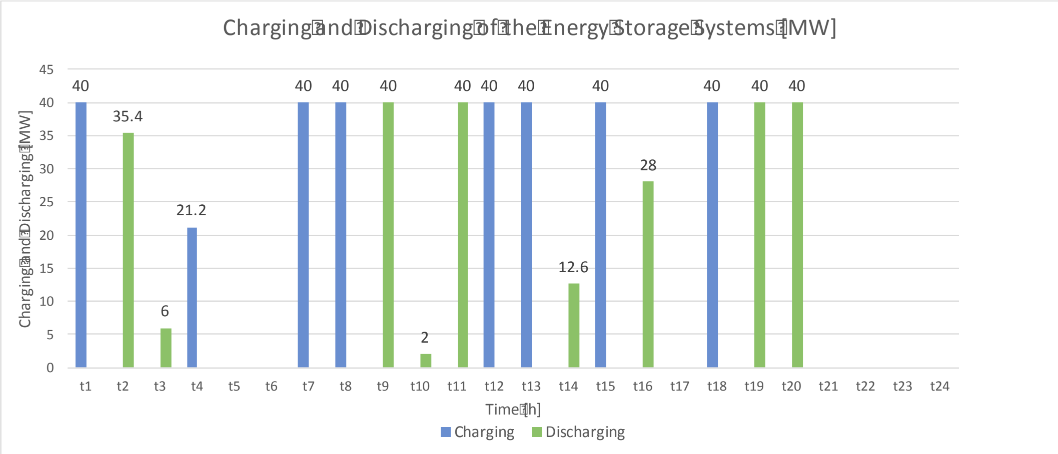

Fig. 6. Charging and discharging of the ESSs in case 0

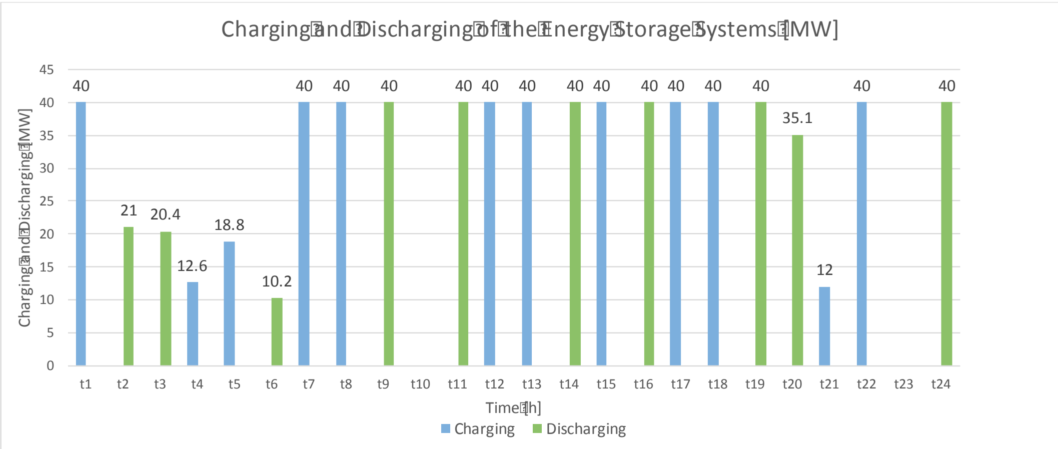

Fig. 7. Charging and discharging of the ESSs in case 10

It can be seen that in Fig. 7 the charging and discharging processes is done with more power than in Fig. 6 as the power of the hydro generating unit is 0.

In Fig. 8 the power produced by the wind power plants in both cases is represented. The power produced by the wind power plants is the same in both cases due to the fact that the wind power has a lower cost than the other generating units and thus the wind power plants are operating at maximum power. The forecast of the wind generating units for the reference day in 2030 is assimilated with the reference day from 2018 to which the consumption increased with 20%.

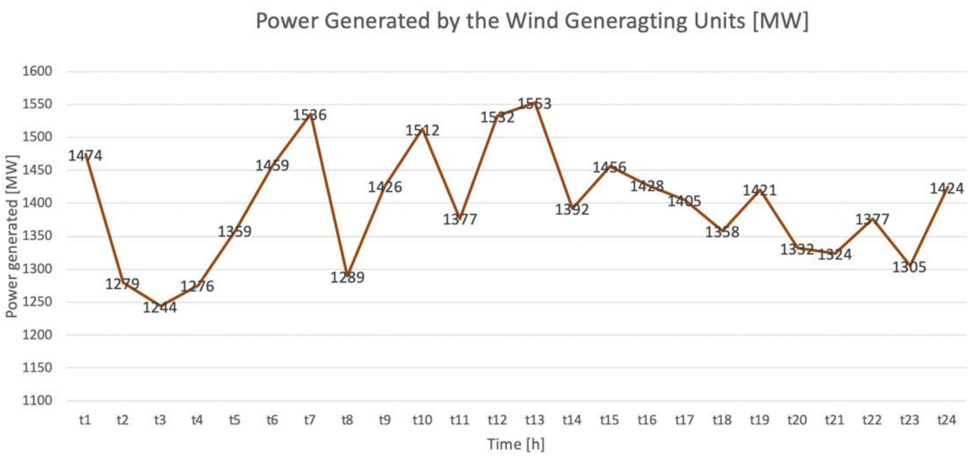

Fig. 8. The power produced by the wind power plants in case 0 and 10

In Fig. 9 the state of charge of the ESSs in case 0 in 2030 is presented and in Fig. 10 the state of charge of the ESSs in case 10 in 2030. It can be seen that the variations are more frequent in case 10 (the charging and discharging processes are realized with more power than in case 0) due to the fact that the hydro power plant is not producing energy and when is it possible and cheaper the power that should be produced by the hydro power plant is replaced by the ESSs and the thermal power plants. The production from wind power plants is the same and it is the maximum possible.

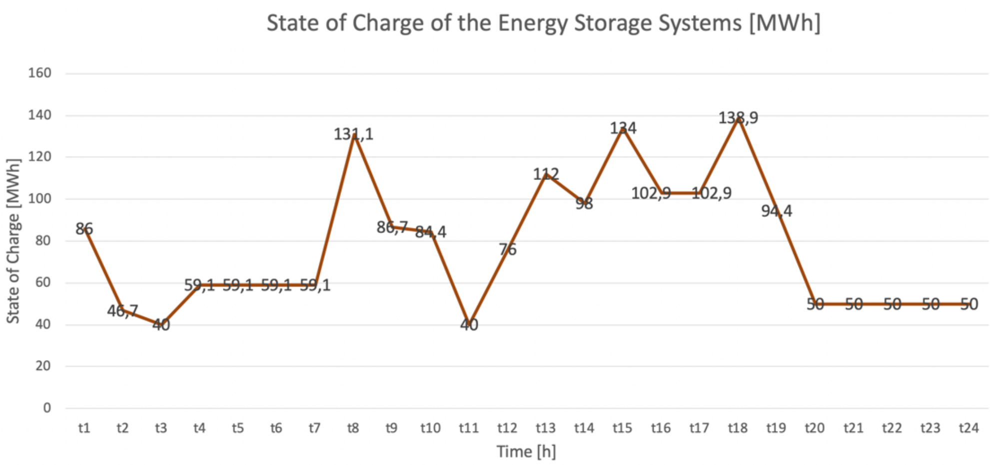

Fig. 9. The state of charge of the ESSs in case 0

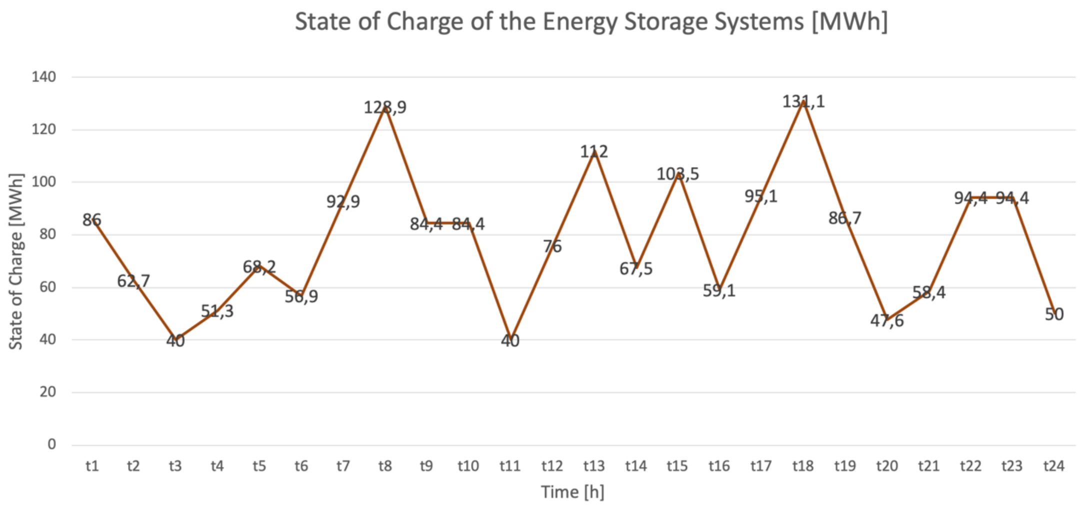

Fig. 10. The state of charge of the ESSs in case 10

The sensitivity of the FOB is presented in Fig. 11. It can be seen that with the decrease of the power produced by the hydro generating unit the value of the FOB increases (the operation costs increase) starting with 0.7% and end up with 1.33% if the hydro power plant is not functioning.

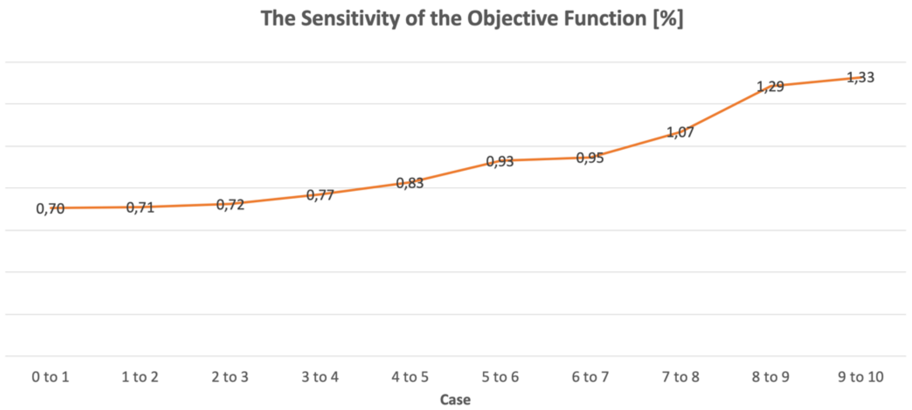

Fig. 11. The sensitivity of the FOB

5. Conclusions

The MM allows to determine the optimal economic dispatch/operation of the smart grid analyzed for the year 2030. In 2030 the consumption can grow with 20% compared to year 2018 and taking into account the global warming, the evolution of the seasons, droughts can appear thus the power generated by hydro power plants can decrease. The MM can be used by the national energy dispatcher that is in charge to economically dispatch the power generated in order to balance the power required (the consumption) taking into account the constraints of the transmission network. The analyzed grid is located in the southeastern area of Romania which leads to the possibility of drought occurring in this area, thus, the hydro power plant may have less power than the maximum power used. The optimal operation of the smart grid is determined by analyzing the sensitivity of the FOB when the power of the hydro generator is decreasing in case of drought. The value of the FOB is increasing concomitant with the decreasing of the maximum power limit of the hydro generating unit, thus the operational costs are increasing if the generating units that have a lower production costs are not functioning.

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