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Optimal Power Flow Analysis of a Power System with Distributed Generators and Storage Considering Seasons

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Abstract: The operation of the power systems is based on the power flow analysis, while the optimization is based on the optimal power flow analysis. The purpose of the study is to determine the generation cost and the power losses based on the optimal power flow analysis. The optimal power flow analysis starts by calculating the power flow in order to ensure the safe operation of the system, then the actual optimal power flow is performed considering the mathematical model. These studies are performed for the modified IEEE 39 bus system for an entire year, considering the seasons (spring, summer, fall and winter), and the average load power demand for these seasons, respectively. In this system are connected three distributed generation sources and two storage units. The optimization (optimal power flow) performed is multi-objective, minimizing the generation cost and the power losses (active and reactive) for the considered seasons. The results give, for all seasons, that the generation cost is higher, while the power losses are lower when the distributed generation sources and storage units are connected to the analysed power system.

Keywords: distributed generators; multi-objective optimization; optimal power flow; seasons; storage units

1 INTRODUCTION

The operation of the power systems is based on the power flow analysis, whilst the optimization is based on the optimal power flow analysis. The power flow (steady-state) analysis allows the verification of the conditions for safe operation of the electric power system. In order to solve the systems of nonlinear equations, iterative methods such as Seidel-Gauss or Newton-Raphson are used that allow obtaining the solutions after performing an indeterminate number of operations, through successive steps, approaching the result to the final value. The power flow analysis is the starting point in any subsequent analysis of the electric power system, such as the optimal power flow analysis.

The optimal power flow analysis allows planning and decision making for the system operator in order to ensure a reliable operation and management of power systems. A fixed generated power corresponds only to a single operating condition. An optimized operation, for a period of time, requires the generation sources to adapt, as loads change their power demand, and also due to power variations from renewable energy sources, sources which have been more present in the last decade. The optimal power flow problem is complex and nonlinear. The optimal power flow analysis is performed according to given objective functions, usually considering the minimization. Such usual objectives functions are the minimization of power losses or the minimization of generation cost. The application of this objectives immediately involves system constraints [1-4].

Such constraints are required so that the system's security is maintained, so each component in the power system must be kept between its desired operational range or bounds. The constraints include, for e.g., limits on bus voltages or maximum and the minimum power outputs for the generators [5-7].

In most power systems are now present renewable energy sources and storage units. Many of the renewable energy sources are installed near or at the load premises, so they are called distributed generation sources or distributed generators. Distributed generation sources help reduce power losses, increase the bus voltage, reduce the pollutant emissions and improve the reliability. These sources have a smaller installed power compared with traditional power plants. A disadvantage of these sources is the power variation caused by the primary resource, disadvantage that can be overcome by installing storage units. The storage systems that can be used are: compressed air energy storage, pumped hydro storage, hydrogen fuel cell storage, flywheels, supercapacitors, superconducting magnetic energy storage and batteries. These storage systems can store power for a limited time, such as supercapacitors, flywheels and superconducting magnetic energy storage, or for a long time, such as pumped hydro, compressed air, batteries energy storage and hydrogen. Considering the cost, power that can be stored, storage time and capacity, the option that will be considered in this paper are batteries [8, 9].

The current state of research includes: optimal power flow analyses (OPF), scheduling and power dispatch, capacity and location, management, control, configuration and restoration. The researches were carried out for systems in which were connected renewable energy sources and/or storage systems considering the steady-state of the systems or for a limited time frame, such as a day, with specialized software. In [2] it was studied a dynamical optimal power flow (DOPF) for active distribution networks and was performed for a time period of 24 hours (a day). The DOPF models curtailment of renewable energy sources, energy storage systems and flexible demand, maximized export and revenue, while the considered constraints maintained the supplied power by the generating units, voltage levels and power flows between limits. An AC-DC optimal power flow considering the installed power of the generation units, generation units cost coefficients and power demand was studied for the IEEE 14-bus system which was connected to two DC microgrids in [3]. The two objective functions minimized the total electricity generation cost of the network and the cost of active power from the AC grid to the DC microgrids. An OPF analysis was performed in [4] for an islanded microgrid considering the installed power of the microgrid components so the power losses were minimized. Optimal power flow analyses were performed for a day in [5-7, 10, 11] considering a Norwegian demo network, IEEE 14 bus test system, and the IEEE 30 bus system, that comprised energy storage units. The generation cost was minimized, while the constraints respected.

In [8] a review of the type of batteries was presented. The optimization of the capacities and location of dispatchable and non-dispatchable distributed generating units and storage units was studied in [9]. An OPF analysis was performed for a day considering the power demand in [12] for a distribution network (a modified IEEE 34 system) with distributed generation units based on genetic algorithm. The objective function purpose was to minimize the generation cost, generation cost and power losses, generation cost and voltage deviation, or the generation cost, power losses and voltage deviation. The optimal dispatch of the controllable loads, generating units and storage units of two microgrids was determined in [13], resulting in a lower cost of generating electricity. The optimal output power of the generating units and the battery charging/discharging schedule was determined in [14] so the generation cost was minimized, considering a day. The optimized control of the power flow of smart grids with renewable energy sources, flexible loads, storage units and electric vehicles was studied in [15], while the power flow to the electric vehicles was maximized. The OPF analysis performed in [16] considered the power dispatch for a medium voltage distribution network, and the minimization of the generation cost, respectively. A power flow management scheme for a microgrid by means of hybrid techniques was studied in [17, 18], and the optimal amount of power that was supplied by the sources was determined. An OPF analysis for microgrids with storage units was performed in [19] so that the storage units are optimally controlled. The objective was the minimization of the overall cost of power import from the main, while the constraints for the storage, voltage, currents and power limits were considered.

In [20] the OPF study was performed for the IEEE 37 system and for a smart microgrid, considering the minimization of either the generation cost or the power losses.

So, after the literature review, the following research gaps were identified. The power flow or optimal power flow studies of other researchers considered the installed power or were performed for a single day. However, the power demand and power supplied by the distributed generators have variations, especially considering the seasons. Also, in the systems with storage units, the OPF purpose was not to minimize two objective functions, namely the generation cost and power losses.

Our contributions by means of this paper are as follows:

- the optimization will be performed for a power system that comprises distributed generators and storage units;
- the optimization will be performed for four seasons (spring, summer, fall, winter) considering average load power demand, outputs from the distributed generation sources and from the storage units for these seasons;
- the optimization will minimize the total power losses and generation cost considering that all constraints must be respected;
- the cases that will be considered are: distributed generation sources and storage units connected to the system, and distributed generation sources and storage units not connected to the system.

In total 192 analyses (4 seasons, 24 hours, 2 cases) will be performed. So, the purpose is to determine an optimal operating point so that the demanded power is supplied to all loads, minimize the total power losses and generation cost considering that all constraints must be respected, obtain the values of the power losses and generation cost for each analysis and observe how the power losses and generation cost vary over the seasons. Then, the results (power losses and generation cost) for each season will be compared. Thus, it is possible to determine which is the season with the highest and lowest generation cost, and the power losses, respectively.

The paper is organized as follows. In Section 2, Materials and Methods, are presented the methods on which the optimization (optimal power analysis) is performed, and the modified IEEE 39 system data, respectively. In Section 3, Results and Discussion, are presented the results of the analyses and the interpretation of the results. In Section 4, Conclusions, are presented the conclusions regarding the paper, and the main ideas regarding the analyses performed and their importance.

2 MATERIALS AND METHODS

The optimal power flow analysis starts by calculating the power flow in order to ensure the safe operation of the system. After the parameters of the steady-state regime are known and is ensured the safe operation of the system, it is possible to perform the optimal power flow analysis. The optimal power flow analysis performed is based on the mathematical model that comprises the optimization variables, objective function and constraints [21].

The optimization variables are the power supplied by the generators, bus voltages, and the power flows from the generators to the loads, respectively.

The optimization (optimal power flow) performed is multi-objective, therefore the objective function purpose is to minimize the generation cost and the power losses. The two objective functions (generation cost and power losses) are correlated with each other. Therefore, each objective function has the same importance.

The equation is:

$$\min f\left(x\right)=GC\left(x\right)+\Delta S\left(x\right) \tag{1}$$

GC represents the generation cost €/h, ΔS represents the apparent power losses (total power losses) MVA.

The generation cost is expressed as follows:

$$GC\left(x\right)=a\cdot P_{Gi}^{2}+b\cdot P_{Gi}+c,\ €/\mathrm{h} \tag{2}$$

P_{Gi} represents the installed power of the generator i MW, a represents the cost of installing a MW for a generator €/MWh^2, b represents the cost of generating a MWh €/MWh, while c represents the cost of repair €/h.

The total power losses are expressed as follows:

$$\Delta S=\Delta P_L+j\cdot\Delta Q_L,\ \mathrm{MVA} \tag{3}$$

ΔP_L represents the active power losses MW, while ΔQ_L represents the reactive power losses Mvar.

The constraints are as follows.

The active power supplied by the generator must be between the minimum and maximum limits:

$$P_{G\min} \le P_G \le P_{G\max} \tag{4}$$

$P_{G\min}$ represents the minimum active power supplied by the generator MW, while $P_{G\max}$ represents the maximum active power that can be supplied by the generator MW.

The reactive power supplied by the generator must be between the minimum and maximum limits:

$$Q_{G\min} \le Q_G \le Q_{G\max} \tag{5}$$

$Q_{G\min}$ represents the minimum reactive power supplied by the generator Mvar, while $Q_{G\max}$ represents the maximum reactive power that can be supplied by the generator Mvar.

The bus voltage must be between the minimum and maximum limits:

$$V_{i\min} \le V_i \le V_{i\max} \tag{6}$$

$V_{i\min}$ represents the minimum voltage at bus i kV, while $V_{i\max}$ represents the maximum voltage at bus i kV. The minimum voltage is 0.95 of V_i, while the maximum voltage is 1.05 of V_i.

The power lines power flow must be between the minimum and maximum limits:

$$P_{l\min} \le P_l \le P_{l\max} \tag{7}$$

$P_{l\min}$ represents the minimum power flow that can be supported by the power line MVA, while $P_{l\max}$ represents the maximum power flow that can be supported by the power line MVA.

The active power supplied by the generators must be equal to the active power demand of the loads and the active power losses:

$$P_G = P_D + \Delta P_L, \text{ MW} \tag{8}$$

P_D represents the active power demand of the loads MW.

The reactive power supplied by the generators must be equal with the reactive power demand of the loads and the reactive power losses:

$$Q_G = Q_D + \Delta Q_L, \text{ Mvar} \tag{9}$$

Considering those mentioned above, the optimal power flow analyses will be performed for the modified IEEE 39 bus system for an entire year considering the seasons (spring, summer, fall and winter), and the average load power demand for these seasons, compared with other researches that considered only a limited time period, such as a day.

The modified IEEE 39 bus system has integrated three distributed generation sources (distributed generators), namely two photovoltaic (PV) power plants and one small-hydro generator, and two storage units (batteries). The PV and batteries are connected at bus 3 and bus 27, and the small-hydro generator is connected at bus 21. Bus 39 is the slack bus. G31, G32, G33, G34, G35, G36, G37, G38 and G39 are traditional power plants.

The one-line diagram and data for the system are presented further.

The one-line diagram is presented in Fig. 1.

In Tab. 1 and Tab. 2 are presented the generating unit data and cost coefficients, in Tab. 3 the loads data and in Tab. 4 the power line length.

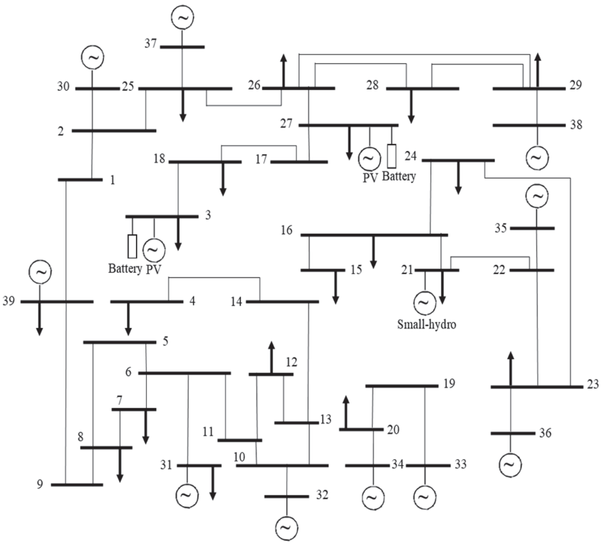

Figure 1 One-line diagram of the power system with distributed generation sources and storage units

Table 1 Generating unit data

Generating unit connected at bus	V / p.u.	$P_{G\min}$ / MW	$P_{G\max}$ / MW	$Q_{G\min}$ / Mvar	$Q_{G\max}$ / Mvar
3	1	0	5	−15	20
21	1	0	8	−20	25
27	1	0	4	−25	30
30	1.0475	0	80	−42	85
31	1.02	0	100	−53	105
32	1.02	0	65	−40	70
33	1.02	0	63.2	−40	68.2
34	1.0123	0	50.8	−40	60
35	1.0493	0	65	−50	70
36	1.04	0	56	−40	65
37	1.0278	0	54	−40	65
38	1.0265	0	83	−42	90
39	1.05	0	100	−80	120

Table 2 Generating units cost coefficients

Generating unit connected at bus	a / €/MWh^2	b / €/MWh	c / €/h
3	0.03	6	0.005
21	0.14	3.75	0.009
27	0.025	5	0.005
30	0.075	2.2	0.01
31	0.083	2.3	0.01
32	0.082	2.7	0.01
33	0.09	3.4	0.01
34	0.02	1.85	0.01
35	0.12	3.6	0.01
36	0.085	2.9	0.01
37	0.095	3.45	0.01
38	0.09	3.25	0.01
39	0.077	2.8	0.01

The installation cost (a) and generation cost (b) are higher for the distributed generation units compared with the traditional power plants, while the repair cost (c) is lower for the distributed generation units compared with the traditional power plants.

Table 3 Load data

Load connected at bus	*P* / MW	*Q* / Mvar
3	32.2	6.4
4	30	5
7	23.38	8.4
8	52.2	10.7
12	17.5	3.88
15	32	15.3
16	32.9	6.23
18	45.8	30
20	62.8	10.3
21	27.4	11.5
23	24.75	8.46
24	30.86	9.2
25	32.4	4.72
26	13.9	1.7
27	28.1	7.55
28	30.6	6.76
29	28.35	8.6
31	29.2	4.6
39	31.04	5.1

Table 4 Power line length

Power line between bus and bus	Power line length / km	Power line between bus and bus	Power line length / km
1 - 2	79.2	14 - 15	81.2
1 - 39	78.9	15 - 16	79.7
2 - 3	91.3	16 - 17	83.4
2 - 25	90.4	16 - 19	108.8
2 - 30	76.7	16 - 21	85.3
3 - 4	85.2	16 - 24	90.7
3 - 18	82.6	17 - 18	87.3
4 - 5	102	17 - 27	84.9
4 - 14	93.3	19 - 20	82.5
5 - 6	88.7	19 - 33	84.5
5 - 8	101.5	20 - 34	80.7
6 - 7	93.2	21 - 22	80.5
6 - 11	90	22 - 23	104.8
6 - 31	96.4	22 - 35	81.5
7 - 8	84.4	23 - 24	112
8 - 9	92.1	23 - 36	89.5
9 - 39	115.6	25 - 26	92.3
10 - 11	98.2	25 - 37	85.3
10 - 13	85.3	26 - 27	83.7
10 - 32	88.8	26 - 28	82.4
12 - 11	85.7	26 - 29	98.6
12 - 13	88.6	28 - 29	87.2
13 - 14	111.2	29 - 38	80.4

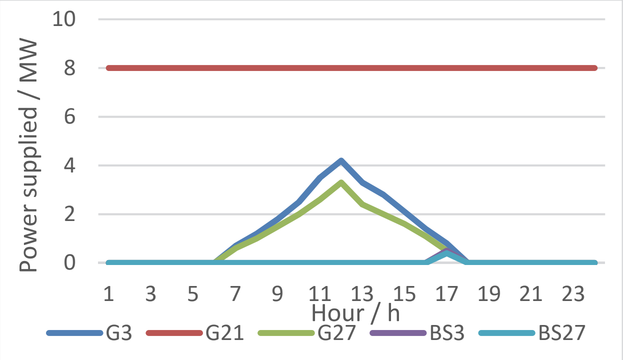

Figure 2 Power supplied (spring)

The active power of the system loads is 605.38 MW, while the reactive power is 164.4 Mvar. So, the total power demand is 627.3 MVA. In Fig. 2, Fig. 3, Fig. 4 and Fig. 5 is presented the power supplied, for the seasons, by the distributed generation sources (DG) and battery storage units (BS).

In Fig. 6 is presented the hourly load, for the seasons, at all buses.

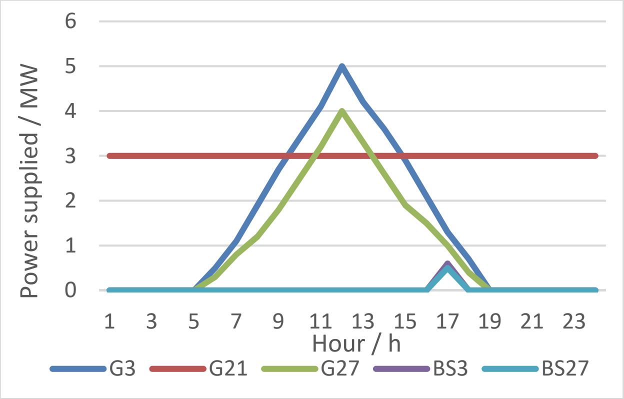

Figure 3 Power supplied (summer)

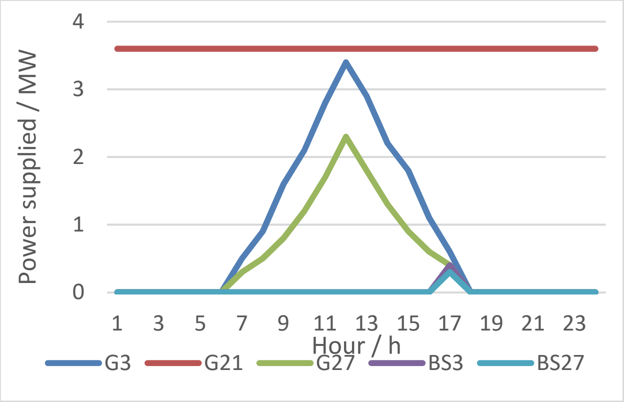

Figure 4 Power supplied (fall)

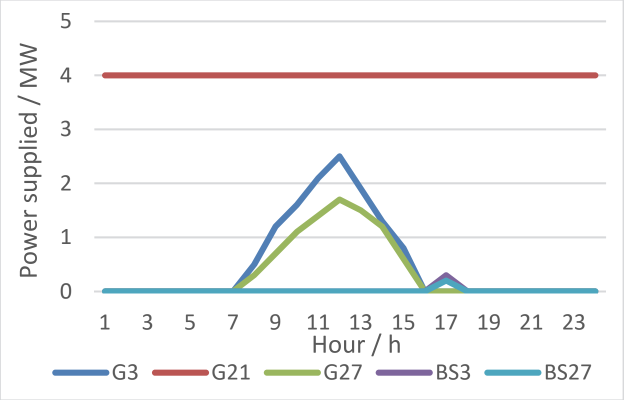

Figure 5 Power supplied (winter)

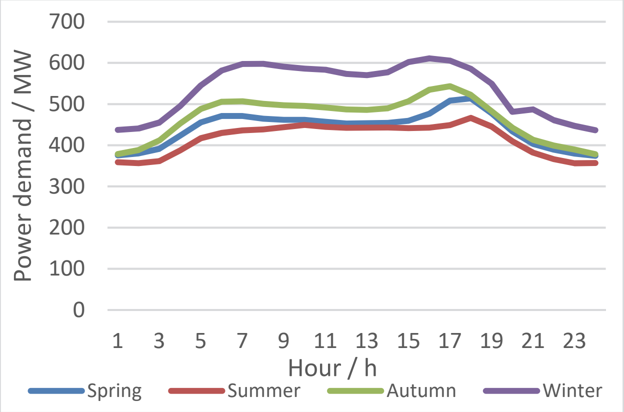

Figure 6 Power demand considering the seasons

This total load demand for the average season day is as follows: 10591.05 MVA for spring, 9969.26 MVA for summer, 11192.7 MVA for fall and 12897.77 MVA for winter. Also, in Tab. 5 is presented the scale factor for the seasons. The scale factor is used to multiply the active and reactive power of each load for the specified season and hour.

Table 5 Seasonal scale factor for loads

Hour	Scale factor (spring)	Scale factor (summer)	Scale factor (fall)	Scale factor (winter)
1:00	0.5986	0.5717	0.6035	0.6971
2:00	0.6062	0.5682	0.6189	0.7029
3:00	0.624	0.5765	0.656	0.7259
4:00	0.6747	0.6177	0.7221	0.7892
5:00	0.726	0.6651	0.7783	0.8692
6:00	0.7508	0.6854	0.806	0.9266
7:00	0.751	0.695	0.8079	0.952
8:00	0.7406	0.6989	0.7982	0.953
9:00	0.7363	0.7078	0.7922	0.9416
10:00	0.7359	0.7164	0.7901	0.9345
11:00	0.7284	0.7089	0.784	0.9301
12:00	0.722	0.7054	0.7764	0.9142
13:00	0.7234	0.7059	0.7743	0.9087
14:00	0.7241	0.7065	0.7809	0.9201
15:00	0.7327	0.7041	0.8079	0.9599
16:00	0.7599	0.7056	0.8526	0.9741
17:00	0.8102	0.7159	0.8661	0.9654
18:00	0.8191	0.7437	0.8329	0.9335
19:00	0.7614	0.7103	0.7693	0.8762
20:00	0.6917	0.6533	0.7059	0.7669
21:00	0.6435	0.6089	0.659	0.7761
22:00	0.6208	0.584	0.6364	0.7346
23:00	0.6054	0.5679	0.6207	0.7128
24:00	0.5967	0.5691	0.6029	0.696

The analyses will be performed with the software NEPLAN [22] for the considered seasons (spring, summer, fall and winter) for the cases when the distributed generation sources (DG) and battery storage units (BS) are connected to the system, and not connected to the system.

Therefore, the power supplied by the distributed generators and battery units for each season considering Fig. 2, Fig. 3, Fig. 4 and Fig. 5, the power demand for each load considering Tab. 5 and Fig. 6, are inserted in NEPLAN. For the other generating units power remains as defined in Tab. 1.

The optimal power flow analysis is performed for each hour and each season, selecting the objective function parameters and inserting the values for the constraints in NEPLAN. So, in total 192 analyses are performed (24 hours, 4 seasons and two cases).

3 RESULTS AND DISCUSSION

The results of the 192 analyses performed are presented further considering the active and reactive power losses, and the generation cost for each season, respectively.

The results are presented in Fig. 7 and Fig. 8 (spring), Fig. 9 and Fig. 10 (summer), Fig. 11 and Fig. 12 (fall), and Fig. 13 and Fig. 14 (winter).

The results for spring are as follows:

- the total power losses for a day (DG and BS connected) are 350.28 MVA;
- the total generation cost for a day (DG and BS connected) is 64000.15 €;
- the total power losses for a day (DG and BS not connected) are 508.76 MVA;
- the total generation cost for a day (DG and BS not connected) is 58760.67 €.

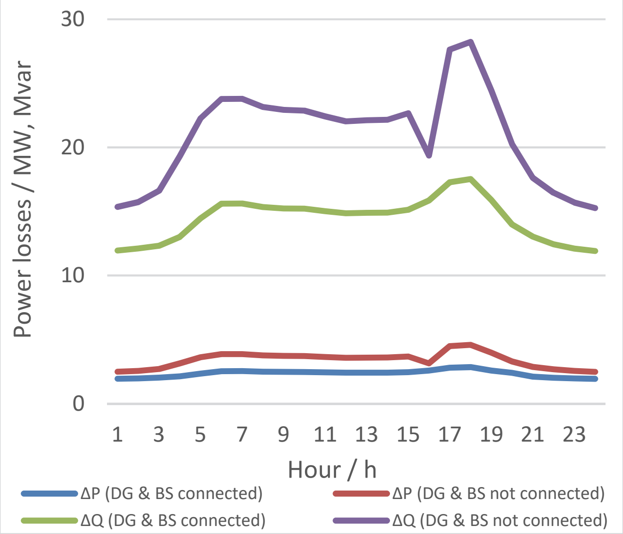

Figure 7 Spring results (power losses)

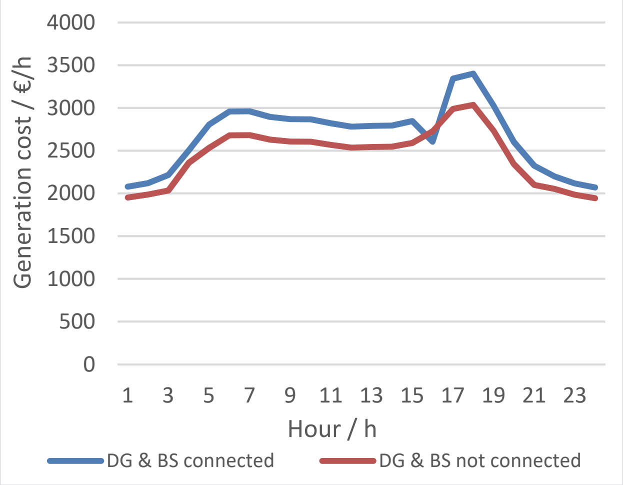

Figure 8 Spring results (generation cost)

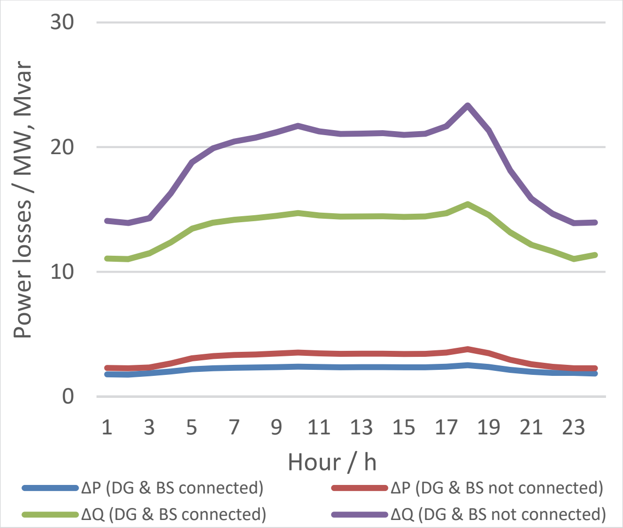

Figure 9 Summer results (power losses)

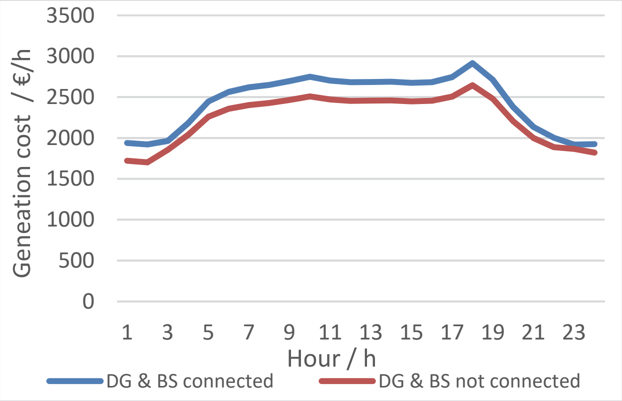

Figure 10 Summer results (generation cost)

The results for summer are as follows:

- the total power losses for a day (DG and BS connected) are 325.95 MVA;
- the total generation cost for a day (DG and BS connected) is 58579.46 €;
- the total power losses for a day (DG and BS not connected) are 456.76 MVA;
- the total generation cost for a day (DG and BS connected) is 53889.14 €.
- The results for fall are as follows:
- the total power losses for a day (DG and BS connected) are 377.73 MVA;
- the total generation cost for a day (DG and BS connected) is 70114.09 €;
- the total power losses for a day (DG and BS not connected) are 567.49 MVA;
- the total generation cost for a day (DG and BS connected) is 63736.09 €.

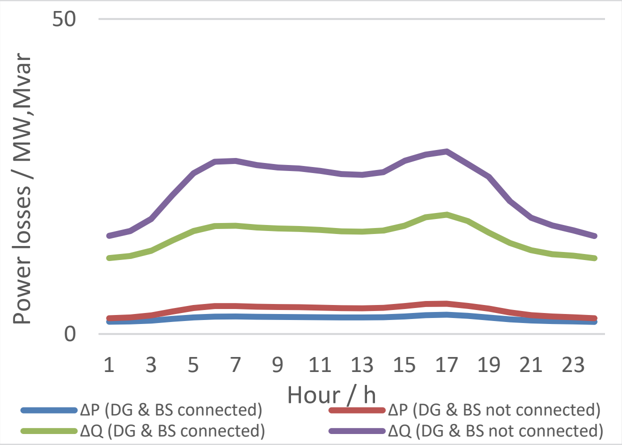

Figure 11 Fall results (power losses)

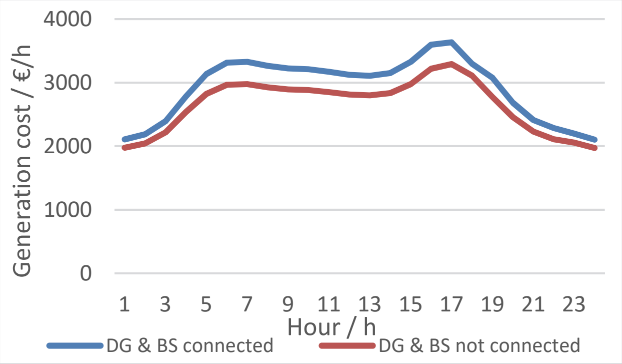

Figure 12 Fall results (generation cost)

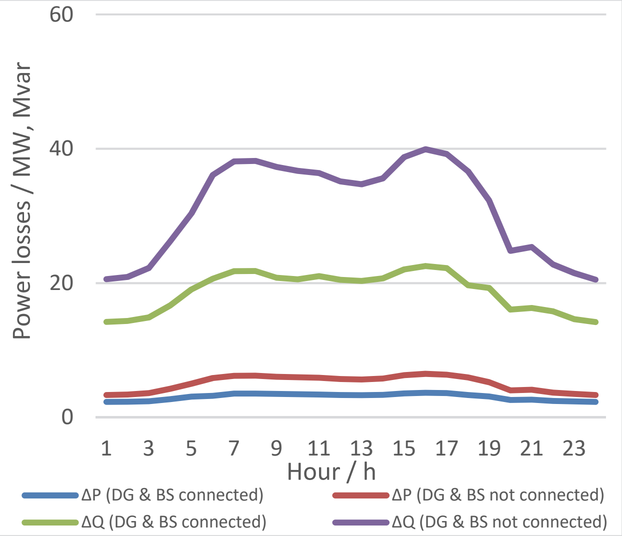

Figure 13 Winter results (power losses)

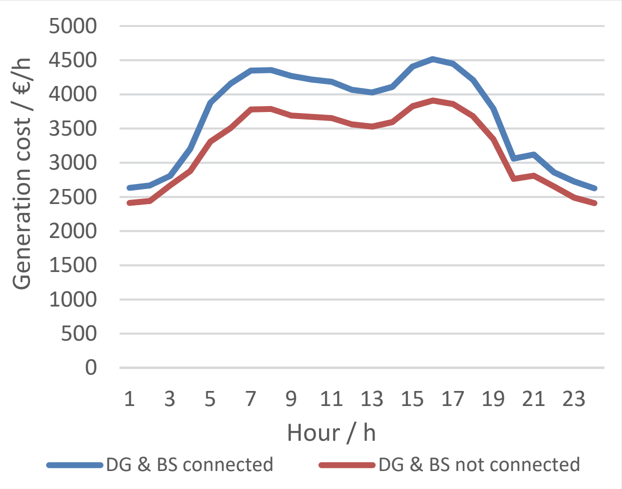

Figure 14 Winter results (generation cost)

The results for winter are as follows:

- the total power losses for a day (DG and BS connected) are 456 MVA;
- the total generation cost for a day (DG and BS connected) is 88694.75 €;
- the total power losses for a day (DG and BS not connected) are 760.25 MVA;
- the total generation cost for a day (DG and BS connected) is 78231.99 €.

The optimal operating point was determined and the demanded power was supplied to all loads. In the case the DGs and BS were not connected, all the other generating units supplied power. In the case the DGs and BS were connected, all the generating units supplied power. In all the cases, for all seasons, the total power losses and generation cost were minimized and the constraints respected. The analyses were performed based on the average load power demand for these seasons. This demand was higher for winter (the highest) and fall, and lower for spring and summer (the lowest).

For all seasons, the generation cost is higher when the DG and BS are connected. This is caused by the higher cost coefficients of the DG. The power losses, also for all seasons, are lower if the DG and BS are connected. This is caused by the power supplied by the DG and BS to the proximity load. The storage units helped lower the power losses when the power demand was high during the afternoon or evening.

Considering the seasons, the power losses and generation cost are lower for the season with the lowest power demand, namely summer and higher for the season with the highest power demand, namely winter. The power losses and generation cost for fall are higher compared with spring. These losses and cost increase or decrease according to the power demand, therefore if the power demand is higher the losses and cost are higher or if the power demand is lower the losses and cost are lower.

Also, based on the power supplied by the DG and BS during the seasons, the difference between the cases in which these are connected and not connected is lower for the summer, increases for spring and fall and reaches the peak for winter.

A comparison of the results determined by the model presented in this study with other models is difficult because the work of other researchers did not consider the same objective functions and constraints, time period (seasons) or distributed generators and storage units connected to the system. However, if we select the results from studies performed for a day then the following can be noticed. The power losses were lower if the distributed generators were connected. The generation cost varied according to the purpose of the study, so it was either higher or lower if the distributed generators were connected to the system or grid (higher if the generation cost was minimized, lower if the optimal management was determined).

4 CONCLUSIONS

In this paper were performed 192 optimal power flow analyses considering the seasons (spring, summer, fall and winter), the average power demand for these seasons, the power supplied by the three distributed generating units and two battery units for these seasons. The cases considered were: distributed generation sources and storage units connected to the system and distributed generation sources, and storage units not connected to the system.

The distributed generation sources and battery storage units had an impact on all seasons, reducing the total power losses and increasing the generation cost. These are lower for summer (325.95 MVA for DG and BS connected, 456.76 MVA for DG and BS not connected, 58579.46 € for DG and BS connected, and 53889.14 € for DG and BS not connected). The total power losses and generation cost increased during the spring and fall and reached the peak for winter (456 MVA for DG and BS connected, 760.25 MVA for DG and BS not connected, 88694.75 € for DG and BS connected, respectively and 78231.99 € for DG and BS not connected). So, if the power demand was higher the losses and cost were higher and if the power demand was lower the losses and cost were lower.

If we compare the power losses, they are lower for the case when the DG and BS are connected with approximately 29% during summer, 32% during spring, 34% during fall and 41% during winter. If we compare the generation cost, it is higher for the case when the DG and BS are connected with approximately 8% during summer, 9% during spring, 9% during fall and 12% during winter.

The studies performed did not consider a sudden drop of the power output of the distributed generation sources, which will be considered in a further study.

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