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Hourly Economic Dispatch of Generation Sources Considering the Minimization of Active losses and Generation Costs

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Abstract

The increase of renewable sources in the electricity sector, especially wind and solar photovoltaic, has drawn attention to the need to develop new models for planning and operating the electrical system. In this sense, this paper presents a model for the hourly economic dispatch of electric energy produced by wind, hydraulic, solar, and thermal sources. For the proposed mathematical modeling, the AMPL software was used, and for solution, the Interior Point Method was used, with the Knitro solver. The simulations were carried out in an IEEE 30-bus test system, considering two objective functions, namely: (1) hourly minimization of active power losses and (2) hourly minimization of generation costs. The simulations were carried out for 24 hours a day and for each hour the amount of energy generated, energy losses and generation costs were determined. Constraints related to the power balance, bus voltage levels, transformer tap limits, power factor limits and generation limitations were considered. Regarding the generation data of the wind and solar plants, large plants connected to the Brazilian electrical system were considered. The model presented proved to be efficient in solving the problem presented.

Keywords: Active power losses; economic dispatch; generation costs, generation sources.

1. Introduction

Population growth, as well as technological and socioeconomic developments, impact energy consumption and the way energy are required, with a notable increase in the demand for electricity.

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Studies carried out in Brazil [1] indicate that the energy supply per inhabitant will increase from the current 1.4 tonne of oil equivalent (toe) in 2019, to 1.7 toe in 2029, the year in which the internal energy supply will reach 380 million toe (growth rate of 2.6% per year). Due to the new environmental policies, as well as the strategy of diversifying energy sources, there is a worldwide search for less polluting and renewable sources. In the European Union for example, there is a target established for the year 2030 of 32% of participation of non-polluting renewable sources in the electric matrix (the previous target, for 2007, was 20%) [2]. In Brazil, where 81.7% of the electric energy produced comes from renewable sources, there has been a notable increase in the supply of wind and solar energy. In the last energy auction, held in June 2019, for example, 6 new solar generation units and 3 new wind generation plants were negotiated, with 203.7 MW and 95.2 MW of capacity and investments of R$ 856.2 and R$ 532 million, respectively [3]. This strong growth in the participation of intermittent sources has an impact on the models of planning and operation, pricing and commercialization of electric energy, and adaptations are necessary so that the intermittences in the generation of electric energy arising from these new generating sources are considered. This is an important problem for researchers linked to the energy sector, with several studies being published with proposals for possible solutions. A paper with the objective of carrying out the Hourly Economic Dispatch (HDE) considering thermal, wind and solar sources of energy generation was presented by [4], who used a methodology called Probabilistic Economic Dispatch Analytical Modeling. For validation of the model, the Interconnected System of Norte Grande (Chile) was considered, with 6% penetration of wind sources. The proposed methodology provided the system's marginal price probability distributions, thermal, solar and wind power generation and load rejection. The authors considered that the method and the modeling used had good performance and allowed a better visualization of the stochastic behavior of the energy dispatch. A methodology called Stochastic Model Predictive Control, to perform the DE of wind energy using Energy Storage Source (ESS) was presented by [5]. Wind power generation was modeled using a numerical programming methodology called Sparse Online Warped Gaussian Process, with wind generation data obtained from a real wind farm in China. The result was satisfactory when dealing with uncertainties, with the dispatch curve being very close to the expected. A model for dispatching renewable energy in real time and for the next day using ESS was proposed by [6]. The deterministic and stochastic Unified Unit Commitment and Economic Dispatch (UUCED) methodology was used to deal with wind load and generation uncertainty. The authors considered two-time frames for optimization, one hour an hour and another for a horizon of 36 hours. The method allowed the system to operate with a shorter cycle of thermal units, reducing operating costs. A Modified Particle Swarm Optimization (MPSO) algorithm was used by [7] to perform the DE with minimization of the total generation cost for the next day, in micro networks with high penetration of wind and solar photovoltaic energy, considering the presence of ESS. The forecast for wind generation was performed with Probability Density Function Weibull (PDF Weibull) and the forecast for solar energy generation with isotropic modeling. For the tests, the authors used a micro network developed by the Taiwan Nuclear Energy Research Institute. The presented methodology was considered effective for the solution of the dispatch problem for the following day in systems with high penetration of intermittent sources. In [8] a methodology called Improved Fireworks Algorithm with Non-Uniform Operator (IFWA-NMO) was proposed to perform the DE for the next day considering the presence of wind and solar generation. PDF Weibull methodology was used to model wind generation and PDF Beta was used to model solar generation. The method used presented good quality of results and was considered promising by the authors.

A distributed and asynchronous structure using mixed integer linear programming to solve the DE problem of Centralized Generation Units (UCED) was proposed by [9]. The conditions of price convergence were established by a Lyapunov function, with relaxed constraints and decomposed into subproblems. Tests carried out with 1,000 buses, considering generation and transmission constraints, demonstrated robustness of the methodology and speed in the solution. When tested in a 10,000 buses scenario, the algorithm just converged, but inefficiently. In this sense, this paper proposes a modeling of the problem of short-term optimal dispatch (hour by hour) of energy considering the presence of conventional sources (thermal, hydraulic) and intermittent renewable sources (wind and solar) from the use of the Interior Point Method. For that, two different objective functions were considered: (1) hourly minimization of active power losses and (2) hourly minimization of generation costs. Wind and solar generation was modeled based on historical generation profiles of two Brazilian plants, as will be presented in item 2.1.

1.1. Structure

This paper is organized as follows:

- Section 1 presents the scope of the work, which describes the problem to be addressed, the proposed objective and the methodology considered for solving the problem;
- Section 2 presents in more detail the materials and methods considered in carrying out the work. This section presents the electrical system used, the proposed modeling, as well as the objective functions and the considered constraints;
- Section 3 presents the tests and results performed, with an analysis of the simulations;
- Section 4 presents a discussion of the importance of the work carried out, highlighting some observed advantages;
- Section 5 presents the final conclusions of the work developed.

2. Materials and methods

In this paper, an Optimal Power Flow (FPO) was modeled based on two different objective functions: (1) hourly minimization of active power losses and (2) hourly minimization of generation costs. The electrical system used to validate the proposed FPO is presented in item 2.1. The power factor limits of the wind and solar photovoltaic units are presented in item 2.2. The optimization equations and the constraints used are presented in items 2.3, 2.4 and 2.5, respectively.

2.1. Electrical system considered

The Figure 1 illustrates the IEEE 30-bus electrical system with the insertion of the wind and solar plants considered. In this sense, the wind and solar plants were inserted in buses 6 and 11, respectively. The final system configuration had the following characteristics:

• Bus 1: Vθ bus (generation and angular reference) - Hydroelectric Plant;

• Buses 2, 5, 6, 8, 11 and 13: PV buses (generation);

• Bus 2: Thermoelectric Plant;

• Bus 6: Wind power plant inserted in the system;

• Bus 11: Solar plant inserted in the system.

For the wind and solar plants in buses 6 and 11, the generation characteristics of the Lagoa do Barro Wind Farm and the Nova Olinda Photovoltaic Complex were considered, for the month of June 2019, both connected to the Northeast Subsystem of the Brazilian National Interconnected System (SIN). These two plants were chosen because they are large and are physically close to each other, which facilitate the observation of the possible complementarity of generation between different sources of the system.

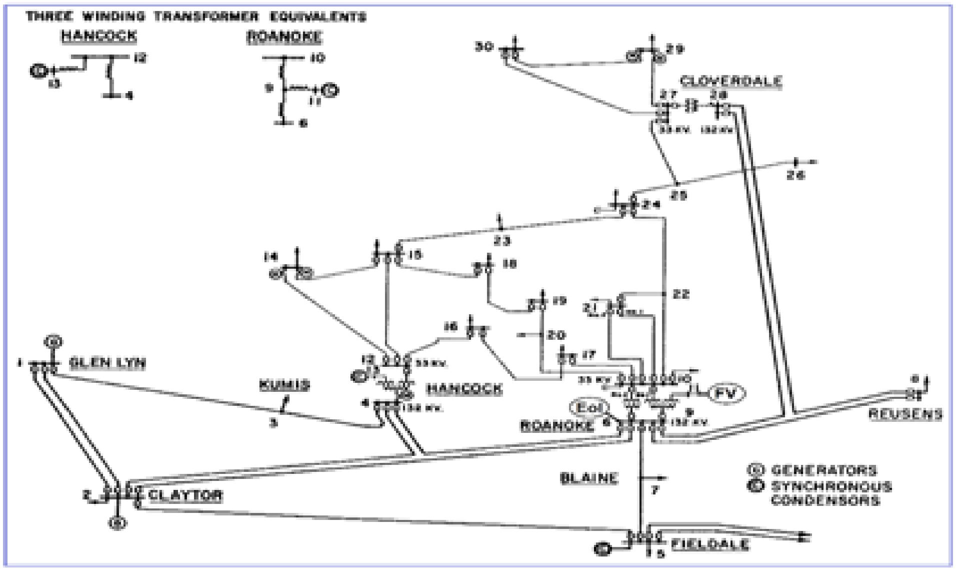

Figure 1: Modified 30-bus IEEE system [11].

The highest electricity generation rates at the Lagoa do Barro Wind Farm occur at night and in the morning. On the other hand, during the day the lowest generation value occurs, having its minimum around 02:00 p.m. The generation profile Lagoa do Barro Wind Farm is illustrated in Figure 2.

At the Nova Olinda Solar Photovoltaic Complex, the highest rates of energy generation occur between 08:00 a.m. and 04:00 p.m. During the night (between 06 p.m. and 05 p.m.) there is no power generation. The generation profile of the Nova Olinda Photovoltaic Complex is illustrated in Figure 3.

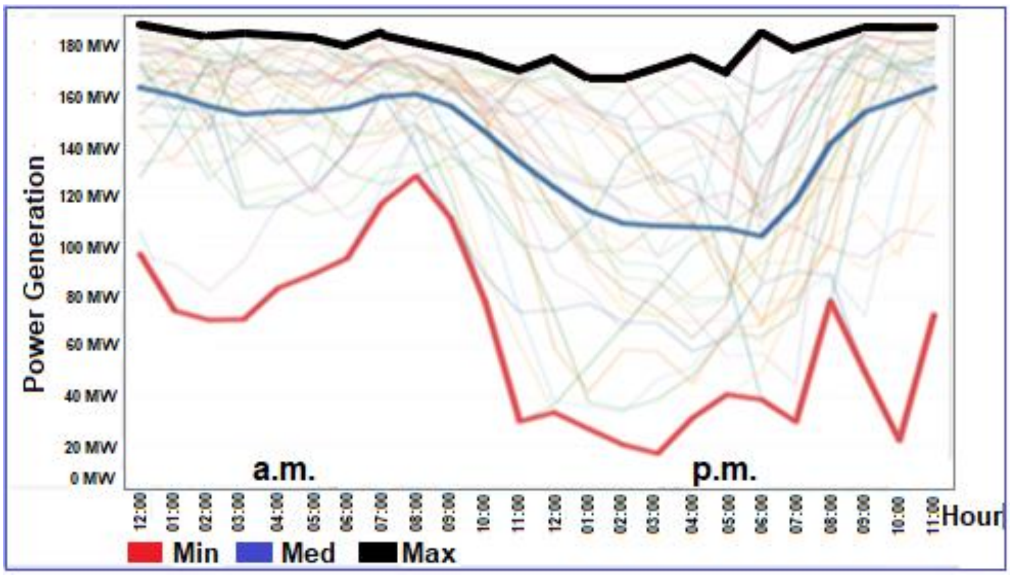

Figure 2: Hourly average generation of wind energy - 2019 / June - Lagoa do Barro Wind Farm - Northeast Subsystem [10].

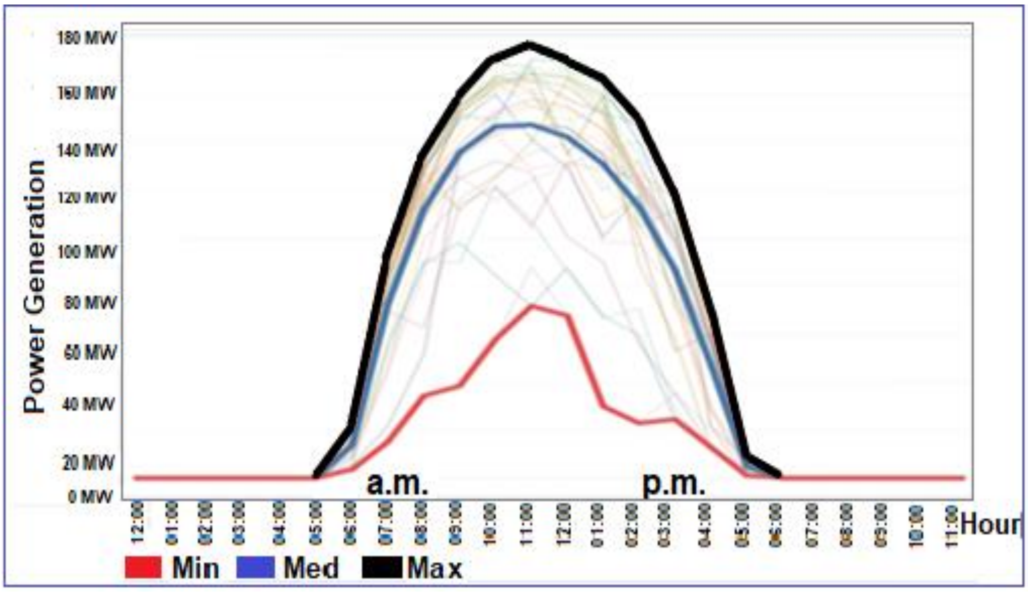

Figure 3: Hourly average generation of photovoltaic solar energy - 2019 / June - Nova Olinda Photovoltaic Complex - Northeast Subsystem [10].

2.2. Hourly dispatch problem model

The model proposed to hourly dispatch problem was performed using the AMPL software, and the Knitro software was used as a solver. As objective functions, hourly minimization of active power losses and hourly minimization of generation costs were considered. For the problem, a set of constraints was considered: power balance; wind and solar plant generation limits (represented in Figures 2 and 3, respectively), as well as hydraulic and thermal plant generation limits (set by the operator); power factor limits were set at 0.95 for the wind plant and 1.00 for the photovoltaic solar plant; bus voltage limits defined between 0.95 and 1.05; and transformer tap limits.

2.3. Hourly minimization of active power losses

The hourly minimization function of active power losses is represented by the Equation *(1)*.

$$Minimize$$

$$f(x,u,t) = \sum_{t=0}^{23}\sum_{K=1}^{NL}(G_{km}.\left(V_{k,t}^2 + V_{m,t}^2 - 2V_{k,t}V_{m,t}cos\theta_{km,t}\right) \qquad (1)$$

with $K = 1, \dots, NL$ where:

NL: Number of branches;

t: Represents the time;

G_{km}: Serial conductance between buses *k* - *m*;

$V_{k,t}$: Voltage magnitude in bus k at the time *t*;

$V_{m,t}$: Voltage magnitude in bus m at the time *t*;

$\theta_{km,t}$: Voltage angle difference between buses *k* – m at the time *t*.

2.4. Hourly minimization of generation costs

The hourly minimization function of generation costs is represented by the Equation *(2)*.

$$Minimize$$

$$f(x,u,t) = \sum_{t=0}^{23}\sum_{K=1}^{NB}(Peol_{k,t}.\rho eol_{k,t}) + \left(Psol_{k,t}.\rho sol_{k,t}\right) + \left(Pterm_{k,t}.\rho term_{k,t}\right) + (Phidr_{k,t}.\rho hidr_{k,t}) \qquad (2)$$

with $k = 1, \dots, NB$, where:

NB: Number of buses;

t: Represents the time;

$\rho eol_{k,t}$: Cost of MWh produced by the wind plant in bus *k* at time *t*;

$\rho sol_{k,t}$: Cost of MWh produced by the photovoltaic solar plant in bus *k* at time *t*;

$\rho term_{k,t}$: Cost of MWh produced by the thermal plant in bus *k* at time *t*;

$\rho hidr_{k,t}$: Cost of MWh produced by the hydraulic plant in bus *k* at time *t*;

$Peol_{k,t}$: MW produced by the wind plant in bus *k* at time *t*;

$Psol_{k,t}$: MW produced by the photovoltaic solar plant in bus *k* at time *t*;

$Pterm_{k,t}$: MW produced by the thermal plant in bus *k* at time *t*;

$Phidr_{k,t}$: MW power produced by the hydraulic plant in bus *k* at time *t*;

2.5. Constraints

The equality constraints associated with active and reactive power balance are shown in Equation (3) and Equation (4), respectively.

$$Pi_{k,t} = P_{Gk,t} - P_{Lk,t} = V_{k,t} \sum_{m \in k} V_{m,t} \left[G_{km} cos\theta_{km,t} + B_{km} sen\theta_{km,t}\right] \quad (3)$$

$$Qi_{k,t} = Q_{Gk,t} - Q_{Lk,t} = V_{k,t} \sum_{m \in k} V_{m,t} \left[G_{km} sen\theta_{km,t} - B_{km} cos\theta_{km,t}\right] \quad (4)$$

with $k = 1, \dots, NB$, where:

$Pi_{k,t}$: Net active power in bus *k* at time *t*;

$P_{Gk,t}$: Active power generated in bus *k* at time *t*;

$P_{Lk,t}$: Active power load in bus *k* at time *t*;

$Qi_{k,t}$: Net reactive power in bus *k* at time *t*;

$Q_{Gk,t}$: Reactive power generated in bus *k* at time *t*;

$Q_{Lk,t}$: Reactive load in bus *k* at time *t*;

G_{km}: k-m element of the conductance matrix;

B_{km}: k-m element of the susceptance matrix.

The inequality constraints are represented by the active and reactive power generation limits, voltage limits and tap transformer limits.

The constraints associated with active and reactive power generation limits in generator buses are given by (5) and (6), respectively.

$$P_{GK_{min},t} \leq P_{GK,t} \leq P_{GK_{max},t} \tag{5}$$

$$Q_{GK_{min},t} \leq Q_{GK,t} \leq Q_{GK_{max},t} \tag{6}$$

where:

$P_{GK,t}$: Active power generated in bus *k* at time *t*;

$P_{GK_{min},t}$: Lower limit of active power generation in bus *k* at time *t*;

$P_{GK_{max},t}$: Upper limit of active power generation in bus *k* at time *t*;

$Q_{GK,t}$: Reactive power generated in bus *k* at time *t*;

$Q_{GK_{min},t}$: Lower limit of reactive power generation in bus *k* at time *t*;

$Q_{GK_{max},t}$: Upper limit of reactive power generation in bus *k* at time *t*.

The operational limits related to bus voltage magnitudes are by Equation (7).

$$V_{k_{min},t} \leq V_{K,t} \leq V_{K_{max},t} \tag{7}$$

where:

$V_{K,t}$: Voltage magnitude in bus *k* at time *t*;

$V_{k_{min},t}$: Lower limit of voltage magnitude in bus *k* at time *t*;

$V_{K_{max},t}$: Upper limit of voltage magnitude in bus *k* at time *t*.

The constraints related to the minimum and maximum tap positions on in-phase transformers are represented by Equation (8).

$$Tap_{k_{min},t} \leq Tap_{K,t} \leq Tap_{K_{max},t} \tag{8}$$

Where:

$Tap_{K,t}$: Transformer tap in branch *k-m* at time *t*;

$Tap_{k_{min},t}$: Lower transformer tap in branch *k-m* at time *t*;

$Tap_{K_{max},t}$: Upper transformer tap in branch *k-m* at time *t*.

3. Tests and results

To validate the proposed model, tests were conducted on the IEEE 30-bus system considering a wind and a solar plant connected to buses 6 and 11, respectively, as shown in Figure 1. In this sense, two scenarios were analyzed, considering different optimization goals, minimization of generation costs or active losses.

To minimization of generation costs, the energy auction values published in [12] were based on the price basis for each generating plant, being:

- Hydraulic plant: R$ 285.00 / MWh;
- Wind plant: R$ 189.00 / MWh;
- Solar plant: R$ 209.00 / MWh;
- Thermal plant: R$ 292.00 / MWh.

3.1. Scenario 1: Hourly minimization of active power losses

For Scenario 1, the hourly minimization of active power losses was considered. The results obtained are shown in Table 1.

- The total active power generated in the 24-hour period was 6,112.89 MW. The total reactive power generated in the 24-hour period was and 2,097.11 MVAr;
- The wind power plant was dispatched with a unit power factor, and between 23:00 and 06:00, it was dispatched with an average of 95.68% of its capacity. Between 07: 00 and 22:00, the wind plant was dispatched with its maximum production capacity, which is because the largest load in this period;
- The wind plant produced 3,321.78 MW in a 24-hour period, accounting for 54.34% of the total system generation. This result is related with the wind plant is closed to the loads, promoting less transmission losses;
- The solar plant produced a total of 506.10 MW in a 24-hour period, which corresponds to 8.28% of the total active power system generation;
- If only the daily useful period of the solar plant (between 6:00 and 17:00 pm) is considered, the solar plant operated with an average of 56.40% of its total generation capacity, despite the cost per MWh produced by solar plant is less than the cost of energy produced by hydraulic and thermal plants. This is because the algorithm prioritized the sources that resulted in the lowest transmission losses, and not those with the lowest production costs.
- The wind and solar plants represented 62.62% in the total dispatched in the system in the 24 hours

considered in the simulation, totaling an amount of 3,827.88 MW;

- The total active power losses were 125.15 MW;
- The total generation cost was R$ 1,350,501.96.

Table 1: Simulation results - IEEE 30 bus system - Hourly minimization of active power losses.

Hour	P Generation Wind Plant (*MW*)	P Generation Solar Plant (*MW*)	P Generation in the System (*MW*)	Q Generation in the System (*MVAr*)	P Losses (*MW*)	Generation Costs
12 am	155.85	0.00	224.63	67.63	3.67	R$49,338.75
1 am	149.86	0.00	216.77	63.33	3.40	R$47,673.77
2 am	146.85	0.00	212.83	61.13	3.27	R$46,839.06
3 am	146.85	0.00	212.83	61.13	3.27	R$46,839.06
4 am	146.49	0.00	212.35	60.93	3.25	R$46,737.62
5 am	150.24	0.00	217.28	63.59	3.42	R$47,780.96
6 am	152.29	13.69	237.52	73.82	4.13	R$52,311.64
7 am	160.60	20.44	258.35	85.55	4.95	R$56,938.76
8 am	161.60	25.73	268.40	91.53	5.38	R$59,306.04
9 am	156.90	33.63	275.61	96.37	5.72	R$61,211.35
10 am	146.30	41.41	275.11	97.18	5.73	R$61,495.60
11 am	134.30	46.42	267.98	94.03	5.45	R$60,234.11
12 pm	124.00	59.70	278.47	103.72	6.04	R$63,201.95
1 pm	114.70	69.18	284.41	110.81	6.44	R$65,067.46
2 pm	109.60	72.54	284.23	112.20	6.48	R$65,252.40
3 pm	108.60	71.17	279.96	109.05	6.26	R$64,234.21
4 pm	108.10	47.30	264.80	93.68	5.58	R$61,775.88
5 pm	107.50	4.90	271.23	100.15	7.18	R$33,848.55
6 pm	104.40	0.00	275.76	104.95	7.91	R$68,848.30
7 pm	119.00	0.00	271.79	100.18	6.97	R$66,315.30
8 pm	141.70	0.00	274.51	99.44	6.41	R$64,912.66
9 pm	154.50	0.00	265.83	92.52	5.59	R$61,208.52
10 pm	159.30	0.00	249.21	81.91	4.66	R$56,013.21
11 pm	162.25	0.00	233.03	72.28	3.98	R$51,116.82
Total	3,321.78	506.10	6,112.89	2,097.11	125.15	R$1,358,501.96

From the results obtained in Scenario 1, the following points were observed:

3.2. Scenario 2: Hourly minimization of energy generation costs

For Scenario 2, the hourly minimization of generation costs was considered. The results obtained are shown in Table 2.

Table 2: Simulation results - IEEE 30-bus system - Hourly minimization of generation costs.

Hour	P Generation Wind Plant (*MW*)	P Generation Solar Plant (*MW*)	P Generation in the System (*MW*)	Q Generation in the System (*MVAr*)	P Losses (*MW*)	Generation Costs
12 am	164.30	0.00	225.14	69.22	4.18	R$ 48,393.36
1 am	161.10	0.00	217.25	64.77	3.88	R$ 46,450.04
2 am	156.80	0.00	213.30	62.58	3.74	R$ 45,737.07
3 am	153.50	0.00	213.31	62.68	3.75	R$ 46,058.43
4 am	154.60	0.00	212.83	62.42	3.73	R$ 45,814.59
5 am	154.60	0.00	217.79	65.26	3.93	R$ 47,229.03
6 am	156.20	13.70	238.09	75.68	4.70	R$ 51,819.78
7 am	160.60	72.50	259.54	98.68	6.14	R$ 53,041.13
8 am	161.60	106.24	270.93	127.48	7.91	R$ 53,626.47
9 am	156.90	102.59	277.53	127.19	7.64	R$ 56,353.79
10 am	146.30	102.03	276.64	125.55	7.26	R$ 57,227.55
11 am	134.30	104.33	269.62	123.92	7.09	R$ 56,020.08
12 pm	124.00	93.49	278.96	119.58	6.53	R$ 60,775.64
1 pm	114.70	79.95	284.47	115.24	6.50	R$ 64,266.31
2 pm	109.60	78.15	284.26	114.47	6.51	R$ 64,832.84
3 pm	108.60	86.30	280.07	116.02	6.37	R$ 63,116.96
4 pm	108.10	47.30	265.21	95.11	5.99	R$ 61,760.26
5 pm	107.50	0.00	272.99	106.37	8.94	R$ 33,422.82
6 pm	104.40	0.00	275.76	104.95	7.91	R$ 68,848.28
7 pm	119.00	0.00	271.79	100.18	6.97	R$ 66,315.30
8 pm	141.70	0.00	274.54	99.52	6.44	R$ 64,912.62
9 pm	154.50	0.00	266.22	93.85	5.98	R$ 61,194.75
10 pm	159.30	0.00	249.89	84.19	5.34	R$ 55,959.00
11 pm	164.20	0.00	233.61	74.19	4.56	R$ 50,814.87
Total	3376.40	886.58	6,129.74	2,289.10	141.99	R$ 1,323,990.97

From the results obtained in Scenario 2, the following points were observed:

- The total active power generation in 24 hours was 6,129.74 MW. The total reactive power generation in 24 hours was 2,289.10 MVAr;
- The wind plant was dispatched with maximum production capacity in the simulated 24 hours, and produced 3,376.40 MW (55.08% of the total active power generated in the system), operating with a unit power factor;
- The solar plant produced a total of 886.58 MW in the 24 hours considered (14.46% of the total active power generated in the system). If only the daily useful period of the solar plant (between 6:00 and 17:00 pm) is considered, the solar plant operated with an average of 75.55% of its total generation

capacity;

- The wind and solar plants represented 69.55% in the total dispatched in the system in the 24 hours considered in the simulation, totaling an amount of 3,827.88 MW, which corresponds to a 9.96% increase in the generation of these plants, when compared to Scenario 1, with a total loss of 141.99 MW;
- Finally, in Scenario 2, there was an increase of 11.86% in total losses of active power. This is because the algorithm prioritized the generation sources with lower generation costs and not those that would provide lower technical losses in the system. The total cost reduced was 2.54%;
- The total generation cost was R$ 1,323,990.97.

4. Discussion

The increase of intermittent generation sources in the electrical systems brings positive impacts as it allows an increase in the energy supply and source diversification. On the other hand, the stochastic nature of these energy sources must be considered. In this sense, currently, the predictability of the wind and solar plant generation, in general, is not foreseen in the planning and operation models, pricing and commercialization of electric energy. In this way, this paper was carried out in order to bring a contribution to the HDE problem considering the participation of large intermittent renewable sources, wind and solar, as well as the participation of conventional sources, hydraulic and thermal, in a system interconnected. The wind and solar plant energy generations were modeled in a deterministic way, based on the history of wind and solar generation plants located in the Northeast Subsystem of the Brazilian SIN. The use of generation data from large and physically close plants, connected to the same electrical subsystem, approximates the simulated scenarios to practiced scenarios, making it possible to observe the behavior of the plants in an interconnected system, which allows a forecast of generation complementarity between the different electricity generation sources. Another great advantage of the model proposed in this paper is the possibility of applying conventional deterministic techniques to deal with the stochastic nature of intermittent sources.

5. Conclusion

This paper presented a model for the hourly economic dispatch of electric energy. The problem was modeled mathematically from the AMPL software, where the generation characteristics of wind, solar, hydraulic, and thermal plants were considered. Additionally, some electrical system constraints were considered, such as: power balance constraints, voltage limits, transformer tap limits and generation limits, which could vary from hour to hour. As a solution method, the Interior Point Method was applied, using the Knitro solver. In order to validate the proposed method, tests considering data from the average hourly generation of wind and solar plants located in the Northeast region of Brazil inserted in the IEEE 30 bus electrical system were carried out. For the proposed tests, the generation costs considered for each source were different, varying from hour to hour depending on the investment cost, operation and maintenance costs, plant availability costs and primary energy source costs. For the tests considering the hourly minimization of generation costs, the final value per MW generated was lower. This result was as expected, having been confirmed, and is due to the directing of generation to the plants with lower costs per MW generated. However, an increase was noted in the total losses of active power in the system. The increase in losses in turn resulted in an increase in generation, which is mainly due to the power generation starting from the generation sources with lower costs per MW, even on occasions when it were far from the loads. On the other hand, the tests carried out considering the hourly minimization of active power losses resulted in an increase in the final value per MW generated, which happened due to the algorithm directing the power generation to the plants closest to the loads, which results lower energy losses. This also resulted in a decrease in the total power generated by the system. Based on the results obtained and analyzes performed, it is possible to state that the proposed model proved to be efficient in the search for the solution of the hourly energy dispatch problem presented.

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