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Analysing Renewable Energy Source Impacts on Power System National Network Code

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Abstract: This paper analyses the impact on renewable energy sources integrated into the Romanian power system on the electrical network operation considering the reduction of electricity consumption with respect to the 1990s. This decrease has led to increased difficulties in integrating the renewable energy sources into the power system (network reinforcements), as well as issues concerning the balance of production/consumption. Following the excess of certain proportions of the energy mix, intermittent renewable energy sources require the expansion of networks, storage, back-up capacities and efforts for a flexible consumption, in the absence of which renewable energy sources cannot be used or the grid can be overloaded. To highlight the difficulty of connecting some significant capacities installed in wind power plants and photovoltaic installation, the paper presents a case study for Dobrogea area that has the most installed capacity from renewable energy sources in operation.

Keywords: renewable energy sources; dynamic simulation; maximum share

1. Introduction

The European Union (EU), at the beginning of 2017, reviewed the Renewable Energy Directive 2009/28/EC for increasing the target of the share of renewable energy sources in the overall energy mix to at least 27% in 2030 and to become the world leader in renewable energy [1]. Thus, the interconnection of the high share of renewable energy sources in the existing power systems is a timely topic, with particular solutions applicable for each country. The analysis of interconnection of a large share of renewable energy sources into Greek power systems was investigated in [2], highlighting the impact of wind generators on power system adequacy and secure operation. The investigation of wind farms, mainly offshore, integration into the power systems in Europe and particularly in Germany is carried in [3]. Reference [4] analyses the impact of wind farms on the power system operation in Bosnia and Herzegovina, and the limited capacity that the power system flexibility can accommodate. The renewable energy sources have an intermittent character and their operation in the power system requires additional balancing actions, function of the available measures in the country of origin and net transfer capacity with the neighbouring countries [5]. The integration of the wind farms with important impacts on stability conditions under system faults and balancing reserve in the Spanish power system is investigated in [6]. The impact of wind farms on voltage profile in a power system area of Turkey is investigated in [7]. The analysis of wind farm integration into the California power system on the electricity market, balancing market and ramping necessities is investigated in [8].

The increase of the share of renewable energy sources in the overall energy mix can have important impacts on power systems operation, its level being determined by:

- the operating characteristics of sources and their generated power;
- the characteristics of the electrical grid where these sources are connected;
- the operating characteristics of the classical fuelled plants.

In agreement with national and European regulations, the network operators must allow the access of all customers, including renewable energy producers, to the electrical network. The economic advantages that EU and Romania offered to investors in renewable sources determined their massive development in the last decade. The Romanian power system operation is highly influenced by the interconnection of new renewable energy sources, mainly wind and photovoltaic.

The location of these sources is not consistent with the national power system necessities, but with the atmospheric conditions for renewable sources, determining the concentration of these new sources mostly in the south-east part. Because of this important concentration of renewable energy sources, their impact on the transmission system is highly important, even more as the transmission network was not sized and designed for these new operating conditions. In this paper, the influence of operation com-in of a wind farm of 600 MW (2 × 300 MW), the largest onshore farm in the south-east of Europe, was carried on.

The interconnection of renewable energy sources to the public network requires an analysis focused on three directions:

- analysing the possibilities, variants, conditions for system integration, in the location area—a local analysis involving a delimitation of the location area and verifying the operating conditions in steady-state regime, level of short-circuit currents etc.;
- analysing the operating conditions of the network after connecting the new renewable sources—local area analysis involving the study of network area where the new sources are connected;
- assuring the adequacy in case of high bandwidth variation in large limits of the sources' generated power, from zero to maximum power, for evaluating the operating conditions during one year, by analysing the momentary generated powers with respect to forecasted values on short time intervals.

The interconnection of renewable energy sources (RES) into the Romanian power system, from the transmission and distribution operator's point of view, determined:

- the requirement for infrastructure reinforcements;
- difficulties in balancing the production/consumption, requiring to shut down some priority sources (like hydro power plants) and the cross-border export that is not practically possible;
- the necessity to disconnect the RESs on the occurrence of outages in the Romanian power system, until the implementation of reinforcements;
- the necessity to establish a power reserve that can promptly balance the production/consumption, following the random operation of wind power plants and photovoltaic installations [9,10];
- informing the producers on the current necessity to procure the fast tertiary reserve, used for balancing the sudden variation of powers generated by wind power plants and photovoltaic installations.

The criterion for determining the maximum RES capacity that can be integrated into the power system is the fast tertiary reserve value available in the existing Romanian electrical network. This value is determined by the maximum capacity of wind power plants (WPP) estimated to be turned off/on which can be compensated for by charging/discharging the available fast tertiary reserve [11]. Based on the available production data from 2015, considering an average wind speed of 7.5 m/s, a maximum installed power in WPP of 2526 MW can be integrally taken by the Romanian power system. For the renewable energy sources installed capacity in the Romanian power system (2978 MW), at 1st of

January 2016, the available fast tertiary reserve during 2015 ensures absorbing the entire power production of WPP, for an average wind speed of only 7.1 m/s, for 90% of the year. In the period 2010–2015, the evolution of renewable energy sources installed (wind power plants WPP; photovoltaic installations PV; hydro power plants HPP; biomass) in Romania is illustrated in Figure 1. The national consumption during the period 2010–2015 remained practically the same, around 8000 MW peak load.

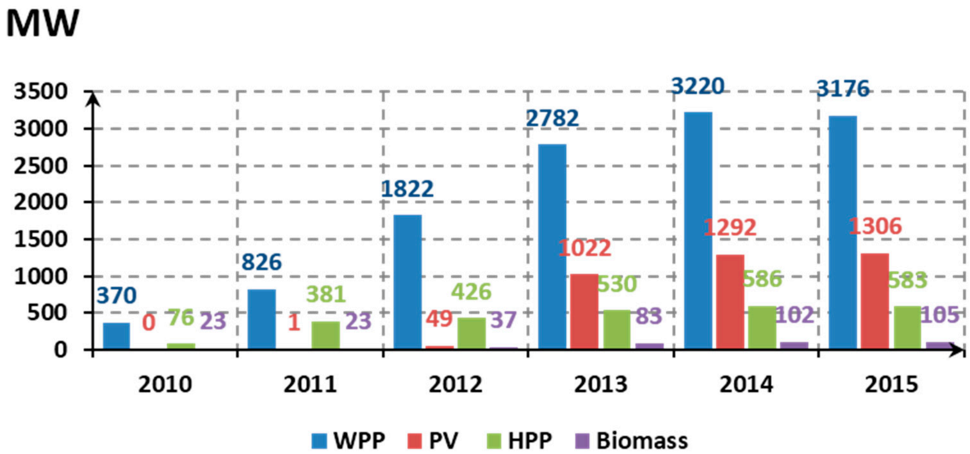

Figure 1. The evolution of renewable energy sources (RES) in Romania in 2010–2015.

As can be seen in Figure 1, wind power plants are more consistent, and their evolution was:

- In 2010, WPP in operation reached a capacity of approximately 370 MW without causing problems in the electrical distribution/transmission network;
- In 2011, WPP in operation reached a capacity of approximately 826 MW; at the end of 2011 WPP with connection agreements reached a capacity of approximately 8534 MW (power approximately equal to the power consumption at peak load); WPP with connection technical approval [12] reached a capacity of 9032 MW. The installed capacity of the photovoltaic installations was 1 MW in 2011. Transmission and distribution network reinforcements were proposed, with the obvious disadvantage that these reinforcements were not considered within the operator's development plans and the achievement of these reinforcements will be possible in a quite long period;
- In 2012, WPP in operation reached a power of approximately 1822 MW; at the end of 2012, WPP with connection agreements reached a capacity of approximately 14,573 MW and connection technical approval reached a capacity of 7850 MW. Photovoltaic installations received connection agreements and connection technical approval (ATRs), totalling 1000 MW of installed capacity. The important increase of renewable sources connection was determined by the governmental incentives, as green certificates, granted for each 1 MWh generation from renewable sources (3 green certificates for wind, and 6 green certificates for photovoltaic). The most strongly influenced by the interconnection of these power sources was the transmission system operator (TSO), because, without any reinforcement of the network, must accept approximately 3000 MW of WPP.
- In 2013, WPP in operation reached a capacity of approximately 2782 MW; at the end of 2013, WPP with connection agreements totalling approximately 14,604 MW and ATRs totalling 4000 MW. Photovoltaic installations received connection agreements and ATRs totalling the installed capacity of 6000 MW, and by the end of the year 1000 MW were put in operation. The important increase of PV was determined by the governmental incentives, as green certificates, granted for each 1 MWh generated from renewable sources (6 green certificates for photovoltaic). A significant share of installed wind power plants was concentrated in Dobrogea, south-east of Romania, and connected to the transmission and distribution networks. The 100 kV lines from districts Constanta and Tulcea (the most favourable for WPP due to high wind speeds) faced

important challenges, the connection decision imposing to the local distribution system operator the construction of over 11 new lines of 110 kV and/or the reconductoring of the existing lines. The end of 2013 brought changes in the legislation concerning the connection of sources to the public grid, determining the owners of these RESs to participate in reinforcing the grid. On long term, the changes in legislation can discourage investors, as shown by the trend in Figure 1;

- In 2014, WPP in operation had a slight growth and the number of sources that obtained connection agreements and connection technical approvals decreased. In this year, PVs of small capacity located in areas not experiencing the problem of reinforcement requirements were introduced. In addition, at the end of the year a governmental regulation decreasing the number of green certificates and rolling the incentives until 2018 was adopted.
- In 2015, no RESs were put in operation.

Currently, the connection agreements for RESs decreased to approximately 6144 MW (a sum that includes the 3176 MW already in operation). The need of reinforcements in the electrical network has not disappeared, being required in the Dobrogea area where there are connected wind power plants whose installed power exceeds 2000 MW.

The total net available power in the Romanian power system at the end of 2015 is reported in Table 1 and Figure 2: at 31 December 2015 was 22,256 MW, of which 29% in hydroelectric, 6% nuclear, 46% in thermal power plants, 13% wind power plants and 5% in photovoltaic.

Table 1. Net available power from power plants in the national power system.

Source Type	Installed Power * (MW)	Net Available Power ** (MW)
Hydroelectric power plant (HPP)	6731	6368
Nuclear power plant (NPP)	1413	1413
Combined heat and power plant (CHP)	11,997	10,256
Wind power plant (WPP)	2980	2944
Photovoltaic plant (PV)	1302	1176
Biomass power plant (BPP)	121	99
Total	24,545	22,256

* Not included: groups in conservation and groups decommissioned for more than a year that are in rehabilitation. Also included are groups in technological tests to commissioning; ** According ENTSO-E methodology, the net available power does not include permanent power cuts or own consumption in power plants. For hydroelectric power plants the net power of related hydraulicity outages was considered.

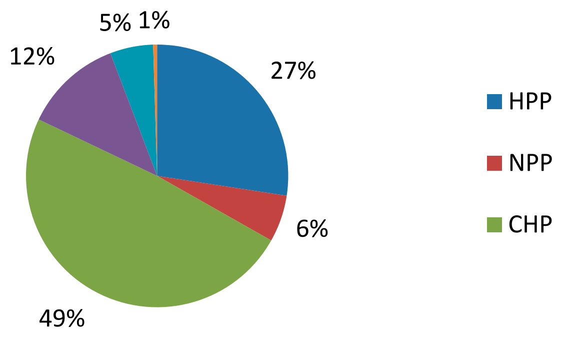

Figure 2. The installed power in various sources in Romania.

The general scope of the research is regarding the operation of the power system in the next period of 2017–2022, facing many uncertainties. If for supplying the end-users there are no important challenges (the installed capacity is highly exceeding the peak load), there are envisaged challenges regarding the energy sources mix and their integration within the production profile.

The structure of energy mix is determined by the electricity market, by the decisions regarding the operation of classical power plants (maintenance, development, etc.), by the future classical power plants, and in particular by the development of renewable energy sources, mainly wind power plants. This structure will influence the possibility of integrating the renewable energy sources on all layers—peak and off-peak, winter, summer—and the requirements for cross-border exchanges for balancing the production at the national power system level, the possibility to ensure enough reserve with the available sources.

The wind power plants are the major contributor to the Europe electrical energy balance, and are characterised by high production variability, a random participation within the whole production profile, and challenges in the frequency-active power control. The wind power plants, connected to the national power system, can lead to an overloading of the transmission and/or distribution networks, and the requirement that some WPPs reduce their production until the level where the congestion is eliminated. Also, the reduction of capacity reserve within the power system can occur.

The importance of the present research is related to the possibility to overcome the network congestions and the operating performance of the whole power system; the required safe operation will depend on the transmission expansion planning, the paper answering to this necessity and analysing the integrity of the system for contingencies with high/low probability of occurrence.

The novelty of this paper is that it gives the guidelines for a decision-making process leading to rapid implementation of renewable sources in the context of Romania's energy network. The scope of the present research is to analyse the challenges of Romanian power system safe operation determined by the interconnection of large wind power plants located in Dobrogea area, south-east of Romania. For evaluating the challenges of the Romanian power system and secure operation, in this paper were investigated:

- The impact of congestions occurring in the power system on the voltage level in the most relevant buses of the Romanian power system connected with the analysed network area;
- The impact of congestions in the transmission system occurring during periods of high power injected by the renewable energy sources;
- The dynamic studies of wind generators after short circuits occurring in the power system.

The current Romanian regulations, in agreement with European Network of Transmission System Operators for Electricity (ENTSO-E) regulations, are requiring that, for connecting dispatchable renewable energy sources to the transmission network, several studies must be conducted. The most important studies are:

- Influence of 70% of WPP installed power on the voltage level in the connection bus and vicinity buses (that means 420 (2 × 210) MW from the 600 MW installed in the WPP analysed);
- The impact of disconnecting a 400 kV line within the analysed area on the adjacent lines power flows, an impact which may lead to new power flows limiting the outgoing power from the WPP within the network;
- Dynamic studies analysing the voltage and frequency variations following the disconnection of the analysed WPP (210 MW);
- the dynamic studies of wind generators due to after short circuits occurring in the power system in the analysed area.

These studies highlight the influence of this new and large WPP on the power system, as well as the supplementary challenges incurred. The network bus where the analysis was conducted is highly important for the power system operation because it is the connection point for the highest capacity of the onshore wind farm (600 MW = 2 × 300 MW) from the south-east of Europe. Thus, the sudden loss of the 210 MW WPP studied within the paper (70% of 300 MW, representing half of the whole WPP) can lead to supplementary problems of secure operation of the power system. In addition, the south-east part of the Romanian power system is an area with production excess, connected with the rest of the country through a few highly loaded transmission lines, as most of the production from south-east of Romania is transferred to the centre and north-east of the country.

2. Transmission Expansion Planning (TEP)

With the development of renewable energy sources, the transmission expansion planning (TEP) problem was studied to investigate the possibilities for power system development (with minimum costs and limited investment budget) to better accommodate the supplementary energy production. Further, after verifying that it is possible through TEP, from the transmission lines capacity point of view, to accommodate all this additional production, we verified the conditions stipulated through National Transmission Network Code and ENTSO-E for the analysed WPP.

The objective function of the mathematical model is minimising the cost associated with the construction of the new transmission lines, the generation cost and load shedding cost:

$$min \sum_{l \epsilon l_p} CI_p^{im} u_l + \gamma \left[\sum_{gk} c_t P_t + \sum_d C_{LS}^d LS_d \right] + \gamma \left[\sum_{gw} c_w P_w + \sum_d c_{LS}^d LS_d \right] + \gamma \left[\sum_{gh} c_h P_h + \sum_d c_{LS}^d LS_d \right] \quad (1)$$

where:

d—demands;
h—hydro energy generation units;
t—thermal energy production units;
w—wind energy production units;
l—transmission lines;
b—buses;
CI_p^{im}—annualised cost for investing in new transmission lines l [Euro];
u_l—binary variable that is 1 if a possible line l is built, and 0 if a possible line l is not built;
γ—time period [hours];
c_t—cost of production of thermal unit t [€/MWh];
c_h—cost of production of hydro unit h [€/MWh];
c_w—cost of production of wind unit w [€/MWh];
P_t—power produced by hydro unit t [MW];
P_h—power produced by hydro unit h [MW];
P_w—power produced by hydro unit w [MW];
c_{LS}^d—load shedding cost of demand d [€/MWh];
LS_d—load shedding of demand d [MW].

In Equation (2), the cost associated with the construction of the new lines must be smaller than the threshold budget.

$$\sum_{l \epsilon l_p} CI_p^{im} u_l \leq BI_p^{ib} u_l = \{0, 1\}, \forall l \in l_p \quad (2)$$

where:

BI_p^{ib}—annualised budget for investing in construction of new transmission lines [Euro];
l_p—transmission lines possible to be build.

In Equation (3) is presented the balance between consumption and production and the power flow.

$$\sum_{t \in t_b} P_t + \sum_{h \in h_b} P_h + \sum_{w \in w_b} P_w - \sum_{l \backslash s(l)=n} PF_l + \sum_{l \backslash r(l)=n} PF_l = \sum_{d \in d_n} (L_d - LS_d), \forall b \quad (3)$$

where:

PF_l—power flowing through transmission line l [MW];
L_d—consumption of demand [MW].

DC power flow is considered in this paper, being expressed as:

$$PF_l = B_l\left(V_{s(l)} - V_{r(l)}\right), \forall l \backslash l \in l_p \tag{4}$$

where:
B_l—susceptance of transmission line l [p.u.]
$r(l)$—receiving node
$s(l)$—sending node
V_b—voltage angle at bus b [rad].

DC power flow is limited by the capacity of the transmission lines in any scenario as:

$$-C_l \leq PF_l \leq C_l, \forall l \backslash l \in l_p \tag{5}$$

where:
C_l—maximum capacity for transmission line l [MW]

$$-u_l C_l \leq PF_l \leq u_l C_l, \forall l \backslash l \in l_p \tag{6}$$

$$-(1-u_l)M \leq PF_l - B_l\left(V_{s(l)} - V_{r(l)}\right) \leq (1-u_l)M,\ \forall l \in l_p \tag{7}$$

The production of each generator cannot be higher the capacity of the generators:

$$0 \leq P_t \leq G_{t,} \forall t \tag{8}$$

where:
G_t—generation capacity of thermal unit t [MW].

$$0 \leq P_h \leq G_{h,} \forall t \tag{9}$$

where:
G_h—generation capacity of hydro unit h [MW].

$$0 \leq P_w \leq G_{w,} \forall w \tag{10}$$

where:
G_w—generation capacity of wind farm w [MW].

Load-shedding of demand d cannot be higher than the consumption of demand d and voltage angle at each bus must be between $-\pi$ and π.

$$0 \leq LS_d \leq L_d, \forall d \tag{11}$$

$$-\pi \leq V_b \leq \pi, \forall b \tag{12}$$

$$V_b = 0,\ reference\ bus \tag{13}$$

The TEP analysis is not presented as it is not the subject of this paper, but it was made in order to be able to proceed with the conducted analysis in the following sections [13].

3. Materials and Methods

In this paper, a network very similar with a part of the Romanian transmission systems was used. The scheme was implemented and analysed with professional software. The map of the Romanian transmission system is illustrated in Figure 3 [14]. A more detailed map of the Romanian transmission system including the wind power plant's location can be found at [15]. As it can be seen, there is a high density of sources in the south-east part of Romania, where the meteorological conditions are favourable. In this part, there is a high excess of production determined by the operation of 2 nuclear units (totalling 1400 MW). Moreover, there is a prospective project of building another two nuclear units.

The methodology approached in the paper deals with the impact studies and analyses stipulated by the network National Code and ENTSO-E recommendations [16,17]. The paper does not deal with the impact of all renewable energy sources from Romania on the entire power system, but only with the impact of the WPP analysed.

The main challenges determined by the consumption reduction and increase of installed capacities in RES are:

(a) technically:

- establishing the network capacities required for the power take in;
- balancing production/consumption, under the specific conditions of the national power plants (nuclear power plant, combined heat and power plant, hydro power plants, thermal power plants, gas-fired turbines);
- feasible trades with neighbouring countries (the transfer limit amounts to 2000 MW), and for which contracts should be established;
- the determination of a fast tertiary reserve allowing the balance of production/consumption in a short time, on the occurrence of power variations of the wind power/photovoltaic production [16,17];
- implementing the necessary network reinforcements for connecting RES under the conditions of volatility of primary source [18], uncertainties on requirements for these consolidations and the time non-correlation between investments and necessities;

(b) regulatory:

- falling under the national targets on the production from RES;
- the annual quotas of green certificate acquisitions [19];
- establishing the contribution method for the reinforcement investments.

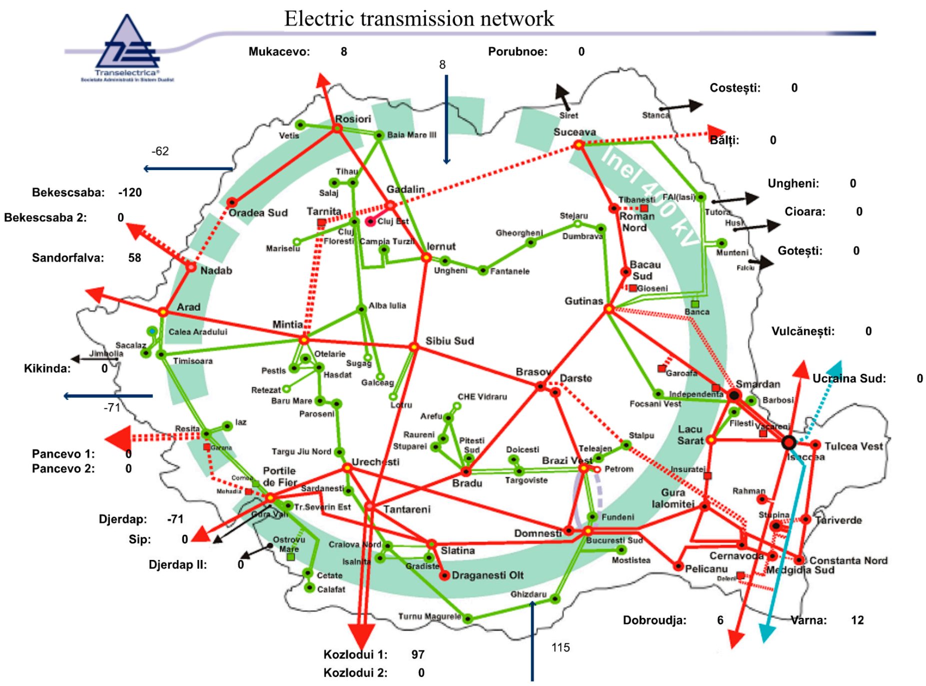

Figure 3. Electric transmission network [14].

Beside the fast-tertiary reserve, another principle of the calculation methodology for determining the maximum allowable RES into the existing power systems is considering RES as having a common mode of operation, being an equivalent generator characterised by an instant capacity to turn on/off. Thus, the maximum power estimated to be stopped/started in RES (almost simultaneously) can be compensated for by charging/discharging the available fast tertiary reserve.

As it can be seen in Figure 3, there is an over-generation in the eastern part of the Romanian power system because of the two future nuclear units (Units 3 and 4 of NPP), and especially wind power plants, totalling more than 5000 MW of connection agreements.

In these conditions, the interconnection of new generation capacities concentrated in areas with a low power consumption, far away from other centres of consumption, leads to important power flows on outgoing transmission lines with possible overloading of existing infrastructure.

The total installed power in Dobrogea region of Romania is 2879 MW in WPP and 118 MW in PV installations. The total outgoing power, i.e., 70% of installed capacity (the average considered production in the Romanian power system) in the same area, is 2015 MW in WPP and 95 MW in PV installations.

Figure 4 illustrates the power system within the Dobrogea area when N elements are in operation.

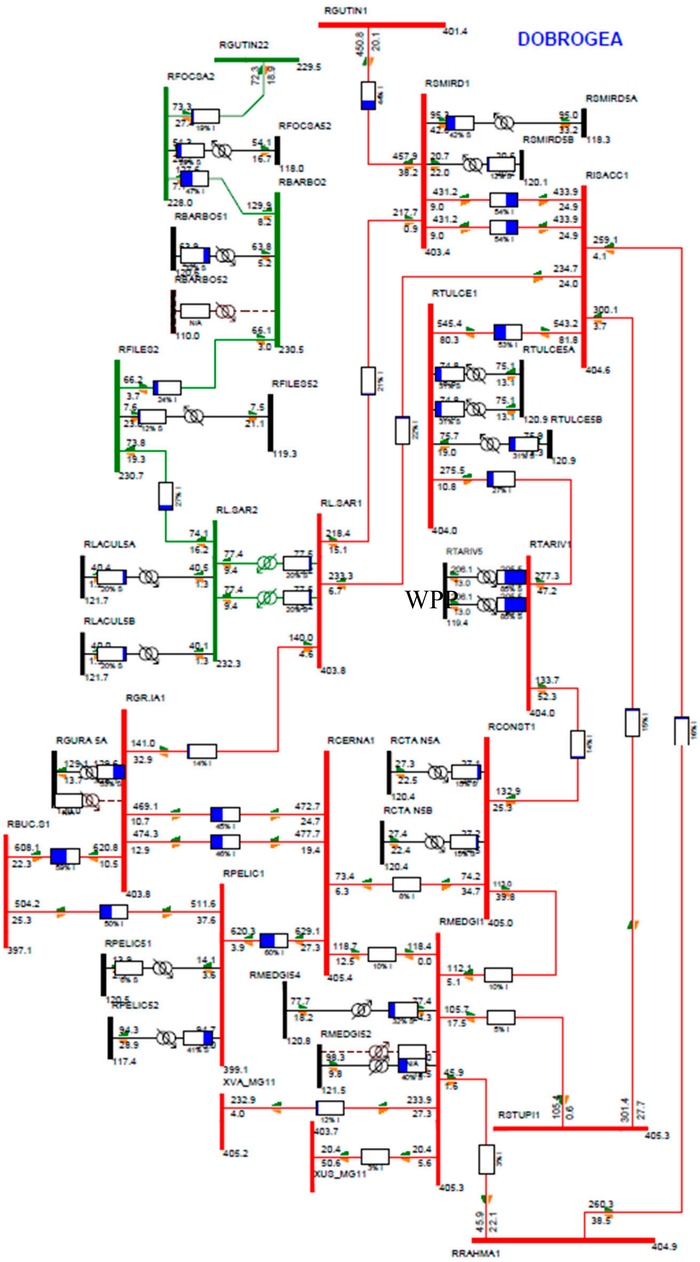

Figure 4. Dobrogea area in the case with N elements in operation.

4. Results

4.1. Voltage Profile Variation and Overloading of Network Elements under Congestions

Different simulations were conducted, considering the disconnection of a 400 kV transmission line, a nuclear unit or a large wind power plant are out of operation, respectively a high capacity transmission line is disconnected.

Figure 5 illustrates the rms voltage levels of 400 kV buses in the Dobrogea area. As shown, the disconnection of a 400 kV line determines a decrease of voltage level with maximum 0.1 p.u. The disconnection of a nuclear unit (Cernavoda unit) or of a large wind power plant (WPP Tariverde) initially determines an increase of voltage level by 0.01 p.u.

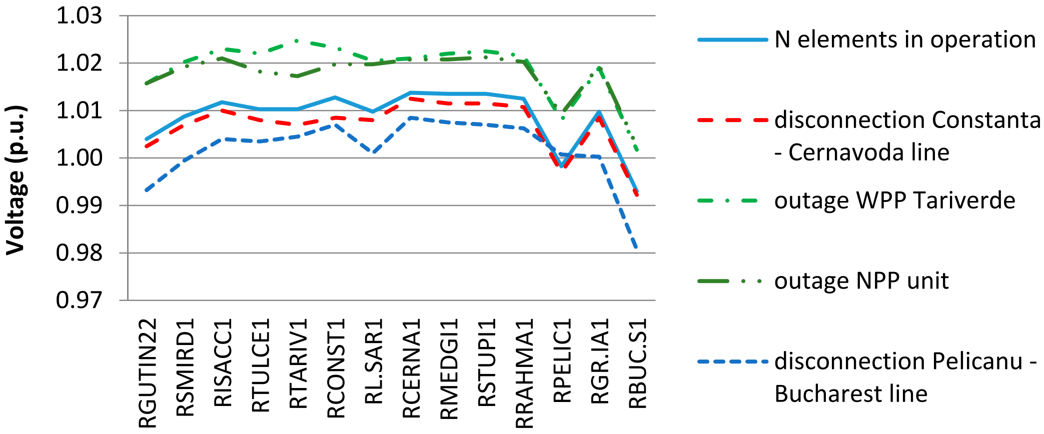

Figure 5. Voltage variation at 400 kV buses (p.u.).

Regarding the overloading of transmission lines, the unavailability of some power system components (like transmission lines or transformers), and simultaneously a high production of renewable energy sources can determine the overloading of the power system within the Dobrogea area. Figure 6 illustrates that the outage of circuit 1 of 400 kV overhead line Isaccea—Smârdan determines the overloading of circuit 2, a function of the high WPP production (90% of installed power).

The overloading of the power system within Dobrogea area is determined by the disconnection of the 400 kV line Cernavoda—Medgidia Sud, determining the overloading of 400/110 kV transformers from Medgidia Sud substation (as shown in Figure 7). The 110 kV area connected to these buses has WPP with capacity exceeding 1000 MW. In this area, a third transformer of 400/110 kV must be connected in Medgidia Sud substation (it is the reserve transformer for the two operating ones). The major challenge to be solved in operation with two transformers 250 MVA 400/110 kV is sizing the breaker within the substation for short-circuits, as operating with three transformers exceeds the limit of 31.5 kA at 110 kV.

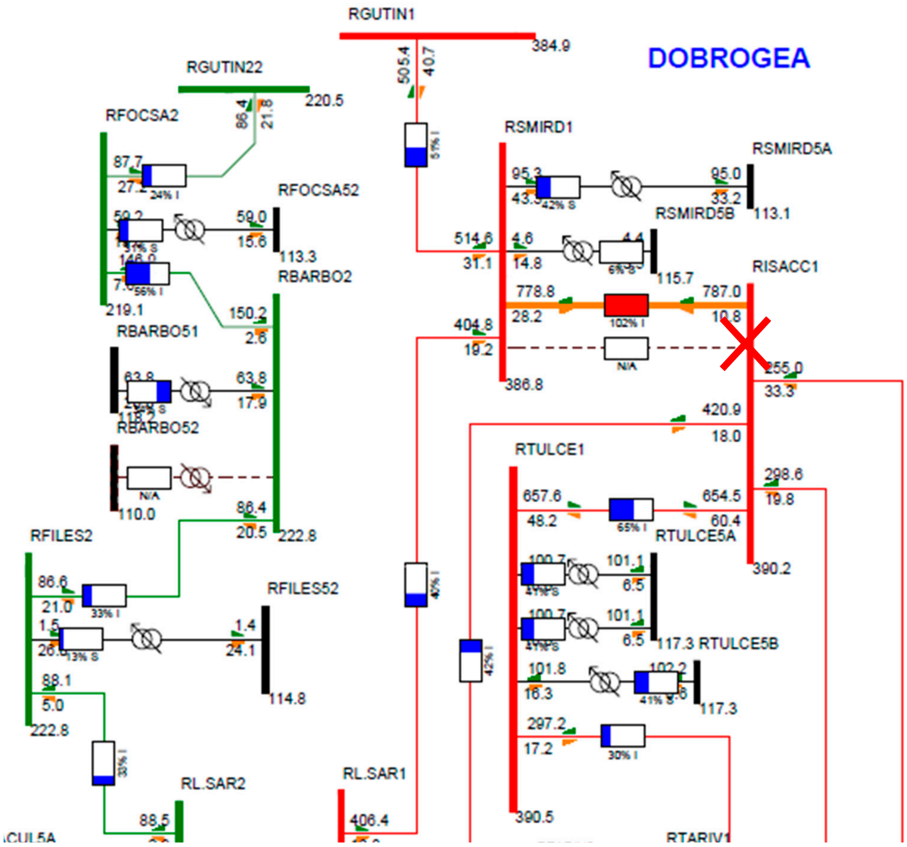

Figure 6. Unavailability of a 400 kV line determining the overloading of other lines.

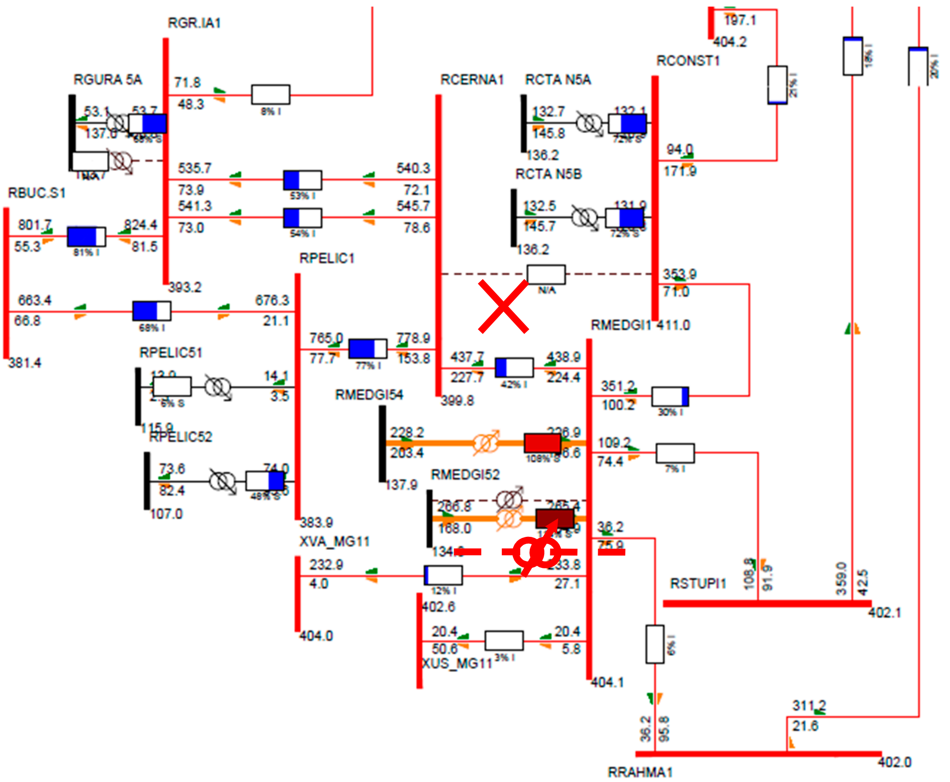

Figure 7. Unavailability of a 400 kV line determining the overloading of transformers.

4.2. Verifying the Transient Stability

For analysing the dynamic behaviour of voltage and frequency within the Romanian power system, the disconnection of a 210 MW WPP is considered. The WPP is, in normal operation, connected at 400 kV level between Tulcea (bus RTULCE1) and Constanta Nord (bus RCONST1) substations (WPP illustrated in Figure 6). The buses where the voltage and frequency variations are analysed correspond to the WPP bus (bus RTARIV1) and Constanta Nord substation (bus RCONST1), as shown in Figures 8–11.

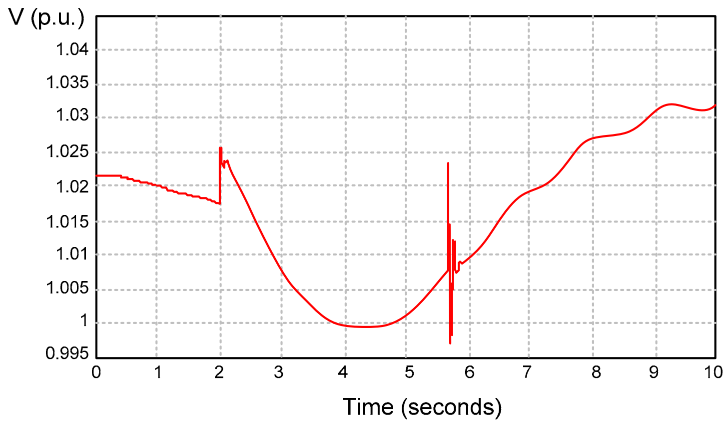

Figure 8. Voltage variation in 400 kV Constanta Nord.

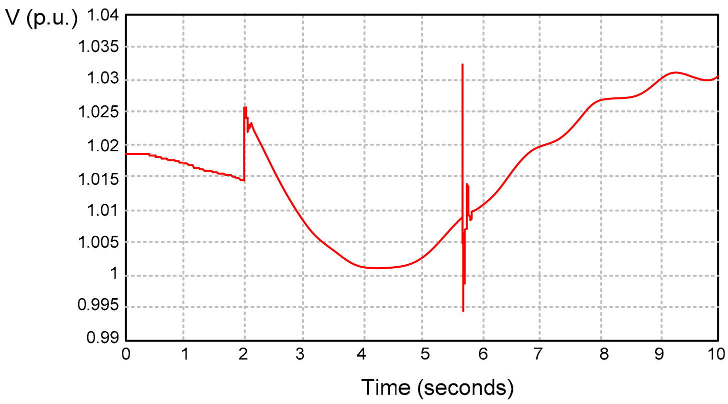

Figure 9. Voltage variation in 400 kV Tariverde.

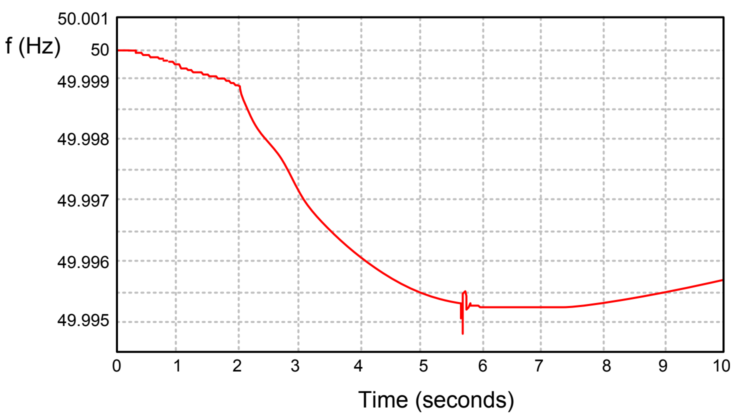

Figure 10. Frequency variation in 400 kV RCONST1 bus.

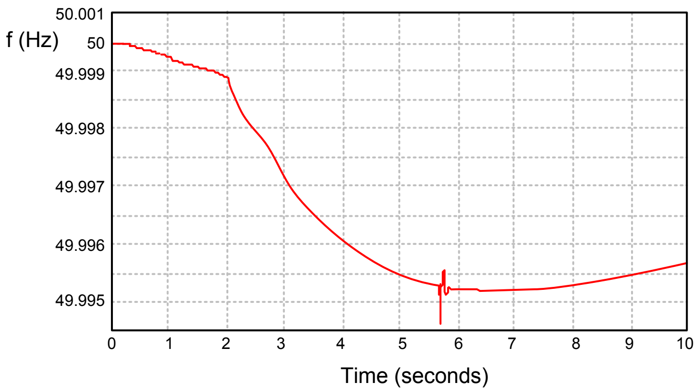

Figure 11. Frequency variation in 400 kV RTARIV1 bus.

The main electric measures whose evolution is monitored during the transient condition for establishing if the operating regime is steady or not, are relative or absolute internal angles of generators (shown in Figures 12–14), active powers generated by the generators, and voltage at their terminals, as well as the voltage at substations within the area.

For the wind power generators, in agreement with the dynamic data base, the following dynamic models were considered (for the WPP presently installed):

- wind generator model with power converter, modelled as synchronous wind power generators (connected to the network through power converters) [20];
- doubly-fed induction generator, modelled as asynchronous wind power generators doubly fed [9,21].

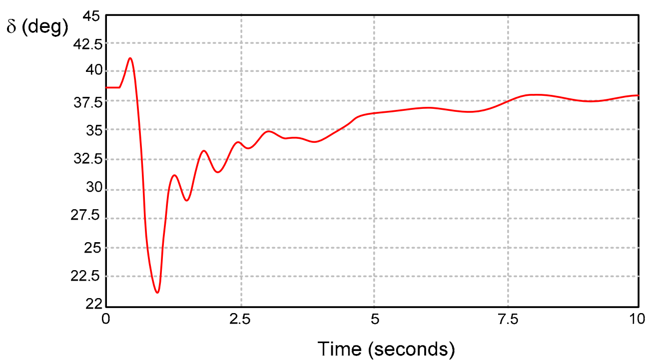

Figure 12. Internal angle of classical generator from thermal power plant connected at bus RPALAST in case of short-circuit on a 110 kV line.

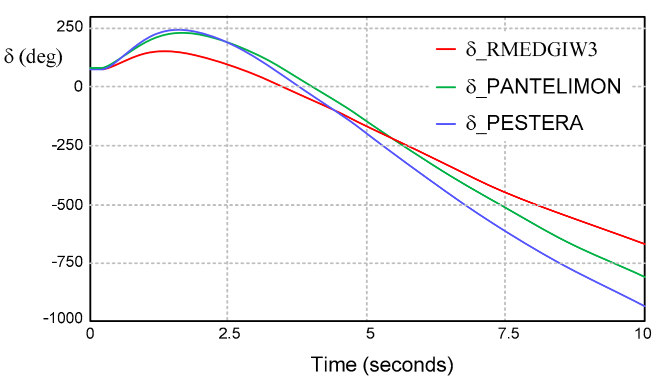

Figure 13. Internal angles of asynchronous wind power generators in case of short-circuit on a 110 kV line.

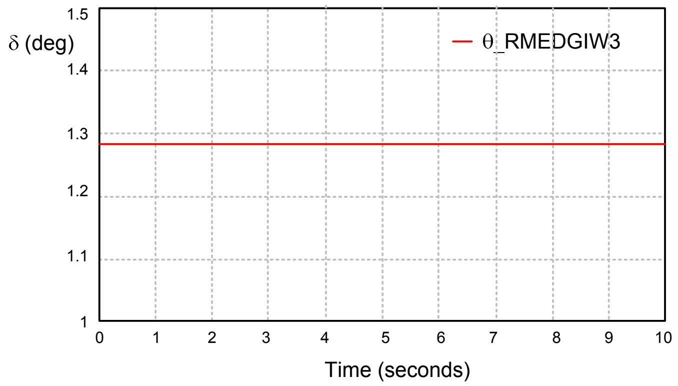

Figure 14. Internal angles of synchronous wind power generators in case of short-circuit on a 110 kV line.

5. Discussion

5.1. Voltage, Grid Load and Frequency Analysis after Disconnection of a 210 MW WPP

Figures 8 and 9 show that:

- when the WPP is disconnected (at time instant t = 2 s), the voltage has a slight increase and afterwards decreases by approximately 0.02 p.u.;
- after about 3 s from the disconnection of the 210 MW WPP, the reactive power control occurs in other available groups, restoring the voltage to a new value.

From the point of view of frequency variation, the disconnecting of a 210 MW capacity has a minor influence on frequency, considering that the Romanian power system operates synchronously with the neighbouring power systems (Figures 10 and 11).

5.2. Verifying the Transient Stability Conditions of Generators in Case of Faults

The effect of a short-circuit on the doubly-fed induction generators requires the adoption of a rotor protection system. The grid side converter provides fast voltage recovery, but in case of a large voltage drop in point of common coupling (PCC) (below 15% of rated voltage), the system can lose the stability and the wind turbine can be disconnected, in agreement with the tolerance graph from [22]. In this case, the system may have to compensate for the loss of production of WPP and accept ancillary services to balance production/consumption.

During three phase short-circuit occurrences, the generated electric power instantaneously decreases (to a value corresponding to the distance from fault), while the mechanical power generated by the turbine remains constant for a few seconds. Due to the unbalance between the mechanical power generated by the turbine and the electric power injected by generators into the power system, their rotors accelerate causing the increase of relative internal angles. This increase is higher as the fault clearing time is higher and inertia of the generator is lower. In all conducted case studies, it was observed that:

- classical generators are stable (like the unit from thermal power plant connected at bus RPALAST), and the variation of rotor angle is smoothed after fault clearance (as shown in Figure 12);
- doubly-fed induction generators have the rotor angle strongly influenced by a fault in the network, but this influence is not transmitted to the voltage at generator terminals or to the 110 kV bus where the generator is connected (as shown in Figure 13);
- synchronous wind generators with power converters are maintaining their rotor angle constant during the fault, considering the galvanic separation from the network (as shown in Figure 14).

6. Conclusions

This paper investigates the operation of an area of the Romanian power system characterised by a high density of renewable energy sources. The south-east part of the Romanian power system is a particular area characterised by a very high density of renewable energy sources (mainly WPP) and a nuclear power plant with two units. This power system area is connected to the rest of the country through three highly loaded transmission lines: two are supplying the city of Bucharest (the capital with high consumption and deficit of production), and one is supplying the north-east side of Romania with a deficit in production. Simulations were performed in the Dobrogea area, and particularly for the case of an important bus where 600 MW WPPs are connected. The loss of a WPP of 210 MW, the largest WPP in operation, connected at this bus is highly important as its loss incurs on the secure operation of the power system. Considering the renewable sources in operation, in this paper were analysed:

- Voltage levels in case of faults in the power system;
- Overloading of power system elements in case of unavailability of lines and transformers;
- The dynamic behaviour of voltage and frequency when a 210 MW wind farm is disconnected;
- The transient stability conditions of classic and wind power plant generators.

The simulation results revealed that:

- in case the WPP produces 90% of the installed power, overloading of the transmission network can occur;
- if a higher share of renewable energy sources present within the power system is considered, then network reinforcement actions are required;
- in case of a short-circuit, the synchronous wind generators connected to the network through converters keep their rotor angle constant during the fault, while the doubly-fed induction generator have the rotor angle heavily influenced by a fault occurrence.

In conclusion, even at this moment when the installed power in renewable sources is around 4500 MW, power system reinforcement actions are required for overcoming network problems determined by these volatile sources.

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Abbreviations

The following abbreviations and definitions are used in this paper:

ANRE = Romanian Energy Regulation Authority
PCC = Point of Common Coupling
ENTSO-E = European Network of Transmission System Operators for Electricity
p.u. = per unit

Connection agreement: agreement established between network operator and customer, with the object of the connection of customer installations to the electrical grid through connection works stipulated in the Connection technical agreement and through energising the installation

Connection technical approval (ATR): Written notification, provided by the network operator for a specific location, regarding the terms and conditions for providing a connection to the electricity network.

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