Impact of Renewables on Frequency Regulation Reserves in Power System of North Macedonia

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Abstract – **Integration of renewable energy sources (RES) causes imbalances in the power system, because of their variable generation and stochastic nature of the source. Photovoltaic (PV) and wind power plants (WPP) are dominant RES in the region of Southeast Europe. This paper is analyzing the impact of RES on frequency regulation reserves in North Macedonia. There are and will be a high increase of installed PV capacity in the power system that will have impact on imbalances and frequency regulation reserves. The methodology for the assessment of RES impact on frequency regulation reserves is based on the data available for the authors for the years 2015 and 2016, about hourly deviations (imbalances) of PV, WPP and load. According to these data necessary frequency regulation reserves capacities are calculated for the years 2023 and 2025. The results and conclusion are presented at the end of the paper.**

Keywords – **Renewable energy sources, frequency regulation reserves, power system.**

I. Introduction

RES have become one of the main electricity sources in some EU countries. WPP and PV have a dominant role from all RES. These kind of power plants in some EU countries have reached such a level of installation that in some days with their generation total electrical energy consumption is mostly supplied.

According to EWEA (European Wind Energy Association), nowadays WPP share is about 16 % of total electrical energy consumption in EU+UK, and Europe installation of WPP in the next five years will be 105 GW. Dominant countries in WPP installations are Denmark, Spain, Ireland, Germany and UK [1]. Total PV installed capacity in Europe in 2022 was 208 GW, and dominant countries with PV installations are Germany, Italy and Spain (source Solar Power Europe-SPE) [2].

The forecast of load and generation is performed with forecast of weather conditions and load behavior. These forecasts are subject of errors. It is especially emphasized in the RES generation forecast due to their variable generation and stochastic nature of the source. This fact will cause imbalances in the power systems, because of deviation between realization and forecast (plan).

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This paper is analyzing the impact of RES on frequency regulation reserves in North Macedonia. There are and will be a high increase of installed PV capacity in the power system that will have impact on imbalances and frequency regulation reserves. The methodology for the assessment of RES impact on frequency regulation reserves is based on the data for the years 2015 and 2016, about hourly deviations (imbalances) of PV, WPP and load. These data will be relevant for activation of aFRR (automatic frequency restoration reserve–secondary reserve) and mFRR (manual frequency restoration reserve – fast tertiary reserve) P/f regulation, although they are performed on a period of 15 minutes. This means, it will be assumed that deviations (realization-plan) in 15 minutes periods are equal to hourly deviations.

The paper is composed of six sections. The second section presents the input data for hourly imbalances of PV, WPP and load. These data is used as a basis for the calculations of the RES impact on frequency regulation reserves. The third section describes the implemented methodology. In the fourth section, results for frequency regulation reserves calculation are presented for 2023 and 2025. The fifth and sixth section are conclusion and references, appropriately.

II. Input data for imbalances of WPP, PV and load

Total available data cover the period 2015-2016 and they refer to one WPP called Bogdanci with rated power 36.8 MW and total PV with rated power 16.7 MW. The imbalances are the differences between realization and forecast: they are positive if the realization is greater than forecast and vice versa. Positive imbalances will cause activation of regulation P/f reserve to down, while negative ones will cause activation of regulation P/f reserve to up.

Fig 1 depicts the hourly imbalances of WPP Bogdanci for the available data period. Forecast errors in hourly generation (imbalance) is less than 10 % of rated power in about 46 % of time, and in total 75 % of time the error is less than 20 % of rated power of WPP. Errors greater than 30 % of rated power are noticed in 25 % of time, and errors greater than 50 % P_{max} are noticed in 12.8 % of the considered time. If 1 % of all maximum errors are omitted, maximum imbalance will be 29,6 MWh/h, or 80,5 % P_{max}.

The average error in forecast of WPP Bogdanci was about 20.5 % of rated power. Such an error level is expected for a single WPP. For example, average error of a group of WPP is significantly lower (in Croatia for a group of WPP with installed power 339 MW, the average error was 9.81 %).

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WPP in Germany, which are in big number, spatially dispersed and with more stable wind, have average errors in forecast less than 5 %.

Fig.2 depicts the hourly imbalances of all PV power plants for available data period. The forecast error for hourly generation was under 10% of rated power in about 82% of time, and in total 96.5% of time was under 20% of rated power of all PV plants. The errors greater than 30% of rated power were in 3.5% of time, and errors over 50% P_{max} are noticed in only 0.6% of considered time. If 1% of all maximum errors are omitted, maximum imbalance will be 7.6 MWh/h, or 45.5% P_{max}.

Analyzing Fig 3, maximum hourly imbalance of load in the available data period was 200 MWh/h in positive direction (difference of realized load minus planned is greater than or equal to zero, meaning that realization is greater than planning and regulation reserve up for load balancing should be activated). Maximum negative imbalance was 214 MWh/h (difference of realized load minus planned is lower than or equal to zero, meaning that realization is lower than planning and regulation reserve down for load balancing should be activated). Average imbalance of total load was 28 MWh/h. Positive imbalances were noticed in 5972 hours (68.2 % of time), and negative imbalances were noticed in 2788 hours (31.8 % of time).

Fig. 4 depicts the total hourly imbalances. The maximum total imbalance was 220 MWh/h, and the minimum was −194 MWh/h. The average total imbalance was 29 MWh/h. The total imbalances in down direction were −170 GWh, and in up direction 81.6 GWh, or as a sum −88.4 GWh. It is assumed that other power plants and entities does not generate imbalances in the power system.

III. Methodology

The following methodology is developed using the referent imbalances for WPP, PV and load presented in the previous section. According to the level of WPP and PV integration, the calculation and estimation of necessary P/f regulation reserves is based on the following assumptions:

- The available hourly imbalances of load remain the same as for the considered period;
- The hourly realization of WPP generation will be proportional to the ratio between total rated power of all WPP in the analyzed year and rated power of WPP in the available data period (WPP was with 36.8 MW rated power in 2015-2016). The hourly forecast of WPP generation day ahead will be also proportional to the ratio between total rated power of all WPP in the analyzed year and rated power of WPP in the available data period. This implies that hourly imbalances of WPP generation, expressed as a percent from the rated power, will remain on the same level.
- Three scenarios for average forecast error of WPP generation will be defined 20%, 10% and 5 %. The decrease of average error should be a case with the improvement of forecast system and construction of new WPPs on different locations with other wind data.
- The hourly realization of PV generation are proportional to the ratio between total rated power of all PV in the analyzed year and rated power of WPP in the available data period (total 16.7 MW). The hourly PV day ahead generation forecast will be also proportional to the ratio between total rated power of all WPP in the analyzed year and rated power of WPP in the available data period. The average forecast error will remain on the same level (about 5%).

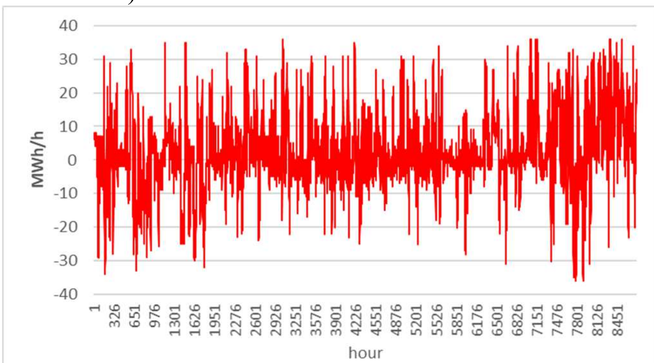

Fig. 1. WPP Bogdanci hourly imbalances

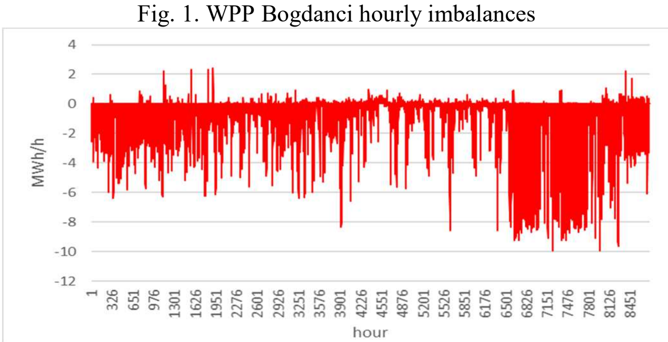

Fig. 2. PV power plants hourly imbalances

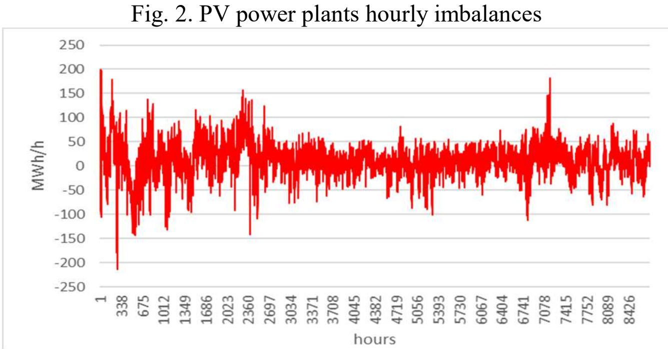

Fig. 3. Load hourly imbalances

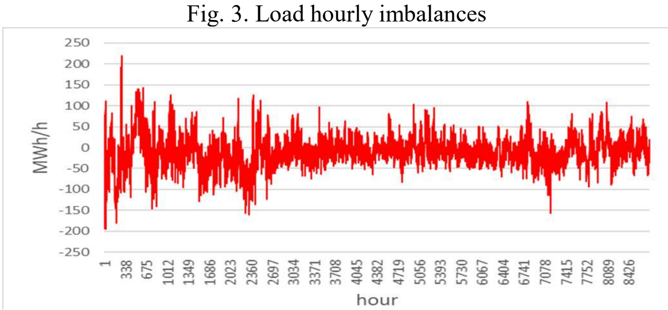

Fig. 4. Total hourly imbalances

Imbalances generated by load, WPP and PV forecast error as a difference between realization and plan in hour i, are as follows:

$$\Delta_{load,i} = \mathbf{load}_{i\ (realization)} - \mathbf{load}_{i\ (plan)} \quad (1)$$

$$\Delta_{WPP,i} = P_{WPPi\ (realization)} - P_{WPPi\ (plan)} \quad (2)$$

$$\Delta_{PV,i} = P_{PVi\ (realization)} - P_{PVi\ (plan)} \quad (3)$$

$$\Delta_{total,i} = -\Delta_{load,i} + \Delta_{PV,i} + \Delta_{WPP,i} \quad (4)$$

where:

$\Delta_{load,i}$ is imbalance in the system caused by load forecast error in hour i, $\Delta_{WPP,i}$ is imbalance in the system caused by WPP generation forecast error in hour i, $\Delta_{PV,i}$ is imbalance in the system caused by PV generation forecast error in hour i, and $\Delta_{total,i}$ – is the total imbalance in the system in hour i.

Positive values of $\Delta_{total,i}$ are surplus energy in the system and its necessary to engage aFRR (aFRR-) and/or mFRR (mFRR–) down. Negative values are lack of energy in the system and its necessary to engage aFRR (aFRR+) and/or mFRR (mFRR+) up.

Considering the defined assumptions and imbalances, for the analyzed year, the following is calculated for each hour i:

$$\Delta_{load,i} = \mathbf{load}_{i\ (realization)} - \mathbf{load}_{i\ (plan)} \quad i=1,..8760 \quad (5)$$

Where: $\Delta_{load,i}$ remains the same as in the available data period.

$$\Delta_{WPP,i} = (P_{rated.,WPP} / 36.8)\Delta_{WPP,i}\, G_{WPP},\ i = 1,..8760 \quad (6)$$

Where: $\Delta_{WPP,i}$ is proportional to to the ratio between total rated power of all WPP in the analyzed year $P_{rated.,WPP}$ and rated power of WPP in the available data period 36.8 MW and G_{WPP} ratio of average error of WPP forecast (20 %; 10 %; 5 %) and the average error of WPP forecast in available data period (20 %). The values of G_{WPP} can be (1.0, 0.5 and 0.25).

$$\Delta_{PV,i} = (P_{rated.PV} / 16.7) \times \Delta_{PV,i},\ i = 1,..8760 \quad (7)$$

where: $\Delta_{PV,i}$ is proportional to the ratio between total rated power of all PV in the analyzed year $P_{rated.,PV}$ and rated power of PV in the available data period 16.7 MW. Total imbalance in the system in hour I is calculated with (4).

The necessary hourly value of the automatic frequency restoration reserve**,** according ENTSO-E formula is dependent on the hourly load realization [4]:

$$\mathrm{aFRR}_i = \pm\sqrt{10\cdot \mathrm{load}_{i(\mathrm{realization})} + 150^2} - 150 \quad i = 1,..8760 \quad (8)$$

The imbalances coverage with the necessary value of aFRR is related with:

$$\Delta_{total\,i} > aFRR_i\pm;\ \Delta_{total\,i} < aFRR_i \pm \quad i = 1,..8760 \quad (9)$$

The engaged aFRR illustrates the energy generated with secondary reserve each hour (i = 1,..8760):

$$\mathbf{aFRR}_{activated,i}+ = \Delta_{total,i},\ \text{if } |\Delta_{total,i}| < aFRR_i\pm \text{ and } \Delta_{total,i} < 0,$$

$$\mathbf{aFRR}_{activated,i}+ = aFRR_i\pm,\ \text{if } |\Delta_{total,i}| > aFRR_i\pm \text{ and } \Delta_{total,i} < 0,$$

$$\mathbf{aFRR}_{activated,i}- = \Delta_{total,i},\ \text{if } |\Delta_{total,i}| > aFRR_i\pm \text{ and } \Delta_{total,i} > 0,$$

$$\mathbf{aFRR}_{activated,i}- = aFRR_i\pm \text{ if } |\Delta_{total,i}| > aFRR_i\pm \text{ and } \Delta_{total,i} > 0 \quad (10)$$

The symmetrical aFRR is calculated according to ENTSO-E formula (8) and hourly load in the system. It is assumed that all additional imbalances caused with the increased integration of WPP and PV are covered with the fast tertiary reserve mFRR.

The engagement and necessary hourly values of fast tertiary reserve mFRR, for all hours (i = 1 до 8760) when aFRR is lower than the total imbalance in the power system, is:

$$\mathbf{mFRR}_i+ = |\Delta_{total,i}(-) + \mathbf{aFRR}_i\pm| \text{ if } \Delta_{total,i} < 0,$$

$$\mathbf{mFRR}_i+ = 0 \text{ if } \Delta_{total,i} > 0,$$

$$\mathbf{mFRR}_i- = |\Delta_{total,i}(-) - \mathbf{aFRR}_i\pm| \text{ if } \Delta_{total,i} > 0,$$

$$\mathbf{mFRR}_i- = 0 \text{ if } \Delta_{total,i} < 0,$$

$$\mathbf{mFRR}_i+ = \mathbf{mFRR}_i- = 0 \text{ ако е } aFRR\pm > |\Delta_{total,i}| \quad (11)$$

The necessary symmetrical mFRR is calculated as maximum hourly fast tertiary reserve after first 88 hours (1% of the time in the year) using the mFRR duration curve. The sum of aFRR and symmetrical mFRR can cover 99% of the imbalances and the greatest 1% imbalances will not be covered. This will result in significant deviations in the exchange with neighboring power systems [5].

IV. Results

Using the described methodology, the necessity for frequency regulation reserves is estimated for 2023 and 2025, according to WPP and PV level of integration in the power system of North Macedonia.

A. Year 2023

The level of renewables integration in year 2023 is expected to be 36.8 MW WPP and 200 MW PV. The average forecast error of WPP generation will be defined 20% and for PV it is assumed 5%. The forecasted hourly load for the year 2023 is defined as in [3]. Maximum load is 1253 MWh/h and minimum is 408 MWh/h.

The maximum load positive imbalance is 199.76 MWh/h and the negative is –214.26 MWh/h. The average load imbalance is 28.02 MWh/h. The maximum imbalance of WPP is 32.62 MWh/h and the minimum is 32.62 MWh/h. The average WPP imbalance is 7.34 MWh/h. The maximum imbalance of PV is 27.36 MWh/h and the minimum is –113.30 MWh/h. The average PV imbalance is 10.00 MWh/h. Table I summarizes the total imbalances for the year 2023. It is obvious that main reason for imbalances is load forecast error and PV negative imbalance according to the increased level of PV integration.

Table II shows the estimation of the necessary aFRR and mFRR in the year 2023. Maximum aFRR is ±37 MWh/h, and in approximately 45 % of time aFRR calculated according to

TABLE I
THE FORECAST OF TOTAL IMBALANCES FOR 2023

MAX imbalance	216 MWh/h
MIN imbalance	-194 MWh/h
AVG imbalance	34 MWh/h
Total imbalance down	-230.3 GWh
Total imbalance up	65.7 GWH
SUM	-164.5 GWh

TABLE II
THE ESTIMATION OF FREQUENCY REGULATION RESERVES FOR 2023

Maximum aFRR (±MWh/h)	37
Number of (h) with sufficient aFRR	3942
Number of (h) with not sufficient aFRR	4818
Maximum mFRR up (mFRR+) (MWh/h)	168
Maximum mFRR down (mFRR-) (MWh/h)	-181
Number of times for activation of MFRR down (h)	955
Number of times for activation of MFRR up (h)	3863
Total activated aFRR up (aFRR+) (GWh)	119.4
Total activated aFRR down (aFRR-) (GWh)	-42.1
Total activated mFRR up (mFRR+) (GWh)	110.9
Total activated mFRR down (mFRR-) (GWh)	-23.7
Total activated reserve up (aFRR+ and mFRR+) (GWh)	230.3
Total activated reserve down (aFRR- and mFRR-) (GWh)	-65.7

hourly load is sufficient to cover the imbalances in the system. The rest 55 % of time it is necessary to engage mFRR, and in case of agreement for symmetrical values, it is ±107 MW.

B. Year 2025

The level of renewables integration in year 2025 is expected to be 82 MW of WPP and 400 MW of PV. The average forecast error of WPP generation will be defined 10% and for PV it is assumed 5%. The forecasted hourly load for the year 2025 is defined as in [3]. The maximum load is 1513 MWh/h and the minimum is 409 MWh/h.

The maximum load positive imbalance is 199.76 MWh/h and the negative is −214.26 MWh/h. The average load imbalance is 28.02 MWh/h. The maximum imbalance of WPP is 35.46 MWh/h and minimum is −35.46 MWh/h. The average WPP imbalance is 7.98 MWh/h. The maximum imbalance of PV is 54.73 MWh/h and the minimum is −226.60 MWh/h. The average PV imbalance is 20.00 MWh/h.

Table III summarizes the total imbalances for the year 2025. It is obvious that main reason for imbalances is load forecast error and PV negative imbalance according to the increased level of PV integration. Table IV shows the estimation of the necessary aFRR and mFRR in the year 2025. Maximum aFRR is ±44 MWh/h, and in approximately 42 % of time aFRR calculated according to hourly load is sufficient to cover the imbalances in the system. The rest 58 % of time it is necessary to engage tertiary reserve, and in case of agreement for symmetrical values, it is ±178 MW.

TABLE III
THE FORECAST OF TOTAL IMBALANCES FOR 2025

MAX imbalance	216 MWh/h
MIN imbalance	-256 MWh/h
AVG imbalance	42 MWh/h
Total imbalance down	-306.7 GWh
Total imbalance up	60.6 GWh
SUM	-246.0 GWh

TABLE IV
THE ESTIMATION OF FREQUENCY REGULATION RESERVES FOR 2025

Maximum aFRR (±MWh/h)	44
Number of (h) with sufficient aFRR	3641
Number of (h) with not sufficient aFRR	5119
Maximum mFRR up (mFRR+) (MWh/h)	232
Maximum mFRR down (mFRR-) (MWh/h)	-179
Number of times for activation of MFRR down (h)	893
Number of times for activation of MFRR up (h)	4226
Total activated aFRR up (aFRR+) (GWh)	127.7
Total activated aFRR down (aFRR-) (GWh)	-38.9
Total activated mFRR up (mFRR+) (GWh)	179.0
Total activated mFRR down (mFRR-) (GWh)	-21.8
Total activated reserve up (aFRR+ and mFRR+) (GWh)	306.7
Total activated reserve down (aFRR- and mFRR-) (GWh)	-60.6

V. CONCLUSION

There are and will be a high increase of installed renewables capacity in the power system that will have impact on imbalances and frequency regulation reserves. The proposed methodology in the paper is deterministic and it is based on the available imbalances data for the period 2015-2016. The symmetrical aFRR is calculated according to ENTSO-E formula based on hourly load in the system. It is assumed that all additional imbalances caused with the increased integration of WPP and PV are covered with the fast tertiary reserve.

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