ANALYSIS OF WIND AND SOLAR SYSTEMS GRID INTEGRATION USING NEW TOOL FOR CURTAILMENT AND PENETRATION ASSESSMENT

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Abstract - An important component of the variable renewable generation (VRG) integration in Romanian power grid represents the wind and solar curtailment energy due to the impact it can have on economics. This paper performs a quantitative assessment of both VRG penetration and curtailment ratio in Romanian grid using the new tool proposed in specialty literature named "C-P map". It was only calculated the penetration ratio, for the curtailment ratio only being made interesting scenarios due to the lack of official data. This has allowed obtaining images of principle regarding near future tendency for the national power network, providing help in planning and decision making in order to optimize the VRG curtailment level and secure grid operating.

Keywords: variable renewable generation, penetration ratio, curtailment ratio, grid flexibility

1. INTRODUCTION

Variable renewable generation has become more and more important with the integration in power networks of renewable conversion systems, wind and solar being the ones that have grown the widest and fastest in the last decade.

Due to variability and unpredictability of the wind and solar resources the electricity generated by the conversion systems presents fluctuations in output power which it introduces a new factor of uncertainty on the grid, resulting in negative impact on network security and power quality [1].

The challenges regarding system security due to high penetration of the VRG in power networks are related to the effects on [1]:

- Power imbalance, when VRG generate electricity in excess, combined to a low demand period;
- Reserve management, system operator must have enough reserve to counter the variable generation from VRG;
- Voltage control, due to the fact that most VRG are not capable of injecting reactive power to the grid and the system operator must take care that the nodal voltage distribution on the network to be within normal limits.

VRG impact on the produced electricity includes all power quality components [1]: flickers, harmonic distortions, voltage imbalance, voltage sag and voltage swells.

Studies conducted in [3,4,7] have shown that with the increase in penetration of wind energy generation systems (WGS) and photovoltaic systems (PVS) there has been an significant increase in VRG curtailment. In these paper we refer to curtailment in terms defined by [3], as *a reduction in the output of a generator from what it could otherwise produce given available resources (e.g., wind or sunlight), typically on an involuntary basis.* Curtailment may result from the grid operator command wind and solar systems to reduce the output due to the flowing causes [3]:

- Transmission congestion or lack of transmission access;
- Excess electricity generation during low load periods;
- Voltage stability or interconnection issues;
- Frequency requirements issues;
- Energy balancing in power system.

For the WGS and PVS, curtailments have important economic implications due to their specific economy and operation: their economics depends on maximum power that can be generated whenever the renewable resources are available. The investment cost is high, but the variable costs are minimal, due to the fact that these systems do not required fuel costs. Accordingly, maximization of the produced electricity improves their ability to recover capital costs and to make profit in the future [3]. It results that any reduction in output power due to curtailment ordered by the system operator has a negative impact of the WGS and PVS economics.

2. CURTAILMENT ASSESSMENT TOOLS

In the electric sector curtailment practices vary significantly by region and market design and often had suffered changes during time due to main two factors: the utility scale deployment of the WGS/PVS and the evolution of wholesale power market [3]. If before 2000's curtailment were made by network system operator due to stability reasons of the grid, after this year these practices were "gradually replaced with transparent offer-based mechanisms that base dispatch by economics" [3].

It is to be noticed that regardless of the practices used, monitoring the curtailment concerns both the grid operator and the VRG owner due to the economic implications. In addition it can lead to important evidences regarding the success of measures taken by the grid operator to efficiently integrate VRG systems in its power network [4].

The problem arises when comparing the curtailment level between different power systems. Due to the fact that the measures and factors which lead to curtailments are different and specific for each network, this comparison is not necessarily appropriate [4]. However it can be used an assessment tool for analysis the VRG integration in power systems which can allow a comparison of VRG curtailment levels [5]. According to [6], this assessment instrument named “maximum share of wind power” criterion only refers to WGS and is defined by relation (1):

$$\mathit{Share\ of\ wind\ power} = \\ = \frac{\mathit{Max.wind\ power}\ [MW]}{\mathit{Min.consumption}\ [MW] + \mathit{possible\ export}\ [MW]} \quad (1)$$

In relation (1) maximum wind power is obtained from annual electricity production curve, minimum consumption is supplied by the consumer consumption curve and possible export is given by the total capacity of the transport line on which the export of energy is made.

A more quantitatively approach for the share of VRG and that can take into account both the WGS and PVS is proposed by [4]. The new evaluation tool is called “C-P map” and defines the following indicators:

VRG penetration ratio (P) defined as a rapport between total VGS generated energy and annual gross generation in a selected network/area, relation (2):

$$P = \frac{WGS + PVS\ \mathit{generated\ energy}[GWh]}{\mathit{Anual\ gross\ generation}\ [GWh]} \qquad (2)$$

VRG curtailment ratio (C) is defined as a rapport between annual curtailed energy and estimated VRG generated energy in a selected network/area, relation (3):

$$C = \frac{WGS{+}PVS\ \mathit{curtailed\ energy}\ [GWh]}{WGS{+}PVS\ \mathit{generated\ energy}[GWh]} \qquad (3)$$

In case of penetration ratio indicator, the statistical data regarding annual gross generation both at the system level and VRG level are easy to obtain because the grid operator published official annual reports. Not the same thing can be said about the curtailment ratio indicator because there are no mandatory rules regarding the publishing of statistical data on VRG energy curtailment by the system operators [4]. Consequently it can happen that for a specific network/area, VRG curtailment data may not be available.

By correlation between these two indicators is obtained two new metrics. The first one named “C-P ratio” (R) is defined as *the quotient of the given curtailment ratio by the given penetration ratio for the selected grid/area in the selected year* [4], relation (4).

$$R \equiv \frac{C}{P} \qquad (4)$$

Using the “C-P ratio” indicator it can be plotted the curtailment level in a selected network/area on a year or on several years (if the statistical data are available). According to [4] it can be experimentally defined three zone of interest represented in fig. 1:

- For R ≤ 0,1 it is associated the “Green” zone to which it corresponds a “well operated network”, meaning that despite a high level of VRG penetrations there are maintained a low level of curtailment;
- For 0,1≤R≤0,5 it is associated the “Yellow” zone to which it corresponds a “to be improving” in network operation, meaning that for certain level of VRG penetration there are still a relatively high level of curtailment;
- For R ≥ 0,5 it is associated the “Red zone” to which it corresponds a “must improve” network operation, meaning that the level of VRG curtailment is very high for a certain level of penetration.

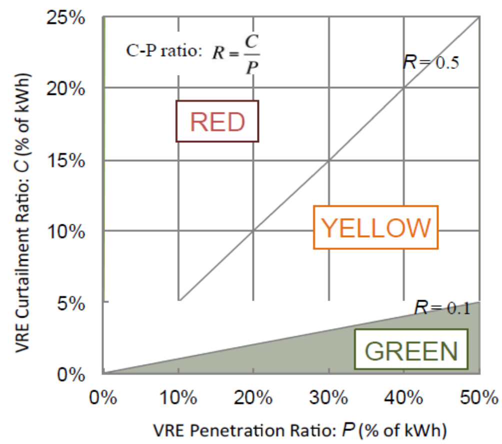

Fig. 1. The zones associated with the C-P map [4]

The second indictor, named “C-P gradient” represents *the gradient of the C-P curve at the given pint on the C-p map* and indicates the historical curtailment trends [4], being calculated by relation (5).

$$G \equiv \frac{\Delta C}{\Delta P} \qquad (5)$$

Referring to relation (5) *Δ*C and *Δ*P represents the backward difference of C and P indicators [4].

This VRG curtailment trends can give an image of the efforts in reducing curtailment level in a selected network/area, conceptually presented in fig.2., thus [4]:

- G ≤ 0,1 implies an improving effort to reduce the VRG curtailment ratio;
- 0≤G≤0,5 indicates a stability between penetration ratio and curtailment ratio;
- G ≥ 0,5 express a degradation in grid operation regarding VRG curtailments.

Trend classification of the future VRG curtailments that may occur in a selected grid/area results from combination between the two plots, fig. 3 presents the conceptual model.

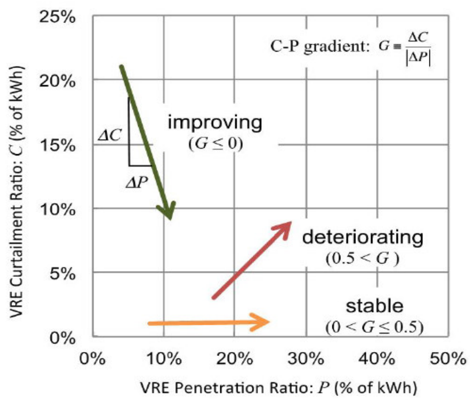

Fig. 2 The concept of the G-indicator [4]

Thus can appear nine situations in which a network can be regarding VRG curtailment and penetration and, if the statistical data are available, a comparison between different grids can be done. This situation is stated in [4] and we presented here for a clearer outlook:

- (1a) red but improving,
- (1b) red and stable,
- (1c) red and even deteriorating,
- (2a) yellow and improving,
- (2b) yellow and stable,
- (2c) yellow and deteriorating,
- (3a) green and still improving,
- (3b) green and stable,
- (3c) green but deteriorating.

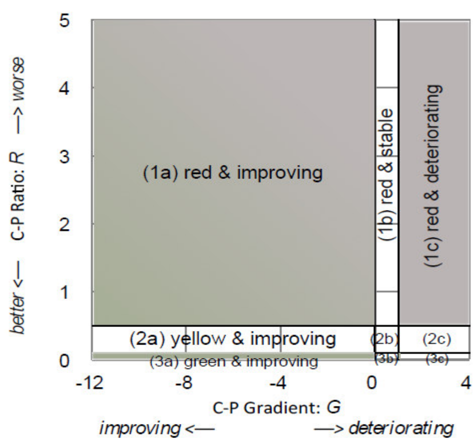

Fig. 3 The conceptual model for the classification of curtailment trend [4]

It is understood that the above mentioned method can be applied even the grid/area have only a single type of VRG, either WGS or PVS.

3. ANALYZING ROMANIAN POWER GRID

VRG integration in Romanian power network was made by commissioning a growing number of wind and solar power plants as a result of National Action Plan for Renewable Energy Sources implementation [11]. Thus if in 2008 were installed only 5MW in WGS, in 2016 total installed capacity reach 4335 MW both in WGS and PVS, tab. 1.

Table 1. Total VRE installed capacity [MW] in Rumania during 4 year period [8, 9,10]

Year / VRG type	2013	1014	2015	2016
WGS	2605	2935	2978	2989
PVS	860	1223	1301	1346
Total (WGS+PVS)	3465	4176	4279	4335

From the statistical data published by National Energy Regulatory Authority (ANRE) the most significant growth in installed power was in 2014 when there are added a total of 452,71 MW of wind and solar power plants without any definitely withdrawal in capacity of conventional generating groups, as shown in tab.2.

Table 2. Total new capacities commissioned in Rumania [8, 9, 10]

New Installed Capacity [MW] / Year	WGS	PVS	Classic Power Plant*
2014	321,25	100,70	452,710
2015	10,00	13,00	81,233
2016	41,50	17,28	132,002

* Including hydro power plants

It is worth mention the fact that in 2015 was decommissioned the Suceava Thermal Power Plant with 108 MW installed capacity and in 2016 the 50 MW coal unit of Oradea Power Plant was replaced by a 56 MW gas unit [10].

The gross electric energy generated presents fluctuations during time, 2014 being with the largest share due to the significant leap in renewable area, mostly wind and solar, tab. 3.

Tab. 3 Annual gross power generated in Romanian grid [8, 9, 10]

Year / Month	Total gross power generation [GWh]			
	2013	**2014**	**2015**	**2016**
January	5452	5876	6226	6279
February	4902	5136	5470	5167
March	5177	5362	5744	5156
April	4606	5034	5526	4756
May	4239	5041	4811	4500
June	4335	4918	4311	5126
July	4620	5346	4667	5627
August	4502	5385	4508	5270
September	4450	5134	4450	4846
October	5207	5833	4989	5526
November	5366	5678	5142	5819
December	5802	6090	5409	6399
TOTAL YEAR	**58658**	**64860**	**57740**	**64472**

With the data available in tab. 3 and in [10] it is possible to obtain an assessment of the VRG penetration ratio in Romanian power grid using the relation (2) from the new method presented in section 2 of this paper. Tab. 4 shows that during a four years period the penetration ratio varies due to fluctuations in electricity generations, in 2016 reaching 13 %.

Tab. 4 The VRG penetration ratio in Romanian grid [8,9,10]

Year	Total generation [GWh]	Wind [GWh]	Solar [GWh]	Penetration ratio [%]
	a	b	c	P=(b+c)/a
2013	58658	4721	413	8,7
2014	64860	6201	1634	12,0
2015	57740	7062	2003	15,7
2016	64472	6590	1820	13,0

Data thus calculated presents the advantage of possibility to compare P-ratio with other countries, knowing the fact that previously this indicator was calculated for Rumania by share from gross final energy consumption [12]. In fig. 4 VRG penetration ratio was compared with the top 5 countries with the "well operated" grid, in terms of both VRG penetration and curtailment [5].

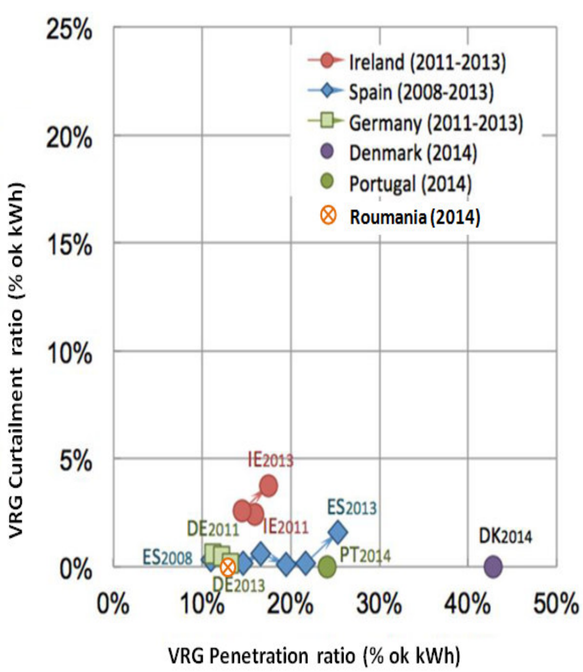

Fig. 4 C-P map for the penetration ratio comparison with top 5 countries [5]

Due to the fact that there are no statistical data regarding VRG energy curtailment in Romanian grid, it couldn't be calculate the annual curtailment indicator and plotting the resulting metrics o a C-P map.

Nevertheless with the available data regarding VRG annual penetration ratio it can be done some interesting considerations such as:

- In the past three years P-ratio is between [10-20]% which situates Rumania in the top five EU countries with high penetration of the VRG;
- To remain in the "green" zone, Romanian grid must have the R-indicator below 0,1, which means that the VRG curtailment ratio should be kept between 1% and 2% respectively, as shown in fig. 5;

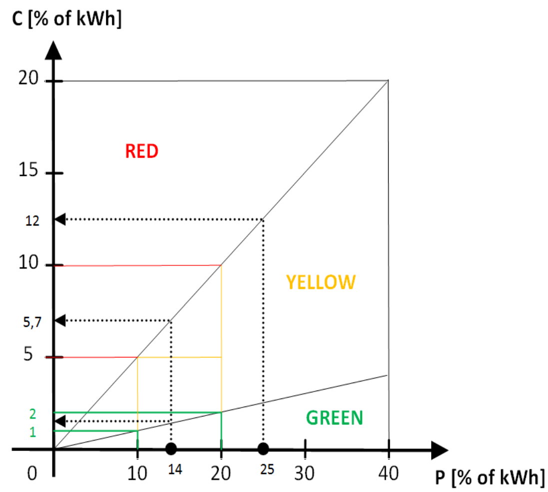

Fig. 5 C-P map for Romanian grid scenarios

- If in the near future we are expecting a growth in P-ratio, if it reach 14%, than the C-ratio shouldn't exceed 1,5% to remain in the "green" zone. Until the C-ratio reach 5,7% the grid is situated in "yellow" zone from the operating point of view, above this value it enters in "red", where the curtailed energy from VRG is too high;
- If the P-ratio grows at 25%, to remain in the "green" zone, the grid operator must kept the VRG curtailment level under 2,5% and not exceed 12% when it enters directly in "red" zone;
- In the less probable scenario that P-ratio decreases till the level of year 2014, meaning a 12% value, to remain in the "green" zone of grid operating, C-ratio must not exceed 1,15% . Any other value above 5,3% lead the grid directly in "red" zone.

These scenarios can offer to the grid operator an idea about the tendency of the VRG curtailment ratio considering VRG penetration ratio, so that the power network can be maintained in reasonable operating parameters, helping also in planning and decision making to optimize the curtailment of the WGS and PVS.

Regarding the G-indicator, without available data it cannot follow the real tendency of the VRG curtailments for a near future or the effect of the actions in reducing VRG curtailments in the grid. However it can be draw some possible scenarios as:

- For a P-ratio of 20% and C-ratio of 2% necessary to maintain the grid in "green zone", the G-ratio must be bellow 0,5 to obtain an (3b) type indicator, meaning "a well operated network with stable tendency in VRG curtailment for the future";
- A G-ratio above 0,5 indicates a deterioration in grid operation regarding the tendency of VRG curtailments, with all the negative impact on economics and market.

5. CONCLUSIONS

This paper aims to utilize a new tool in quantitatively assessment of the VRG penetration and curtailment level in Romanian grid, the probable future tendencies and the possible international comparison.

In the Romanian electrical sector as a VRG is considered wind generation systems and photovoltaic systems, a significant installed capacity of this kind being commissioned in the last four years.

Statistical data supplied by ANRE allow an objective assessment only for the VRG penetration ratio, using "C-P map" tool it resulted that the Romanian grid is situated among the EU countries with VRG penetration level between 10% and 20%.

Due to the fact that currently there are no statistical data regarding VRG energy curtailment, mainly because there are no mandatory rules in publishing such information, it could not be calculated the curtailment ratio. By plotting the available data in C-P map it still can be obtained an overview on the current state of the grid. This is still important to grid operator providing useful information in more efficient future curtailment planning thus improving grid security and economics. In addition, the grid operator can have a principle image on the possible tendencies of VRG penetration and curtailment ratio improving operational practices of the grid. So it can calculate the VRG curtailment ratio for a certain penetration level on a given period of time, being able to plan in advance the GWh curtailed from VRG in order to remain in the "green" zone of well operated network.

It can happen also that after the assessment, the grid operator can be warned about a possible exceeding in GWh curtailed in a given period of time, which can lead the grid in the "red" zone of too much curtailed energy for a given VRG penetration ratio.

The future trends can be assessed by the C-P gradient" indicator which can lead to useful information about future states of the grid from operational practices point of view: stable, improving or even deteriorating.

Using the C-P map tools and gathering precise statistical data from different countries, it can be done an international comparison regarding VRG penetration and curtailed energy. Still these comparisons must take into account a series of specificities such as: network degree of flexibility, operational practices, regulatory lows etc. Such a comparison can be informative for the Romanian grid operator helping to adopt the best actions so that the wind and solar curtailment can be optimized in the future with positive technical and economical impact.

REFERENCES

[1]. T.R. Ayodele et al., *Challenges of Grid Integration of Wind Power on Power System Grid Integrity: A Review*, International Journal of Renewable Energy research, 2012, [Online], disponibil pe: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.458.7515&rep=rep1&type=pdf/ 30.11.2017.

[2]. Debra Lew et al., *Wind and Solar curtailment*, Paper, October 2013, *[*Online], disponibil pe: https://www.researchgate.net/publication/259575369_Wind_and_Solar_Curtailment / 03.12.2017.

[3]. Lori Bird et al., *Wind and Solar Energy Curtailment: Experience and Practices in the United States*,March 2014, [Online], disponibil pe: https://pdfs.semanticscholar.org/0050/566dea4fb22c92df8c81c287a59e3b2c2d2d.pdf/13.12.2017.

[4]. Yoh Yasuda et al., *International Comparison of Wind and Solar Curtailment ratio*, Proceedings Workshop Brussels 2015, [Online], disponibil la: https://community.ieawind.org/HigherLogic/SysteS/DownloadDocumentFile.ashx?DocumentFileKeD=52ce6334-ce38-38c9-f210-f3a56ee6aaf5/ 16/12.2017.

[5]. H. Holttinen et al., *Design and operation of power systems with large amounts of wind power*, Final report of IEA Wind Task 25 Phase one 2006-08 (2009), [Online], disponibil la: http://www.vtt.fi/inf/pdf/tiedotteet/2009/T2493.pdf/ 16.12.2017.

[6]. L. Soder et al., *Experience from wind integration in some high penetration areas* , IEEE Trans. on Energy Conversion [Online], disponibil pe: https:// http://www.vtt.fi/inf/pdf/tiedotteet/2009/T2493.pdf / 16.12.2017.

[7]. ***, *RE Wind Europe Views on Curtailment of Wind Power and Its Links to Priority Dispatch*, EWA Report June 2016, [Online], disponibil pe: http://www.irena.org/ https://windeurope.org/wp-content/uploads/files/policy/position-papers/WindEurope-Priority-Dispatch-and- Curtailment.pdf/ 03.12.2017.

[8]. *** , Raport privind realizarea indicatorilor de performanță pentru serviciile de transport, de sistem şi de distribuție a energiei electrice şi starea tehnică a rețelelor electrice de transport şi de distribuție 2014, [Online], disponibil la: http://www.anre.ro/ro/energie-electrica/rapoarte/rapoarte-indicatori-performanta/ 19.12.2017.

[9]. *** , Raport privind realizarea indicatorilor de performanță pentru serviciile de transport, de sistem şi de distribuție a energiei electrice şi starea tehnică a rețelelor electrice de transport şi de distribuție 2015, [Online], disponibil la: http://www.anre.ro/ro/energie-electrica/rapoarte/rapoarte-indicatori-performanta/ 19.12.2017.

[10]. *** , Raport privind realizarea indicatorilor de performanță pentru serviciile de transport, de sistem şi de distribuție a energiei electrice şi starea tehnică a rețelelor electrice de transport şi de distribuție 2016, [Online], disponibil la: http://www.anre.ro/ro/energie-electrica/rapoarte/rapoarte-indicatori-performanta/ 19.12.2017.

[11]. ***, National Energy Efficiency Action Plan, Version of 2014, The Official Journal Of Roamnia [Online], disponibil la: https://ec.europa.eu/energy/sites/ener/files/documents/NEEAP%20Romania_en%20version.pdf/20.12.2017.

[12]. ***, *Romanian Energy Strategy 2016-2030*, Ministry of Energy, [Online], disponibil la: http://www.solarthermalworld.org/sites/gstec/files/news/file/2016-12-30/romanian-energy-strategy-2016-2030-executive-summary3.pdf/20.12.2017.