ON THE DEFINITION AND APPLICABILITY OF KEY PERFORMANCE INDICATORS FOR EVALUATING THE PERFORMANCE OF SMART GRID CONCEPTS

Marco ROSSI
RSE – Italy
marco.rossi@rse-web.it

Benoît BLETTERIE
AIT – Austria
benoit.bletterie@ait.ac.at

Maria SEBASTIAN VIANA
ERDF – France
maria.sebastian-viana@erdf.fr

Jesús VARELA SANZ
IBERDROLA – Spain
jvsa@iberdrola.es

ABSTRACT

Distributed Renewable Energy Resources (DRES) are having a growing presence in the electrical distribution system and they are one of the fundamental pillars for the achievement of the 2020 energy and climate change targets. The integration of renewables, however, entails several technical issues which could be often solved in a more efficient way than the traditional grid reinforcement strategies: in particular, the field experience has demonstrated that new technologies can be implemented in order to obtain acceptable levels of grid capacity. IGREENGrid collects the field experience in DRES integration from six large scale demonstrators located in different European countries. Their heterogeneous nature defines an environment in which a complete analysis of the benefits introduced by the smart grid solutions can be exhaustively evaluated. The role of this evaluation is assigned to the so-called Key Performance Indicators (KPIs) which represent a new recognized standard in the research and innovation field of electrical networks.
The document proposes an overview of the KPIs adopted by IGREENGrid for the evaluation and selection of the most promising solutions dedicated to the integration of DRES in distribution networks. Details about the adopted calculation procedures, numerical examples and applicability issues have been highlighted and discussed.

INTRODUCTION

Nowadays DRES integration is one of the main objectives in the research and innovation process of electrical networks. In order to meet the European energy and climate change targets for 2020 and beyond, the European electrical transmission and distribution systems must be modernized to enable a cost-effective deployment of low-carbon energy technologies.
At present, even though several advantages can be attributed to the connection of DRES [1][2], distribution networks are not be able to connect a large amount of DG since they were designed to deliver energy from higher voltage systems to the connected loads. In fact, an increasing amount of generation in MV and LV grids often significantly jeopardize the power quality, reliability and stability, fundamental requirements of the hosting network [1][2].
According to this, several initiatives are supporting the research activities and contributing to the network innovation aimed to the increase of DRES penetration in distribution networks. Thanks to these incentives, the application of solutions devoted to reliable integration of renewables is in progress and several benefits are already perceived. This role is attributed to dedicated demonstration projects developed in many countries in order to consider the different national scenarios and situations.
The IGREENGrid consortium includes eight Distribution System Operators (DSOs) from six different countries, currently engaged in large-scale demonstration projects for the implementation of new technologies that will enable the integration and increase the hosting capacity of DRES connected to distribution networks. Through its participants, the IGREENGrid project will encompass six of these demonstration projects. The main goal of this expertise fusion consists in the identification of the most promising solutions for the reliable and efficient integration of DRES at European level.

KEY PERFORMANCE INDICATORS

In order to merge the results obtained in the demonstration projects, and to identify the best performance solutions oriented to the integration of DRES, a common framework has to be defined. For each demonstration project, different evaluation procedures for the adopted solutions have been developed. Of course, most of them can be evaluated in limited scenarios and they are not often suitable for a transversal comparison among other considered demonstration project.
The European Electricity Grid Initiative (EEGI) has proposed a procedure for the evaluation of the benefits introduced by Smart Grid (SG) technologies [3]. This assessment is based on Key Performance Indicators (KPIs) which evaluate the network incremental performance between two different situations:

- Smart grid scenario
  This scenario corresponds to the situation in which the SG solution is implemented and operates on the network assets.
- Business As Usual (BAU) scenario
  This scenario identifies the network situation in which the SG solution is not implemented and the entire network operates as usual.

Once the network performance has been identified in both these situations, the KPI can be calculated in the following way:

$$KPI = K_{SG} - K_{BAU} \tag{1}$$

where K_{SG} and K_{BAU} are the performance indicators of the network in the smart grid and business as usual scenarios respectively. In order to compare the benefits of different solutions, these indicators have to be opportunely normalized. Otherwise, when the normalization is not easily applicable, the KPI can be expressed in terms of percentage incremental benefits, dividing (1) for the BAU indicator:

$$KPI_{\%} = \frac{K_{SG} - K_{BAU}}{K_{BAU}} \cdot 100\% \qquad (2)$$

These general formulas can be used for the performance evaluation of SG solutions from several points of views. In particular, since the IGREENGrid project is focused on the integration of DRES in distribution grids, three aspects have been selected for the evaluation of the tested technologies:

- increase of hosting capacity;
- improvement of the quality of supply;
- energy efficiency improvement.

Increase of hosting capacity

The integration of DRES in distribution grid is one of the main objectives of the SG solutions tested in IGREENGrid demonstrators. An indicator which effectively evaluates the level of installable DG is represented by the Hosting Capacity (HC). HC corresponds to the maximum amount of active power/energy which can be injected by DG in a given electrical system without creating network constraints. In literature, several techniques for the evaluation of the HC have been proposed and exhaustive surveys of them are reported in [4] and [5].

Typically, in order to guarantee the stability and the safety of the grid with limited information from the network, DSOs need to adopt conservative approaches, often based on worst-case scenarios. However, according to the IGREENGrid experience, it has been recognized that this approach is not often accurate for the evaluation of the benefits (in terms of HC) introduced by SG technologies.

In order to effectively calculate the HC of a distribution network and the performance of the tested solutions, the aspects described in the following paragraphs have to be opportunely considered.

Time dependent nature of generation and loads and other network components

This aspect can be faced in different ways. One of the most effective methods for the evaluation of time profiles is based on the computation of a Probabilistic Power Flow (PLF) and the HC is the result of a stochastic process in which most of the possible situations of load consumptions and DG power injection can be taken into account.

Alternatively, the considered network can be simulated in the time domain, reproducing its electrical behaviour for a fixed time window. Of course, this window should be long enough in order to contain most of the possible combinations of injected/consumed power. Even though this method could require higher computational burden with respect to the PLF approach, its simplicity allows an easy coupling with the SG algorithms, especially the ones for which the time dimension is critical (dynamic or storage controllers). Then, for the evaluation of the HC of IGREENGrid demonstrators, the time domain approach has been adopted.

In order to reduce the simulation time, still maintaining the significance of the obtained results, instead of the simulation of long time periods, characteristic profiles of loads and generators have been considered (Figure 1 and Figure 2). Thanks to the adoption of these curves, the HC evaluation can be reduced to a network simulation of only few different days.

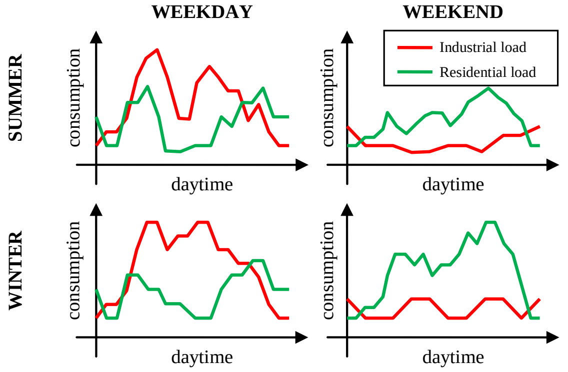

Figure 1. Exemplificative load profiles for different days and seasons.

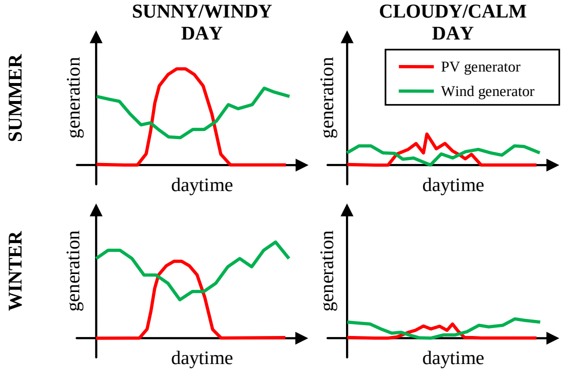

Figure 2. Exemplificative generation profiles for different weather conditions and seasons.

DRES technology

In the previous paragraph, the importance of the time profiles has been explained. This means that, depending on the DRES technology, the differences in the generation profiles could determine different values of HC. Then, in order to obtain a meaningful HC value, the DRES production profile has to be selected carefully. The criterion adopted within IGREENGrid, taking advantage of the known location of the demonstration projects, has been based on the local availability of the primary sources:

- for some demonstrators, only solar energy is exploitable and the typical PV profile (related to the selected area) is adopted;
- for some other demonstrators, only wind energy is widely available and the typical wind generator profiles is adopted;
- for the remaining networks, a linear combination of wind and PV profiles (or other DRES types) will be adopted depending on their respective expected penetration.

Unknown position of new installations of DG

Another fundamental aspect with a relevant impact on the HC is represented by the position of DRES in the distribution grids. According to the surveys [4][5], most of the HC approaches have a strong limitation since they are based on the simulation of a predetermined allocation of DG. Having considered that DSOs usually do not have a complete control on the position of new generators, these HC approaches may lead to unrealistic results.

In order to obtain a more significant evaluation of the maximum generation, the uncertainty introduced by the unknown position of generators (which are not currently installed) has to be taken into account. This evaluation can be performed by simulating several random DG allocation (Monte Carlo approach)[6] and to compute the probability that, for a given value of total generation, the selected constraints (overvoltage, overcurrent, etc.) are violated. In Figure 3 the Probability Density Functions (PDFs) of the HC computed for one of the IGREENGrid SG solutions and for the BAU scenario are reported.

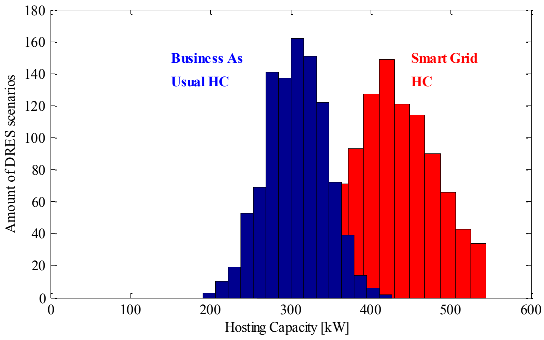

Figure 3. PDFs of the HC in BAU and SG scenarios

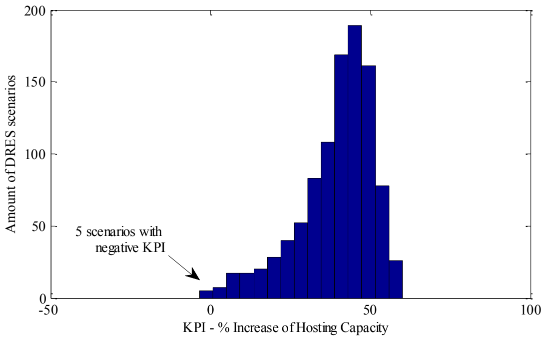

Figure 4. PDFs of the HC increase (IGREENGrid KPI)

The showed results refer to a low voltage distribution network in which the simulated PV sources injects only active power (BAU scenario) and reactive power depending on the PV-terminals voltage (SG scenario) [7]. From the obtained data, referred to 1000 random DG scenarios, the KPI can be easily computed by applying (2) and the performance indication is provided by the PDF reported in Figure 4. It can be noticed that this SG technology applied on the selected grid, for most of the simulated scenarios, has a positive impact on the hosting capacity (except for 0.5% of the total cases, in which the HC decreases because of over-load limitations):

$$KPI_{IGG.1} = \frac{HC_{SG} - HC_{BAU}}{HC_{BAU}} \cdot 100\% = (39 \pm 35)\% \qquad (3)$$

Improvement of Quality of Supply

Power quality and Quality of Supply are relevant aspects of distribution grid, especially for networks in which a deep penetration of DG is expected. In fact, it is universally recognized that the voltage quality is one of the most critical points for DG integration. For this reason, it is extremely important to keep monitored the distributed generation impact on the voltage magnitude.

Taking into account the definition of quality of supply (standard EN 50160), at IGREENGrid level the Voltage Performance Indication *VPI* of a generic working scenario has been designed as follows:

$$VPI = 1 - \frac{\Delta V_{95\%}}{\Delta V_{max}} \qquad (4)$$

where ΔV_{max} is the maximum allowed voltage deviation with respect to the nominal value V_n, while $\Delta V_{95\%}$ is the 95th percentile of:

$$\Delta V(t) = |V(t) - V_n| \qquad (5)$$

where $V(t)$ is the voltage profile in a selected bus of the considered network. Thanks to this normalization, it can be recognized that:

$$VPI \rightarrow \begin{cases} = 1 & V(t) \cong V_n \\ \geq 0 & V(t) \text{ within the limit } \pm \Delta V_{max} \\ < 0 & V(t) \text{ out of the limit } \pm \Delta V_{max} \end{cases} \qquad (6)$$

This evaluation can be easily performed by using the measured voltage profiles of the demonstration projects. However, having considered the voltage control techniques tested in IGREENGrid, often the grid is intentionally operated at non-nominal voltage in order to introduce benefits of different nature (i.e. reduction of power losses). In this case, considering the currently limited penetration of DG and the presence of dead-bands in the control algorithms, the voltage quality benefits could be hard to evaluate from the field measurements.

A possible alternative method can be based on the results obtained from the HC calculation: in fact, having considered the 1000 DG scenarios represented in Figure 3 (BAU case), the VPIs can be computed for each of them and adopted as reference. In order to evaluate the benefits introduced by the selected SG technology, the 1000 scenarios can be re-simulated, maintaining the same DRES configurations (same active power), but applying the selected SG solution. The results of this process are reported in Figure 5.

Thanks to this procedure, the KPI can be evaluated in working conditions for which the SG solution is certainly affecting the grid operations. Finally, from the obtained results and the application of (1), the increase of quality of supply KPI can be calculated as follows:

$$KPI_{IGG.2} = VPI_{SG} - VPI_{BAU} = 0.21 \pm 0.03 \qquad (7)$$

The obtained KPI shows that the selected SG technology, as expected, has a positive impact on the voltage quality for high values of installed DG. It is interesting to notice that, in spite of the scattered DG scenarios (as depicted in Figure 3), the improvement of the quality of supply is characterized by a negligible spread (it does not depend on the DG scenario).

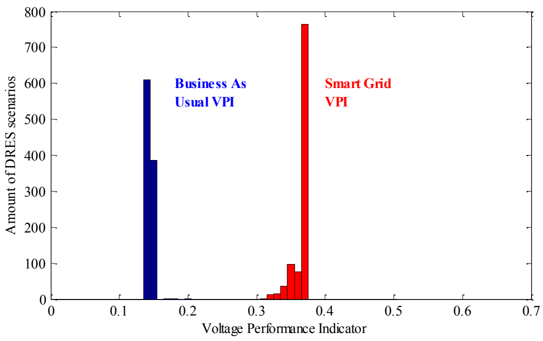

Figure 5. PDFs of the VPIs of the BAU and SG cases in correspondence of the maximum allowed generation in BAU scenario.

Energy efficiency improvement

Energy efficiency represents a relevant aspect of the network operations and the impact of the tested SG solutions on it has to be kept monitored.

As for the KPI described in the previous section, the energy losses can be evaluated from the analysis of the field measurements, especially from the energy meters readings. Unfortunately, when large demonstrators are considered, few drawbacks have to be opportunely taken into account. In particular, for the IGREENGrid demonstration networks, it has been noticed that the meters reading is not often reliable because of:

- metering synchronization issues;
- presence of non-measurable losses contributions.

For this reason, different and more complex techniques have to be often adopted in order to evaluate the grid components efficiency, with a non-negligible impact on the estimation uncertainty. In fact, the traditional approaches for the evaluation of distribution energy efficiency are based on off-line techniques which often are not able to effectively take into account the benefits/drawbacks introduced by SG solutions.

In order to obtain a representative evaluation of the energy efficiency impact, the calculation procedure of this KPI has been based on the simulation of the network with the characteristic profiles depicted in Figure 1 and Figure 2. The proposed simulations can be chained in order to cover all the possible combinations of load and DG. For the particular case in which only PV generation is considered, the simulation has to be performed for the scenarios listed in Table 1.

From the results of the performed simulations, the energy efficiency can be evaluated by computing the energy balancing according to the following formula:

$$\eta = \begin{cases} \dfrac{W_{load}}{W_{DG}+W_{HV}} & \text{when } W_{HV} \ge 0 \\ \dfrac{W_{load}-W_{HV}}{W_{DG}} & \text{when } W_{HV} < 0 \end{cases} \qquad (8)$$

where W_{load} is the total energy consumed by the load, W_{DG} is the energy produced by the DG connected to the considered grid and W_{HV} is the total energy delivered from the upstream network.

Season	Weather	Day	Weighting factor
Summer	Sunny	Weekday	5
		Weekend	2
	Cloudy	Weekday	5
		Weekend	2
Winter	Sunny	Weekday	5
		Weekend	2
	Cloudy	Weekday	5
		Weekend	2

Table 1. Simulation scenarios for the evaluation of the SG solution impact on energy efficiency. The reported situations have been selected, having assumed: same probability of sunny and cloudy weather conditions during both winter and summer; 5 business days (weekday) and 2 weekend days per week.

Multiple DG scenarios can be used for the evaluation of the energy efficiency and the identification of the most suitable one is still in progress. Also in this case, one of the best candidates is represented by the DG scenario resulting from the evaluation of the BAU HC. The simulations have been conducted as described in the previous paragraph, obtaining the efficiency values reported in Figure 6.

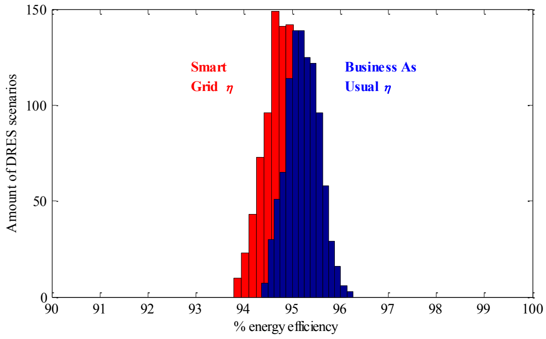

Figure 6. PDFs of the network energy efficiency of the BAU and SG cases in correspondence of the maximum allowed generation in BAU scenario.

Then, from the comparison of the BAU and SG scenarios, it is possible to evaluate the energy efficiency improvement thanks to the application of the KPI formula reported in (1):

$$KPI_{IGG3} = \eta_{SG} - \eta_{BAU} = (-0.38 \pm 0.28)\% \qquad (9)$$

According to the resulting KPI, it can be stated that the adopted SG solution has a little but constantly-negative impact on the network efficiency.

Global evaluation of the SG solution

Thanks to the computation of these three KPIs, it is possible to deduce a global and indicative performance of the tested SG solution. In particular, for this exemplificative case study, it is possible to conclude that the adopted control of DG reactive power [7] determines a significant increase of installable DRES (+39%) in the considered network, but only when the main HC limitation is represented by the over voltage limits. In fact, in case of large penetration of DG, the positive voltage quality improvement is evident (+0.21). On the contrary, for networks in which the HC is mainly limited by the thermal constraints, the tested control is expected to provide very poor benefits, since its impact on the energy efficiency is negative (-0.38%).

COMMENTS ON THE KPIS APPLICABILITY

The physical demonstrators represent a prolific field for the application of SG technologies and the performance evaluation assessment proposed by IGREENGrid can be easily applied by taking into account some simple precautions. However, the grown practical experience shows that the use of KPIs to compare demonstrations is not really meaningful. Indeed, SG solution-A demonstrated in network-1 cannot be simply compared to SG solution-B demonstrated in network-2. KPIs can only be used to compare the performance of a SG solution in different networks or to compare the performance of different SG solutions in a considered network.

In addition, as analysed in the previous paragraphs, the measurements from the field often are not representative of situations in which the SG solutions are introducing benefits. In fact, the demonstration projects usually mainly consist of a functional validation and the current working conditions do not require additional measures for a reliable and efficient operation of the grid.

According to this, the only way to obtain meaningful KPIs is to rely on simulations, allowing considering cases in which the SG solutions are really needed. Of course, the simulations should ideally be based on real measured inputs data and, for this reason, the network monitoring plays a fundamental role for the accurate reproduction of the grid real behaviour.

CONCLUSION

The performance evaluation of SG solutions has to be carried out in order to consider several aspects and, for this reason, different indicators have been proposed by the EEGI team in its last smart grid implementation roadmaps (summarized in [3]). According to the analysis performed in IGREENGrid and the technologies tested in its large-scale demonstration activities, three main indicators have been developed for the evaluation of the benefits introduced by SG technologies in terms of DRES integration.

The document reports a brief description of the KPIs calculation procedures and some exemplificative results aimed to demonstrate the effectiveness of the proposed performance evaluation. The analysis has been carried out considering the practical limitations related to the use of real field measurements for the KPIs computation. According to this, alternative procedures, based on the modelling and simulation of the tested networks and SG solutions, have been successfully applied.

Acknowledgments

IGREENGrid project has received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement no 308864.

REFERENCES

[1] J.A. Peças Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, N. Jenkins, 2007, “Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities”, *Electric Power Systems Research*, vol. 77, 1189-1203

[2] M.H.J. Bollen, Y. Yang, F. Hassan, 2008, “Integration of distributed generation in the power system: a power quality approach,” *Proceedings 13th International Conference on Harmonics and Quality of Power*, 1-8

[3] GRID+ European Project, 2013, “Define EEGI Project and Programme KPIs”, *EU Seventh Framework Programme*

[4] P.S. Georgilakis, N.D. Hatziargyriou, 2013, “Optimal Distributed Generation Placement in Power Distribution Networks: Models, Methods, and Future Research”, *IEEE Transactions on Power Systems*, vol. 28, 3420-3428

[5] A. Keane, L.F. Ochoa, C.L.T. Borges, G.W. Ault, A.D. Alarcon-Rodriguez, R.A.F. Currie, F. Pilo, C. Dent, G.P. Harrison, 2013, “State-of-the-Art Techniques and Challenges Ahead for Distributed Generation Planning and Optimization”, *IEEE Transactions on Power Systems*, vol. 28, 1493-1502

[6] Electric Power Research Institute, 2012, “Stochastic Analysis to Determine Feeder Hosting Capacity for Distributed Solar PV”, *2012-Program-174 Integration of Distributed Renewables*

[7] D. Moneta, P. Mora, M. Gallanti, G. Monfredini, M. Merlo, V. Olivieri, 2011, “MV Network with Dispersed Generation: Voltage Regulation based on Local Controllers”, *Proceedings CIRED conference*