

Smart Grid Performance Indicators

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Abstract – In this paper a review of smart grid performance indicators is provided. The objectives of smart grids are discussed with the aim of clarifying the evaluation criteria which arises from them. Several metrics are presented, illustrating drawbacks and difficulties in their calculation. The evaluation of Demand Response performance is analyzed in order to give further insights on smart grids performance assessment.

Keywords – Smart grids, power grids, power systems, performance indicators, demand response, reliability

I. INTRODUCTION

Smart grids (SGs) can be seen as a paradigm, whose implementation is the result of continuous evolution, so that the exact moment of transition from the traditional grid to the smart one will never be given, at least from a strictly technical point of view. Indeed, the SG doesn't rely on a single technology, but on multiple technological advances. Moreover, change should be gradual because new systems should coexist with older ones in order to ensure continuity to the electric service. In a sense, SG vision is more ambitious than actual implementation designs which are tied to cooperate with the traditional grid.

A recent review of features, functionalities and characteristics of SGs is presented in [1] whereas several papers have pointed out challenges and complexities of them [2]-[4].

In the absence of a mandatory set of rules to follow, stakeholders choose and propose different technical solutions with different objectives. In this context, not only technological aspects should be considered, but also environmental and social ones.

One of the drivers of change towards SGs is surely the need to reduce the environmental footprint of energy production and consumption by permitting, for example, the growth of renewables. Indeed, technological improvements in photovoltaic, wind and thermoelectric generators have made more feasible and more reliable the production from renewable sources and energy harvesting [5]-[24]. The increased complexity of SGs has motivated researches on: monitoring instruments [25]-[31]; advanced signal and data processing [32]-[39]; applications of image processing [40]-[48]; distributed monitoring and measurement networks that integrate or

extend the scope of the SG to realize a cyber-physical system[49]-[58].

The purpose of this paper is to provide a brief review of indicators that have been proposed to quantify SG performance.

This paper is structured as follows: in Sec. II the complexity of multiple objectives that apply to SGs is introduced; in Sec. III some metrics for evaluating the performance in reaching that objectives are presented; in Sec. IV the particularly important aspect of Demand Response (DR) performance assessment is discussed; finally, in Sec. V, the conclusions are drawn.

II. MULTIPLE CRITERIA ANALYSIS

The evaluation of SG performance should be based on multiple criteria dependent on different objectives. For example, one is the power quality improvement. Further objectives can be evaluated through different criteria, such as: the degree of diffusion of the knowledge about the new services made available by SGs; the performance of communication between utilities and consumers and, in particular, the diffusion of DR requests, the ease of access to power consumption and additional information.

Many different benefits of SGs are analyzed in [59]. They are grouped into four fundamental categories: economic; reliability and power quality; environmental; security and safety. The proposed methodology consists in correlating the enabling technologies and SG functions to the benefits that arise from them, quantifying the costs of SG functions and the economic value of benefits.

In [60] several performance indicators of product quality and of service quality are considered. Product quality indicators are: steady state voltage, power factor, harmonics, voltage imbalance, voltage fluctuation, frequency variation. Service quality indicators are: average time of service to emergencies, equivalent duration of interruption, equivalent frequency of interruption, number of consumers with smart meters and bilateral consumer communication. The methodology described in [60] starts from the evaluation of the current level of each indicator, by assigning a score, quantifying the change in attractiveness due to the decrease of each indicator. That methodology served as the starting point for decision makers to express the following recommendations: improve the number of installed meter and, eventually, use multi-utility meters (electricity, water, gas); allow customers' access to measured data;

improve grid self-healing and reliability; increase responsiveness to distribution network failures; improve grid capacity planning by processing the available data; Improve real-time monitoring; and forecast the interaction of the SG with other utilities and the creation of added value services.

In general, providing a quantitative and objective assessment of performance, rather than a subjective one, according to the given criteria and objectives is rather difficult but necessary. For example, one should consider that, from one point of view, energy efficiency and reduction of demand may reduce utilities incomes, so trade-off and incentives should be carefully determined. For these reasons, the availability of open data on grids is highly beneficial for the understanding and the design of the future SG. It is auspicious that a larger amount be made available in order to calculate the metrics mentioned in Sec. III.

III. SMART GRID METRICS

One of the most notable effort in defining metrics for SGs is given in [61]. There, the deployment status of SG technologies, practices and services is evaluated through a set of metrics: *build* metrics are relative to the technical implementation status of SG, while *value* metrics are relative to consequences and impact of SG realization. Table 1 shows a summary of the selected metrics, with a short description.

The analysis of the metrics leads to several remarks. A first observation is that many metrics are too unspecific because they are based simply on the number of elements rather than quantifying the specific properties of those elements. For example, the number of customers participating in DR is quantified, but the performance of that participation may not be given. Similarly, the number of deployed smart meters can be quantified, but the characteristic of them, such as the report rate, their accuracy and the availability of measured data may not be quantified. Another example is quantifying the status of deployment of the advanced metering infrastructure, without specifying which quantities are measured and shared with stakeholders.

Another aspect is that capacity factors are averaged over the entire infrastructure in order to give a synthetic index. However, it should be noted that equally important is the analysis of the bottlenecks and criticalities due to single elements of the infrastructure.

The transmission and distribution infrastructure are facing several changes, among which the upgrade and improvement of the measurement infrastructure. Wide Area Measurement Systems (WAMS) integrate several measurement devices, such as digital fault recorders and Phasor Measurement Units (PMUs), with a certain amount of overlap of functionalities among them, constituting the data sources of SCADA systems. In general, WAMS should support higher sampling rates

(such as 30 Hz), which are useful to analyze fast variations before and after grid events such as outages, and should be able to measure the dynamic performance of the grid. In this complex scenario, it is auspicious that metrics will be not limited to the percentage of substations possessing advances measurement technology, and be not limited to discriminate among specific measurement devices, but that a more analytic approach be carried out based on the concrete specification of measured quantities, reporting rates and accuracies.

Table 1. Smart grid metrics.[61]

Dynamic Pricing: fraction of customers and total load served by RTP, CPP, and TOU tariffs
Real-time System Operations Data Sharing: Total SCADA points shared and fraction of phasor measurement points shared.
Distributed-Resource Interconnection Policy: percentage of utilities with standard distributed-resource interconnection policies and commonality of such policies across utilities.
Policy/Regulatory Progress: weighted-average percentage of smart grid investment recovered through rates.
Load Participation Based on Grid Conditions: fraction of load served by interruptible tariffs, direct load control, and consumer load control with incentives.
Load Served by Microgrids: the percentage total grid summer capacity.
Grid-Connected Distributed Generation (renewable and non-renewable) and Storage: percentage of distributed generation and storage.
EVs and PHEVs: percentage shares of on-road, light-duty vehicles comprising of EVs and PHEVs.
Grid-Responsive Non-Generating Demand-Side Equipment: total load served by smart, grid-responsive equipment.
T&D System Reliability: system average interruption duration index, system average interruption frequency index, momentary average interruption frequency index.
T&D Automation: percentage of substations using automation.
Advanced Meters: percentage of total demand served by advanced metered (AMI) customers.
Advanced System Measurement: percentage of substations possessing advanced measurement technology.
Capacity Factors: yearly average and peak-generation capacity factor.
Generation and T&D efficiencies: percentage of energy consumed to generate electricity that is not lost.
Dynamic Line Ratings: percentage miles of transmission circuits being operated under dynamic line ratings.
Power Quality: percentage of customer complaints related to power quality issues, excluding outages.
Cyber Security: percent of total generation capacity under companies in compliance with the NERC Critical Infrastructure Protection standards.
Open Architecture/Standards: Interoperability Maturity Level – the weighted average maturity level of interoperability realized among electricity system stakeholders
Venture Capital: total annual venture-capital funding of smart-grid startups located in the U.S.

The considered power quality metric consists in the percentage of customer complaints. As noted in [61], even though a standard for power quality exists, power quality grades that customers can agree with utilities are not provided. The definition of quality grades can be

considered as a prerequisite for improving power quality metrics.

Cyber security development inside SGs has been considered a serious concern. The metric refers to compliance to protection standards. It should be noted that, in this scenario, security involves not only the protection of sensitive information, but also the protection of SG operations and critical functions. It is difficult to concretize security objectives into actual design specifications and security assessments, due to the lack of a standard SG implementation.

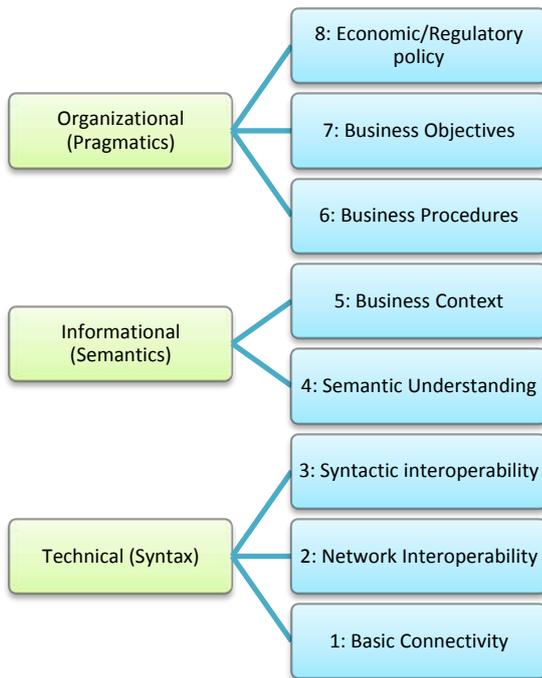


Fig. 1. Interoperability levels

The interoperability of the components of the SG is considered among the greatest challenges. To increase SG implementation success, proprietary protocols are gradually abandoned in favor of open ones. Moreover, devices which support multiple protocols have greater possibilities of widespread deployment. This is due to the large number of different protocols and standards available today at different levels of the architecture. To provide a framework for describing this complexity, GridWise Architecture Council has defined interoperability levels grouped into three categories, as illustrated in Fig. 1, which span from the physical level (basic connectivity) to the level of political and economic objectives. One metric for evaluating each level is the Interoperability Maturity Level, shown in Table 2, which was defined by the National E-Health Transition Authority of Australia (NEHTA) in the context of health industry.[64].

Communication infrastructure is a characterizing aspect of SG. To understand its performance, several

indicators should be calculated: bandwidth, cost of infrastructure building and maintenance, cost per bit, energy per bit and reliability. The communication infrastructure may be separated from energy infrastructure, similarly to what happens in a living being where arterial, venous, nervous and lymphatic systems are distinct. A strategy can be that of reserving resource of the cellular communication infrastructure to support SG needs, while ensuring improved reliability, with respect to normal customers' services, proportional to the importance of the energy distribution system. Internet is the best candidate, due to its intrinsic characteristic of integrating networks which are heterogeneous from a physical point of view. A global strategy to respond to attacks and damages to the communication infrastructure should address, at the same time but with tailored priorities, the communication needs of residential clients, business clients as well as utilities. For example, the cellular communication network may be repaired, in case of emergencies, by using mobile self-powered radio towers. It is clear that the dependence of the SG on communication infrastructure should be analyzed in order to find the points of weakness and to determine which services are unaffected and which services are altered by communication impairment.

Table 2. Interoperability Maturity Levels [64].

Optimized	Driven by feedback from monitored processes, interoperability capability continuously improves overall capability.
Measured	Processes for appraising interoperability, e.g. conformance/compliance or run-time monitoring.
Defined	Defined guidelines for standards, services, policies, processes and legal compliance. Established governance.
Managed	Begin adoption of standards. Shared understanding of data/services/internal processes. Early governance.
Initial	Awareness interoperability requirement. Initial small scale interoperability solutions.
None	No awareness of interoperability issue nor processes to support it. Isolated system design, development, and procurement.

IV. EVALUATION OF DEMAND RESPONSE PERFORMANCE

Customers' DR consists in the modulation of power consumption according to price signals and SG events. The most extreme DR capability is direct load control, in which supply parties are able to shut down loads.

One parameter that affects DR performance is the notification time for dispatch, which is the time customers are notified in advance before DR requests. Other relevant parameters are: response duration, which is the duration the customer modifies power consumption in response to DR requests; maximum number of DR requests in a given period; and flexibility of the program

trigger.

Several different DR strategies have been proposed, which have to be evaluated to understand if they are effective in reducing operating cost and cost of infrastructure, energy consumption, power loss, energy transmission and distribution. IEEE standard 2030.6-2016 describes a framework to perform that evaluation [63].

Cost evaluation should comprise all stakeholders. For example, it should be noted that one cost for customers due to DR may come from reduction of productivity and from the reduced use of their appliances. Another one may be due to the use of local generators to provide energy instead of utilities.

There are two clearly positive effects of DR: load curtailment during DR events; variation of energy consumption over a large period of time due to the participation to DR. However it has been observed that, after the end of load reduction phases, power consumption may increase abruptly (load rebound) threatening grid stability. Since total load and the typology of load changes continuously, the fluctuation of load curtailment as well as load rebound should be quantified in order to measure the efficacy of DR. The very definition of load curtailment poses measurement challenges, since it is based on the difference between actual load due to the DR and a high uncertain value which is the predicted load or baseline. Indeed, baseline calculation is difficult and there is the risk that customers increase baseline in order to obtain, in a second moment, greater incentives.

V. CONCLUSIONS

Several aspects of SG performance evaluation have been discussed. The complexity due to the multi-objectiveness in SG paradigm has been pointed out and several metrics have been illustrated that allow one to quantify the degree of achievement of those objectives. These metrics should go further than the simple quantification of the number of items, such as smart meter or PMU that belong to a particular implementation of a SG, and be rethought in terms of achieved performance and benefits. We have mentioned several measurement difficulties, nevertheless it is authors' opinion that only the knowledge arising from rigorous measurements will contribute to the successful understanding and verification of SG designs and implementations.

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