DEFINITION AND VALIDATION OF KEY PERFORMANCE INDICATORS TO ASSESS THE EFFECTIVENESS OF “SMARTING ACTIONS” ON A DISTRIBUTION NETWORK

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ABSTRACT

The paper aims at presenting part of results of the research activity developed in the context of quantifying the impact of a renewed Transmission & Distribution (T&D) infrastructure on EU 2020 goals. More in details, the definition, validation, update and use of Key Performance Indicators (KPIs) are pointed out, in order to comparatively assess the effectiveness of different smarting interventions on the distribution electric grid. The KPIs are mainly related to environmental issues and power quality aspects. The validation of the proposed KPIs is performed by means of a specific methodology developed for the evaluation of the benefits and the optimization of the effectiveness due to smarting actions on the distribution network.

INTRODUCTION

The European Union (EU) climate and energy policy, has established targets for year 2020 on efficiency, CO_2 reduction and increase of renewable energy sources [1]. The energy supply system can successfully help achieving such environmental targets. T&D infrastructure efficiency has to be increased in order to make the system perform at its best possibility, allowed by state of the art technology. In this context, the attention to innovation and improvement of all the processes in the energy conversion and transportation has become a primary issue, attracting the interest of those who want to invest in the improvement and modernization of the electric infrastructure. Many studies on such topic have been carried out by Universities and Research Centres. As a main example, a general simulation tool, called PRIMES, has been proposed in a recent past to assess the impact of EU policies in the power sector [2]. It is highly probable that, in a very close future, many different projects or innovative ideas will be proposed to improve the electrical infrastructure in the direction traced by the EU climate and energy policies, especially at the level of distribution networks where smart grids and distributed generation are deeply growing and will gain more and more importance on operating strategies. As a consequence, there is a strong need to develop some reliable and general tools aiming at evaluating the effectiveness of the new proposals. In particular, it is necessary to identify and define some Key Performance Indicators (KPIs) to evaluate and compare the different proposals of innovation, in order to support effective and concrete projects for the achievement of EU 2020 targets. The aim of the present article is proposing a methodology to define and evaluate environmental oriented KPIs for distribution networks directly related to the 2020 EU targets. Simulations performed on a codified distribution benchmark network will be presented in order to verify the adequacy of KPIs definition, to judge if the KPIs can be either calculated or measured and, as a consequence, to propose an efficient methodology for their evaluation.

STRUCTURE OF EUROPEAN T&D INFRASTRUCTURE

The electric T&D infrastructure represents a complex interconnection between different players which lays on different levels of operation. From the KPIs definition point of view, it can be useful to identify the players and their correlation as shown in the diagram of Fig. 1.

The electrical grid infrastructure accounts for multiple operators that own and manage their grid share; the electric transmission grid is divided among (national) TSOs, each one receiving power (A) from producers and feeding significant customers (B), as well as transferring most of their flows towards the distribution grid (D). Neighbouring TSOs account for mutual support (C) in normal and/or emergency operation. The electric distribution grid is divided among DSOs, each one feeding a large amount of customers (B), receiving at the same time a large number of diffuse generation contributions (A) e.g. Distributed Energy Resource (DER) and Renewable Energy Sources (RES), as well as interacting with the transmission level of the grid (D).

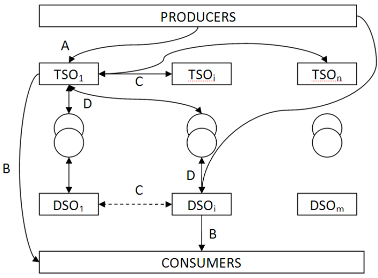

Fig. 1 – Schematic representation of the European T&D electric system. Prospective interactions among DSOs (dotted double arrow with label C) is highly encouraged.

KPIS DEFINITION

KPIs can be defined and evaluated in order to assess several performance aspects of the electric grid. A first set of KPIs can be associated to environmental aspects, namely:

- network efficiency;
- renewable generation integration;
- greenhouse gasses emission.

Other KPIs can be defined considering technical aspects related to quality aspects such as:

- voltage profile improvement;
- line loading optimization;
- reactive power flow reduction.

Each aspect of the previous list can be associated to a well-defined measurable quantity, that will allow the calculation of the correspondent KPI. In the present article, the attention is drawn on environmental aspects such as network efficiency and distributed generation integration, (greenhouse gasses KPI is not directly evaluated as this KPI is more related to the transmission network were the presence of large thermoelectric power plants is more relevant) as well as to quality issue of the voltage profile improvement.

Power Saving (PS) KPI

The network efficiency is one of the most important aspects to measure the good performance of the electric system. With respect to the electric distribution infrastructure, its easiest evaluation criterion is based on the evaluation of power losses due to Joule effect. For this reason, the Power Saving KPI is defined as the impact on the reduction of power losses in the distribution network as a consequence of a smarting intervention. From an analytical point of view, this KPI will be defined as:

$$PS_{KPI} = \frac{P_{jb} - P_{ja}}{P_L} \cdot 100 \ [\%] \tag{1}$$

Being respectively: $P_{ja(b)}$ the Joule losses in the network after (before) the smarting intervention and P_L the network total load.

Share of RES (SoR) KPI

This KPI aims at highlighting the benefit introduced by a generic smarting intervention on the RES hosting capacity of the system. The RES hosting capacity is the maximum amount of power coming from renewable sources that the grid is capable to manage according to assigned service quality and security levels. The present analysis concerns a steady state modelling of the electric system and, for this reason, the limits introduced for the increasing of renewable generation are basically related to the maximum thermal rating of the transmission/distribution lines and limits on node voltage ranges. The related KPI is defined as:

$$SoR_{KPI} = \frac{RES_{HCa} - RES_{HCb}}{P_L} \cdot 100 \ [\%] \tag{2}$$

Being respectively: $P_{HCb(a)}$ the RES hosting capacity before (after) the smarting intervention and P_L the network total load.

Voltage Profile Improvement (VPI) KPI

For the definition of KPIs related to steady-state quality in distribution networks, the attention is mainly focused on voltage, according to the present operating practice proposed by utilities all around the world. The evaluation of voltage grid profile requires a steady-state analysis of the electrical system, usually performed via power flow computations. Consequently it is possible to evaluate the sum of node voltage deviations (absolute values) from the ideal flat profile. The KPI is then defined as:

$$VDI_{KPI} = \left(VD_b\left[p.u.\right] - VD_a\left[p.u.\right]\right) \cdot 100\left[\%\right] \tag{3}$$

being $VD_{a(b)}$ the voltage deviation before (after) the intervention, defined as:

$$VD = \sum_{h=1}^{n} \left|V_h\left[p.u.\right] - 1\right|, \tag{4}$$

being n the total nodes of the system.

METHODOLOGY DESCRIPTION

The proposed methodology is based on the application of the classical Optimal Power Flow (OPF) algorithm for the identification of the best asset of the intervention in order to evaluate the maximum impact on the considered KPI. For the evaluation of the proposed KPIs three main actions are taken into account in the present article, namely:

- the application of FACTS devices,
- the increasing of network rated voltage,
- the control of reactive power from renewable generation..

These interventions belong to three distinct classes of actions namely: installation of new devices, better operation of the electric system and new control strategies for renewable energy producers.

The OPF problem is composed of a set of constraints that represent the physical electric power flow equations and the limits on some electric variables. Nevertheless, in presence of an intervention that drastically changes the topology of the network (the application of FACTS devices) the classical equations need to be a little updated, as will be detailed in the following subsections.

Application of FACTS devices

FACTS devices allow to introduce degrees of freedom in the system that can in principle be used to match the environmental and quality targets defined in the previous section. As proposed in [3], from a static point of view, it is possible to model the effect of the compensators by controlled voltage and/or current sources (depending if one is considering a series, shunt or combined device) as depicted in Fig. 2:

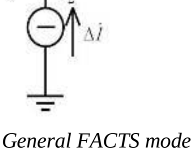

Fig. 2. General FACTS modelling.

Series, shunt and combined devices could account either for active configurations, that is with provision of real power too, or for reactive ones, that is with no net production of active power by the compensator. In this representation, the quantities $\Delta\dot{V}$ and $\Delta\dot{I}$ are the effects of the compensation, $\dot{V}$ and ($\dot{I}$) are the voltage (current) at the sending node and $\dot{V}_L$ ($\dot{I}_L$) are the voltage (current) at the receiving one.

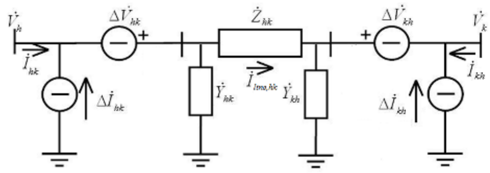

Fig. 3. Modelling of a generic "h-k" branch with FACTS compensators.

The proposed modelling takes into account the possibility of implementing FACTS devices at each end of each line, as shown in Fig. 3, which represents the adopted model for the generic branch of the grid. On the basis of the configuration proposed above, it is now possible to draw a general formulation for the problem of investigating how FACTS can affect the performance indicators defined in the previous sections.

From a mathematical point of view, the problem can be formulated as follows: find out the values of $\Delta\dot{V}_{hk}$ and $\Delta\dot{I}_{hk}$ to be inserted at each terminals of each branch of the network, which maximize an objective function constrained by the load-flow equations, that is to say:

$$\min f\left(\dot{V}_h, \Delta\dot{V}_{hk}, \Delta\dot{I}_{hk}\right),\ h,k = 1..N \tag{5}$$

where *f* is a real function of the node voltages $\dot{V}_h$ and of the shunt and series compensations $\Delta\dot{I}_{hk}$ and $\Delta\dot{V}_{hk}$ related to the specific KPI under investigation (in principle, the function f could be the KPI itself). The constraints of the problem are represented by the load-flow equations [4]:

$$\dot{S}_h = \dot{V}_h \sum_{\substack{k=1,\\ k\neq h}}^{N} \dot{I}^*_{hk}\left(\dot{V}_h, \dot{V}_k, \Delta\dot{V}_{hk}, \Delta\dot{I}_{hk}, \Delta\dot{V}_{kh}, \Delta\dot{I}_{kh}\right) \tag{6}$$

where the expression of the current $\dot{I}_h$ as a function of the variables of the problem is the following (see Fig. 3):

$$\dot{I}_{hk} = \left(\dot{V}_h + \Delta\dot{V}_{hk}\right)\left(\dot{Y}_{hk} + \frac{1}{\dot{Z}_{hk}}\right) - \frac{\dot{V}_k + \Delta\dot{V}_{kh}}{\dot{Z}_{hk}} - \Delta\dot{I}_{hk} \tag{7}$$

Inserting (7) into (6), one obtains the explicit formulation of the load flow constraints. In addition to these equality constraints, the formulation takes into account the static current limit on every line, limits on the maximum amplitudes of the current and voltage compensations and limits on the real power produced by the devices, that is to say:

$$\begin{cases} \left|\dot{I}_{line,hk}\left(\dot{V}_h, \dot{V}_k, \Delta\dot{V}_{hk}, \Delta\dot{I}_{hk}, \Delta\dot{V}_{kh}, \Delta\dot{I}_{kh}\right)\right| \le \mathrm{I}_{\mathrm{m}ax} \\ V_{\min} \le \left|\dot{V}_h\right| \le V_{\mathrm{m}ax} \\ \left|\Delta\dot{V}_{hk}\right| \le \Delta V_{\mathrm{m}ax} \\ \left|\Delta\dot{I}_{hk}\right| \le \Delta I_{\mathrm{m}ax} \\ \mathrm{Re}\left(\Delta\dot{V}_{hk}\left[\dot{I}^*_{hk} + \Delta\dot{I}^*_{hk}\right] + \dot{V}_h \Delta\dot{I}^*_{hk}\right) \le P_{comp\,\mathrm{m}ax} \end{cases} \tag{8}$$

Variation of the Distribution Voltage Level

The voltage levels of distribution networks have a strong and significant effect on the performance of the electric system. As the modelling of the electric system is developed in relative values, the rated voltage of the system does not appear explicitly in the power flows equations. Nevertheless, its variation leads to the changing of all the base values (current, impedance, etc.) and consequently affects the result of the problem solution. Since the KPIs only depend on the base voltage, a sensitivity analysis can be performed in order to assess the effectiveness of the considered intervention. The voltage level variation was assumed in the range (20 ÷ 50) kV.

Reactive Power Regulation of Renewable Generation

Up to now, renewable generation units were operated in order to maximize the active power coming from the renewable resources, without putting much consideration to their possible role as ancillary services suppliers. However, because of the distributed nature of these resources, they can play today an important role on the power quality asset of the distribution networks, since the new challenges of the inverter controls allow to fully exploit the potential of renewable generation in terms of reactive power support [5]. In the present study, the effect of controlling the reactive power of renewable generation units will be analysed referring once again to the multivariable optimization problem **(**5**)**-**(**8**)**, in which all the compensations $\Delta\dot{V}_{hk}$ and $\Delta\dot{I}_{hk}$ are nullified and the RES reactive powers (i.e. the imaginary parts of the LHS of **(**6**)**) are optimized. This intervention generates a number of degrees of freedom potentially equal to the number of renewable units present in the grid. The degrees of freedom will be represented by the reactive power of every renewable unit, that will be considered as a variable within suitable limits related to capabilities of PWM inverters.

BENCHMARK NETWORK DESCRIPTION

The distribution test case network is a modified Cigrè benchmark network [6] characterized by 12 nodes and 10 lines. The network topology appears in Fig. 4.The grid is operated at the rated voltage of 20 kV and accounts for several players such as loads, classified as household and industry, small renewable and distributed generation. The transformer and line data are reported in [6]. The grid is characterized by 26 MW of maximum installed RES power of and an actual total load of 19.58 MW.

SIMULATION AND RESULTS

Several simulations have been performed in order to test the validity of the defined KPIs. Nevertheless, for the sake of brevity, in the following one specific intervention for each KPI is going to be discussed, in order to highlight the main features of the methodology and to show how the proposed KPIs can be quantified.

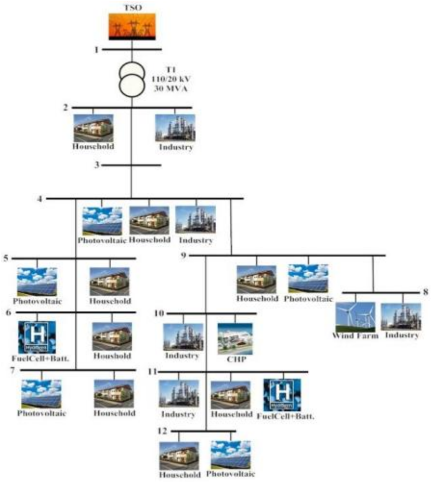

Fig. 4. Revisited CIGRÉ 12 node distribution test network

PS KPIs – Application of FACTS Devices

The Benchmark Network presents nine branches, therefore there are eighteen possible locations of the FACTS devices. The best location for the installation of one combined FACTS device is reported in Tab. 1, together with its effects on the Joule losses.

Tab. 1. FACTS installation - losses reduction

	Reactive	Active
Location	3-4	9-10
Losses Before [MW]	1.04	1.04
Losses After [MW]	0.99	0.72
P_{comp} [MW]	0.00	-2.45
Q_{comp} [MVAR]	0.26	-0.13

The application of a reactive FACTS leads to a reduction of the system losses up to 0.99 MW. The results obtained by the application of active compensation too, meant as the use of either a generation or a storage facility providing both ancillary and primary service, denote an even greater impact on the losses reduction. From the results obtained it is possible to calculate the Power Saving KPI as in Tab 2.

Tab. 2. Power saving KPI evaluation

	Power Saving KPI
Active Combined FACTS	$\frac{1.04MW - 0.72MW}{19.584MW} \cdot 100 = 1.63\%$
Reactive Combined FACTS	$\frac{1.04MW - 0.99MW}{19.584MW} \cdot 100 = 0.26\%$

Share of RES KPIs – Increasing of distribution voltage

The simulations performed in this section take into account the increasing of the distribution voltage up to 50 kV.

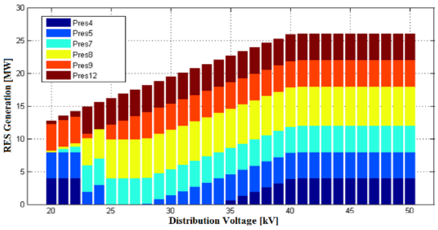

Fig. 5 – RES HC as a function of the distribution rated voltage.

In Fig. 5, for each distribution voltage value, the maximum amount of renewable generation that can be hosted by the grid is depicted. Different colors represent different renewable plants located in the grid. From the simulations it can be seen that, at the value of 40 kV all the renewable generation available can be integrated in the grid giving a RES hosting capacity of 26 MW.

Tab. 3. Share of RES KPI evaluation

.	Share of RES KPI
Increase of Distribution Voltage	$\frac{26.00MW - 12.25MW}{19.58MW} \cdot 100 = 70.21\%$

VPI KPI – RES Reactive Power Control

The chance of exploiting the reactive power deliverable from the PWM inverter of the renewable generation units could give a significant improvement to the voltage profile uniformity. The reactive powers delivered by each RES unit at the optimized point are detailed in Tab. 4:

Tab. 4. RES reactive power generation

Q_4 [MVAR]	Q_5 [MVAR]	Q_7 [MVAR]	Q_8 [MVAR]	Q_9 [MVAR]	Q_{12} [MVAR]
0.968	-0.131	0.00	-0.081	-0.969	-0.242

This intervention allows the reduction of the voltage deviation from 0.5058 *p.u.* to 0.1361 *p.u.*, almost 73%. The KPI is equal to:

Tab. 5. VPI KPI

	Voltage Profile Improvement KPI
RES Reactive Power Control	$(0.5058\,p.u. - 0.1361\,p.u.) \cdot 100 = 37.0\%$

CONCLUSIONS AND FUTURE DEVELOPMENT

The present article details a comprehensive definition of a methodology for the quantification of the KPIs that measure the effectiveness of smarting actions on an electric distribution grid. The proposed methodology is based on the application of Optimal Power Flow algorithms for the evaluation of several situations and targets. Simulations performed on a distribution Cigré benchmark networks highlighted the validity of the proposed KPI definitions in order to point out the effectiveness of the intervention considered in the specific study case. Future developments of this work could account the extension of the evaluation techniques to different goals as long as the application of the present KPIs approach to real project proposals.

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