Towards a Renewal of Transmission & Distribution Infrastructures to meet EU 2020 goals

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I. Introduction

The month of December 2008 marks an important date in European action against climate change, since the so-called 'triple 20s' integrated energy and environmental policy has been adopted by European Commission to strengthen the application of the Kyoto Protocol [1]. Such policy is aimed at setting Europe on the right track towards a sustainable future with a low-carbon, energy-efficient economy by:

- cutting greenhouse gases by 20%;
- reducing energy consumption by 20% through increased energy efficiency;
- meeting 20% of EU energy needs from renewable sources.

The idea is that all nations in Europe will be forced to alter their industrial systems so that they fit to the requirement on carbon reduction and increasing demand on renewable energy by year 2020.

Many studies on such topic have been carried out by Universities and Research Centres, Electrical Companies, International Agencies for Energy Saving and International Workgroups [2 – 4].

As far as the T&D infrastructures are concerned, it should be noted that they are both directly and indirectly involved in the efficient use of energy at any stage. In particular, the following intervention strategies can be identified for the networks modernization:

1. Replacement/refurbishment of power components;
2. Wide area measurement, monitoring and control systems (WAMS/WACS), upgrading protection and control devices for communication;
3. Increase of voltage level;
4. Installation of power quality devices (Distribution Networks);
5. High voltage direct current transmission systems – HVDC (line and forced commutated);
6. Flexible ac transmission systems – FACTS (Transmission Networks).

In this paper, a methodology is proposed to evaluate the impact of the aforementioned actions on the power grids in terms of possible beneficial effects in the context of EU 'triple 20s' integrated energy and environmental policy. Such methodology is based both on the identification of suitable "performance (technical) indices" to be used to rank the benefits brought by the different grid upgrading measures and on the definition of suitable "test networks", which can be employed as benchmarks to perform the numerical evaluation of the introduced indices. Then, a procedure is presented in order to determine and compare the quantitative effect of each single corrective action on T&D power grids. Finally, some considerations on possible side effects and advices on strategies for the implementation of the corrective measures are discussed.

II. Performance Indices to Rank T&D State-of-the-Art Technologies Impact

As already mentioned, the EU energy targets for the year 2020 include improved efficiency, improved environmental compatibility, basically linked to CO_2 emissions reduction and improved renewable generation.

In order to perform a more comprehensive analysis of the possible beneficial effects (environmental + functional) provided by renewing actions on T&D infrastructures, it is possible to integrate these targets with the additional concept of quality of service.

Table I proposes a possible "technical translation" of such targets into the electrical domain. The electrical performance indices can be defined in several forms. The first one is a short term (instantaneous) approach, translated in technical merit, which evaluates the benefits of the introduction of T&D state-of-the-art (modern) technologies mainly in terms of energy per time units, which is power, or electrical aggregated flag quantities. The second way can be considered as an integral approach (energy), to be computed on a specified time frame, which proves liable to be converted in an economical merit, such as simple payback time. This approach includes accurate estimation of investment costs for any additional device to be proposed. The third approach embraces also probabilistic concepts, particularly useful to rate dynamic performance indices. A complete evaluation should be based on all the three approaches; in spite of this, here the choice has fallen into the first one, since it is the most straightforward and does not require the collection of a large amount of data.

TABLE I

Definition of Electrical Performance Indices

T&D EU Energy Targets	**Technical Indices**
Efficiency	Branch steady state indices (losses containment)
CO_2 reduction	Generation planning and operation planning (unit commitment – dispatching)
Renewables	
Quality in transmission	Node steady state indices (voltage within limits)
	Dynamic indices (time behaviour compatible with grid protection intervention curves; load shedding, out of step)
Quality in distribution	Node steady state indices (voltage within limits)
	Harmonic indices (Harmonic Distortion Factors)
	Dynamic indices (time behavior compatible with grid protection intervention curves; voltage dips, sags, swells, interruptions)

II.A Index for efficiency

Energy efficiency should concern with the whole process of energy assessment from power plant conversion to final user exploitation. The concept of efficiency, in the broadest sense, is significantly linked to the availability and localization of primary resources, as well as to their being low cost and/or renewable. If the focus is centered on the electrical segment of the energy transferring process, we should therefore account for specific efficiency in Generation (introducing highly efficient generators) ; Utilization (profiting of highly efficient motors and drives); Energy conveying (usually proposed in terms of loss reduction, but extendable to power quality).

As far as Energy convey is concerned, efficiency in conveying energy implies CO_2 emission reduction, since losses containment at constant load profile requires less generation amount (Fig. 1).

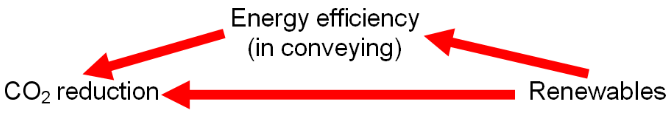

Fig. 1. Conceptual interdependencies between EU targets at constant load profile.

At the same time, renewables connected in distribution grids as Distributed Energy Resources (DER) contribute to decrease current circulations and therefore enable reducing Joule losses and improving energy efficiency. Again, renewables adoption results in CO_2 diminishment, since the same load is satisfied by less polluting sources.

The proposed index for efficiency is related to the goal of electrical grid losses containment: efficiency and losses containment coincide if constant load profile is assumed.

A steady-state model for each branch connection is therefore necessary, and a comprehensive analytical evaluation of complex losses is required; at the same time, steady-state models for specific present state-of-the-art technologies are available and/or ready to re-elaborate from literature, just in order to assess their effect on component efficiency.

It should be noticed that different approaches have to be followed in dealing with transmission and distribution grids: in the former, state-of-the-art technologies redistribute flows and losses but ask for a new production profile (dispatching scenario) from all committed power plants. Conversely, in the latter infrastructure, redistribution of flows and losses does not include the modification of generation profile, since DER is not usually asked a load following service, but interconnection to EHV/HV transmission grid acts a power balance compensation system (slack bus).

State-of-the-art technologies could otherwise affect DER penetration level by relaxing constraints or improving margins, therefore modifying the overall generation mix.

On the basis of such considerations, the performance index for energy efficiency can be thus defined as ***"Network losses normalized to total load request".***

The computation of grid total complex losses can be carried out according to Kron-Early loss formulas [5 – 6], which are easy to implement within classical Optimal Power Flow (OPF) formulations.

II.B Index for CO_2 reduction

The problem of environmental compatibility of electric power infrastructures is mainly related to the emissions associated to the energy conversion process at the generation stage. Correct management of the interconnection facilities may result in a more environmental friendly scenario, since it could enable commitment of units characterized by reduced CO_2 emission or pushing these units to their maximum possible production capability.

The same steady-state model use in subsection A. for any state-of-the-art technologies become useful also to rate their effect on network complex losses amount, since efficiency in conveying energy implies CO_2 reduction.

The possible performance index for CO_2 emission can therefore be the "***Total grid CO_2 emissions normalized to total load demand".***

This is the computation of an optimal generation profile which minimizes greenhouse pollution profile, having previously determined a reliable analytical dependence of emissions on produced power. These optimization procedures enable to account for grid total losses via Kron-Early loss formulas [5 – 6] and for generating unit and grid constraint by means of Kuhn-Tucker conditions [7], which act as penalty factors. From a conceptual point of view, it is a widely adopted energy management procedure, this time extended from minimization of fuel costs to the maximum containment of greenhouse emissions potential of the generation set.

II.C Index for renewables penetration

Conveying energy from sites of renewable production to final users is presently an arduous task to face in the modernizing process of the electrical power infrastructure. Time-varying generation profile, as well as development of renewable power in-feed, pose significant challenges in electrical network configuration and management: it sometimes occurs that the infrastructure itself, or its control and protection features, are not ready to completely host renewables access, asking for reconfiguration at several levels.

In order to define an index for renewables penetration, again steady-state model for specific T&D state-of-the-art technologies are required to rate the effect of renewable DER on complex losses. As shown in Fig. 1, efficiency in conveying energy is indeed affected by renewables, but state-of-the-art technologies could contribute to improve renewables percentage with respect to the total admissible generation set.

The proposal for an index for renewable penetration is then the ***"Total generation from renewables normalized to total load request".***

This index requires the use of optimization techniques, either at unit commitment or generation scheduling level, where cost-production functions are needed for all the installed generation and being the renewables' ones equal to zero. State-of-the-art technologies affect both grid total losses (again computed via loss formulas) and branches constraints (again expressed via Kuhn-Tucker conditions and reported in terms of penalty factors).

II.D Index for steady-state quality in transmission and distribution grids

The electric power infrastructure satisfactorily fulfils its tasks if operated in normal conditions, where components and devices are typically characterized by their rated values, fixed by manufacturers to meet best exploitation and duration targets. Any deviation from such profile is paid in terms of a performance reduction. Therefore, it is common interest to limit discrepancies from ideal working scenario, basically related to node voltages and branch currents.

As a preliminary proposal for a steady-state quality index, attention is mainly focused on voltage, according to the present operating practice proposed by utilities all around the world. Tolerance in component correct working allows maximum voltage magnitude deviations of 5% in steady-state conditions thus limiting narrower than corresponding (minimum and maximum voltage) protection settings.

The evaluation of voltage grid profile requires a steady-state analysis of the electrical system, usually performed via the so-called power flow computation. The steady-state models for specific T&D state-of-the-art technologies is again useful for inclusion in the power flow simulation, leaving a direct chance to detect the relevant modified voltage profile.

Investigation on this point reveals that the concept of system adequacy, that is the assessment of a robust operating condition with respect to credible perturbations, must be extended to other flag quantities, like for example branch currents. Current magnitude must not exceed an overload limit, after which a control centre operator intervention is required.

Most of the commercial simulations tools consider node voltage and branch current limits in the final violation report, without affecting calculation process. Probably, an improved version of power flow analysis could include such additional constraints in the solution procedure.

In light of these considerations, the proposal for a steady-state quality index is the ***"Total mismatch from ideal uniform node voltage and branch rated current profile".***

This requires the computation of an adapted OPF, where the function to be minimized is the sum of node voltage and/or branch current deviations from the ideal working scenario.

II.E Index for distribution harmonic power quality

Voltage and current waveforms must respect quality standards in order to avoid malfunctioning of end user sensible apparatuses. Time-varying, non linear and discontinuous working components often represent a threat in preserving ideal behavior at the so called points of common coupling, meaning nodes where specific quality constraints are set for contractual reasons. Both converters and unsymmetrical components negatively affect voltages and currents especially at the distribution level, imposing the use of mitigating devices to contain harmonic pollution.

As a first proposal for an index for distribution harmonic power quality, one can think at the Harmonic Distortion Factors (HDF), linked to node voltages and branch currents, in terms of indicators of the distance between actual and ideal waveforms. The basic idea considers the definition of harmonic distortion limits, according to residential and industrial context, followed by the use of the harmonic power flow to evaluate HDF in every node and branch.

The role played by specific T&D state-of-the-art technologies requires the formulation of their harmonic model and the computation of harmonic distortion in the modified distribution system.

The current proposal for the harmonic power quality index is therefore: the ***"Network total harmonic (node voltage, branch current) distortion factor average or variance".***

It is included the computation of a conventional harmonic power flow and the evaluation of the sum of all node HDFV and of all branch HDFI, normalized respectively to the *n* nodes and the *b* branches inside the distribution grid.

II.F Index for transmission dynamic quality

Quality of service is often referred in its steady-state meaning, whereas it becomes difficult to uniquely express a satisfactory transient performance of the electrical power infrastructure. Probably, the most reliable quantity to evaluate should be the system energy, but its definition and computation is far from being elementary and shared. Here, we propose to compare the dynamic evolution of the grid under investigation with the intervention characteristics of the protection devices operating at the transmission level, so that cascading phenomena due to a single event are considered as the main problems to overcome.

According to such an approach, a first proposal for the transmission dynamic quality could be related to the comparison between system time behavior and the intervention curves of the installed protection devices. To do this, grid component dynamic models are required, and the installed control loops as well; in addition, credible contingencies have to be defined and it is necessary to identify also the protection set to be considered within this analysis. Then, transient stability simulations can be proposed to assess grid dynamics and capability to recover a correctly operating working point. Dynamic and control models are expected for specific state-of-the-art technologies, so as to include them in the transient stability simulation and evaluate their impact on the system evolution.

Being aware of the quantities able to express unacceptable dynamic condition at the transmission stage, which essentially consist in voltage and current magnitudes, frequency deviations and angle displacements, the index for transmission dynamic quality can therefore be defined as the " ***Network cumulative proximity to starting thresholds of line distance relays (voltage, current and angle phenomena) and load shedding relays (frequency phenomena)".***

This requires the computation of transient stability and the following monitoring of trajectories in terms of impedances at every transmission line ends and of frequency at every transmission bus bars.

II.G Index for distribution dynamic quality

Distribution system dynamics is usually related to instantaneous deviations of voltage waveforms at each point of supply, again a typical contractual clause to be met to avoid penalties. At the present penetration level of distributed generation, electromechanical dynamics is of minor concern, even if liable to become increasingly interesting in the future. Voltage dips, sags, swells and interruptions are detectable as typical phenomena in a short term time frame and represent a frequent cause of economical and physical damage for the final user.

With regard to the just outlined occurrences, the first proposal for a distribution dynamic quality index is centered on the compatibility of the system time behavior with grid protection intervention curves, basically linked to over-currents and under-voltages. Such an approach requires the collection of network components dynamic models, associated to the available control modes, as well as the definition of credible contingencies and protection systems operating at the distribution level. Then, a computation of electromagnetic transient and short circuit simulations is expected, in order to either validate the actual system design or identify its evident weaknesses. Dynamic and control models for specific state-of-the-art technologies are subsequently necessary, in order to assess their impact on the dynamic profile of the distribution grid. According to these considerations, the proposal for distribution dynamic quality index becomes the ***"Network cumulative proximity to ideal voltage and current waveforms (in case of dips, sags, swells)"****, and the* ***"Network cumulative unsupplied energy (in case of interruptions)".***

This requires the computation of electromagnetic transients and the relevant monitoring of voltage and current waveforms for generic disturbances, whilst an additional time computation, starting from outage instants at customer supply point, in case of interruptions is required.

Table II summarizes the proposed performance indices for each considered objective.

TABLE II

TARGETS AND RELEVANT PERFORMANCE INDICES

Target	**Performance index**
Efficiency	Network losses normalized to total load demand
CO_2 reduction	Total grid CO_2 emissions normalized to total load demand
Renewables rate of penetration	Total generation via renewables normalized to total load demand
Steady-state quality in transmission and distribution grids	Total mismatch from ideal uniform node voltage and branch rated current profile
Distribution harmonic power quality	Network total harmonic (node voltage, branch current) distortion factor average or variance
Transmission dynamic quality	Network cumulative proximity to starting thresholds of line distance relays (voltage, current and angle phenomena) and load shedding relays (frequency phenomena)
Distribution dynamic quality	Network cumulative proximity to ideal voltage and current waveforms (dips, sags, swells) Network cumulative unsupplied energy (interruptions)

III. Test Networks

All the main components of a typical grid must be modeled in the test-network in order to represents their impact on the system performance and also the interaction with other components, such as large generators, Distributed Energy Resources (DER), renewables, distribution transformers, large, concentrated, industrial loads, or residential "distributed" loads.

Several test systems can be found in literature with reference to different specific topics under investigation. In [8] a benchmark network for simulation of FACTS devices in load flow control is presented. In [9], a part of a 20 kV distribution network in a rural area is represented as a "micro-grid". This system has been used in a pilot project to establish how a network can be operated with a large amount of non-dispatched power sources.

A scheme of a test network potentially useful for the analysis of the previously defined indices is depicted in Fig. 2.

The main characteristic of the system are:

- Minimum number of nodes;
- Division into two sub-systems at two main voltage level;
- Availability of HV-MV transformer;
- Availability of both meshed and radial topology;
- Availability of generation sources at different locations;
- Availability of load at different locations.

Here, we decide to identify all T&D systems and components by resorting to suitable generalized circuital representations, able to describe different technologies and solutions, according to the parameters choice.

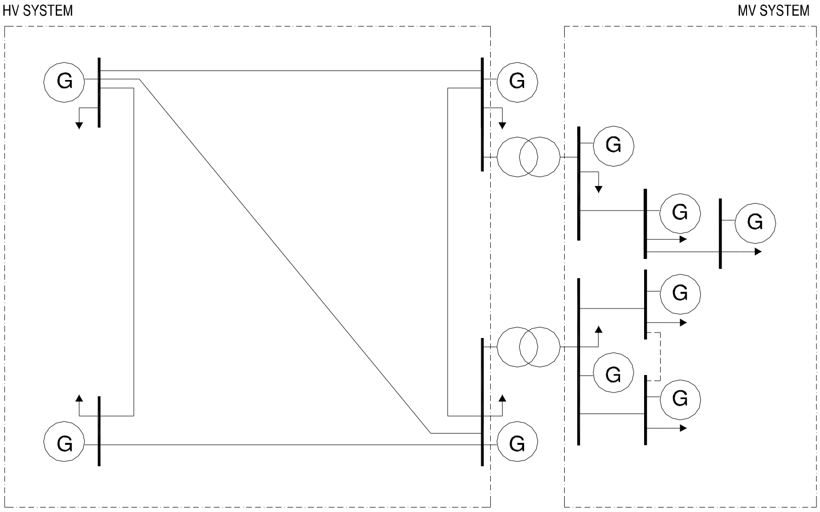

Fig. 2. HV-MV network for the evaluation of performance indices.

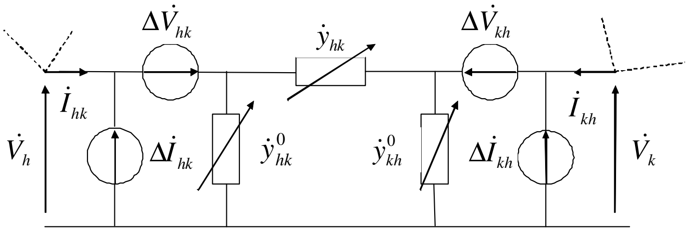

Fig. 3. Generalization of T&D state-of-the-art technologies in families: steady-state model.

In the steady-state domain, a proposed generalized model is sketched in Figure 3.

The insertion of new branches is covered by the triple of arrowed internal passive components, which also account for any replacement/refurbishment performed on existing branches. Series voltages and shunt currents contributions, including Δ (variation) to intend them as modifications of the existing morphology, accomplish all possible contribution of compensating devices, as well as innovative transmission and/or distribution systems. Correspondence to specific state-of-the-art technologies is ensured by functional relationships of mutual dependence between the indicated voltage and current incremental generators.

Harmonic models for components replacement or refurbishment simply ask for modification of parameters within available or pre-defined harmonic models. The use of advanced compensations or transmission/distribution innovative forms, whenever converters are committed, requires a general harmonic modeling including multi-frequency voltage and/or current generators.

In the end, as far as dynamic models are concerned, if attention is focused on rapid electromagnetic transients, a general set of algebraic differential equations are required to represent both extremely detailed components and fast, dedicated control loops. Conversely, when electromechanical analyses are performed, still a general set of algebraic differential equations are required, this time less devoted to component modeling dynamics (apart for mechanical state variables) and widely concerning control loops at each hierarchical level (with extensive use of transfer functions and non-linearity, whenever present).

IV. THE COMPARATIVE PROCEDURE

In this section, the performance indices, the modeling techniques and the network structures previously outlined are employed for assessing benefits and possible troubles related to the use of state-of-the-art technologies in T&D grids.

In order to give some driving lines about the technical approach to evaluate both direct and indirect benefits on T&D systems, together with side effects and mitigation, due to state-of-the-art technologies, it is possible to conceive a comparative, selective, and flexible procedure.

<u>Comparative</u>: the aim of the procedure is to compare performance indices obtained in a reference operating scenario with those pertaining to upgraded assets including state-of-the-art technology support. As a general remark, several performance indices may be independently affected by upgrading the reference scenario; for instance, the well-known local power factor correction reduces losses and improves voltage profile of the distribution network. In other cases, improving a specific index causes a dependent fall down on some other indices; thus, increasing renewable diffused resource produces a decrement of current flows within the distribution network and consequently reduction of losses (efficiency index) and voltage drops (quality distribution index).

<u>Selective</u>: the procedure should allow to create upgraded scenarios, thank to the state-of-the-art technologies, by including, one at each time, either new devices or advanced control strategies. It may be noted that the action could either integrate or replace components or strategies defined in the reference scenario.

<u>Flexible</u>: the comparison of performance indices has to be accomplished by a sensitivity analysis to capture the best result. In detail, location and size of advanced equipment must be tested to measure direct advantages. A unifying approach would suggest to normalize benefits to a unitary advanced measure: however, difficulties may arise both in quantifying unitary action and in extrapolating results due to non-linear systems constraints. Moreover, impact of different load profiles and modified generation assessment should be investigated to put into evidence indirect benefits.

The fundamental operating steps of the developed procedure are reported in Fig. 4.

It should be highlighted that a sensitivity analysis must be developed in order to define the optimal set-up. Modified scenarios for analysis should be chosen in such a way to explore a limited but at the same time, meaningful set of possibilities covering applications of actual interest. Depending on the specific measure, either analytical or simulation based approaches may be followed for the analysis; in general a refining optimization process could be adopted to catch the best measure to grid fitting.

The evaluation of performance indices with and without state-of-the-art technology devices or control functions makes available evidence of the quantitative impact, together with its sensitivity, of the selected measure. From a general point of view, a mixed set of indices variations (positive and negative values) could result from comparison, thus denoting that a specific advanced provision may, at the same time, favor some operating aspects and worsen some others.

Consequently, a *weighted average index* should be defined, in order to definitely link an advanced measure to the performance index overall set. Finally, a ranking process could be proposed to provide a merit list of the different state-of-the-art advanced solution on T&D system performance.

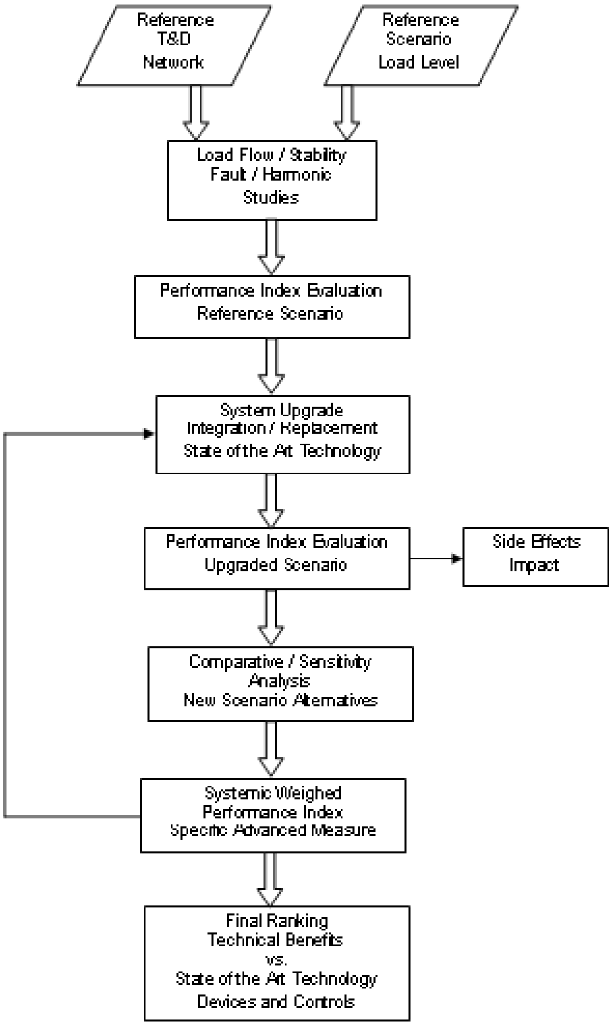

Fig. 4. Performance index evaluation: flow chart of the comparative procedure.

V. RESULTS

Once the methodology has been defined, the successive step is calculating the performance indices for each family of T&D state-of-the-art technology in standardized model grids. This is a hard task, which should be unavoidably split in multiple parallel sub-tasks, faced by different and specialized research teams.

Anyway, an indication on the kind of impact (direct or indirect) provided by the single improving measure on T&D infrastructures can be identified without resorting to any calculations (see Table III).

TABLE III

IMPACT ON T&D EU ENERGY TARGETS PROVIDED BY THE INTRODUCED ACTIONS

Impact of : **Action :**	Efficiency	CO_2 Reduction	Renewables	Steady-state quality in T&D	Harmonic quality in distribution	Dynamic quality in transmission	Dynamic quality in distribution
Replacement/ Refurbishment of Power Components	**Direct effect** (lower losses)	**Indirect effect** (via more efficiency)	**Indirect effect** (removal of bottlenecks)	**Direct effect** (improved parameters)	**Indirect effect** (improved parameters)	**Indirect effect** (improved parameters)	**Indirect effect** (improved parameters)
WAMS/WACS & Upgrading Protection and Control Devices for Communication	**Direct effect** (flow rescheduling)	**Indirect effect** (via more efficiency)	**Indirect effect** (removal of bottlenecks)	**Direct effect** (regulation)	**Indirect effect**	**Direct effect** (improved strategies)	**Direct effect** (improved strategies)
Increase of Voltage Level of the Power Grid	**Direct effect** (lower losses)	**Indirect effect** (via more efficiency)	**Indirect effect** (removal of bottlenecks)	**Indirect effect** (reduced drops)	**Direct effect** (harmonic current sources)	**Indirect effect**	**Indirect effect**
Installation of Power Quality Devices (Distribution Networks)	**Indirect effect**	**Indirect effect** (via more efficiency)	**Indirect effect** (support volatile generation)	**Direct effect** (regulation)	**Direct effect** (as active filters)	**-**	**Direct effect** (as custom power)
HVDC (line and forced commutated)	**Direct effect** (geographically dependent)	**Indirect effect** (via more efficiency)	**Direct effect** (removal of bottlenecks)	**Indirect effect** (regulation)	**Indirect effect** (side effect)	**Direct effect** (dedicated controls)	**Direct effect** (dedicated controls)
FACTS (Transmission Networks)	**Direct effect** (flow rescheduling)	**Indirect effect** (via more efficiency)	**Indirect effect** (removal of bottlenecks)	**Direct effect** (regulation)	**-**	**Direct effect** (dedicated controls)	-

An equivalent, but more explicit, presentation of the expected results of the study is hereafter proposed by means of spider diagrams, reporting in Figures 5 – 10 the effects of each introduced action on the seven targets considered so far.

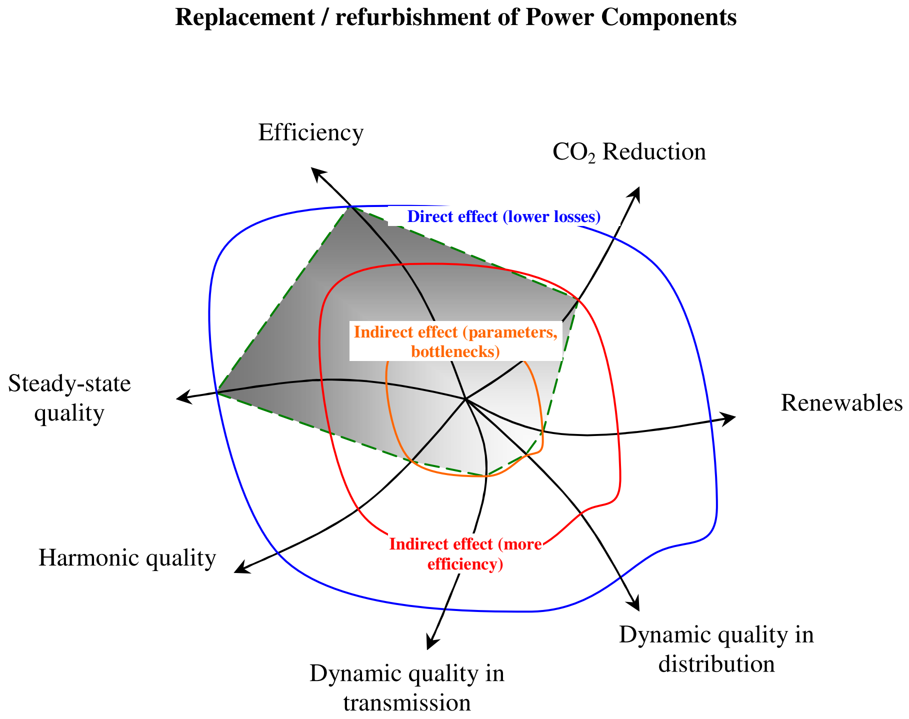

Fig.5. Spider diagram for the effects of replacement/refurbishment of power components.

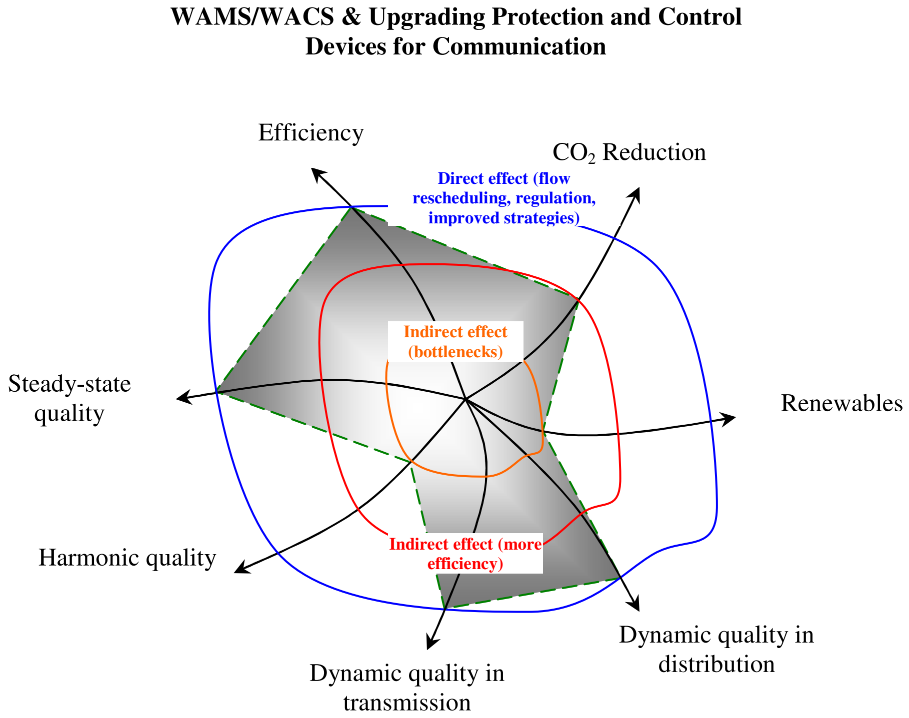

Fig. 6. Spider diagram for the effects of WAMS/WACS & upgrading protection and control devices for communication.

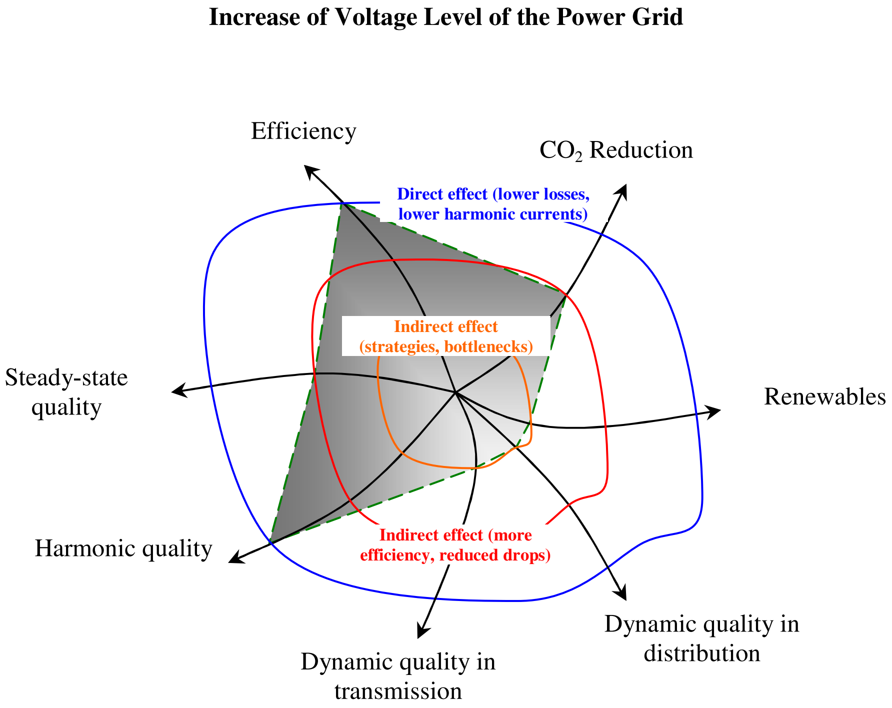

Fig. 7. Spider diagram for the effects of increase of voltage level of the power grid.

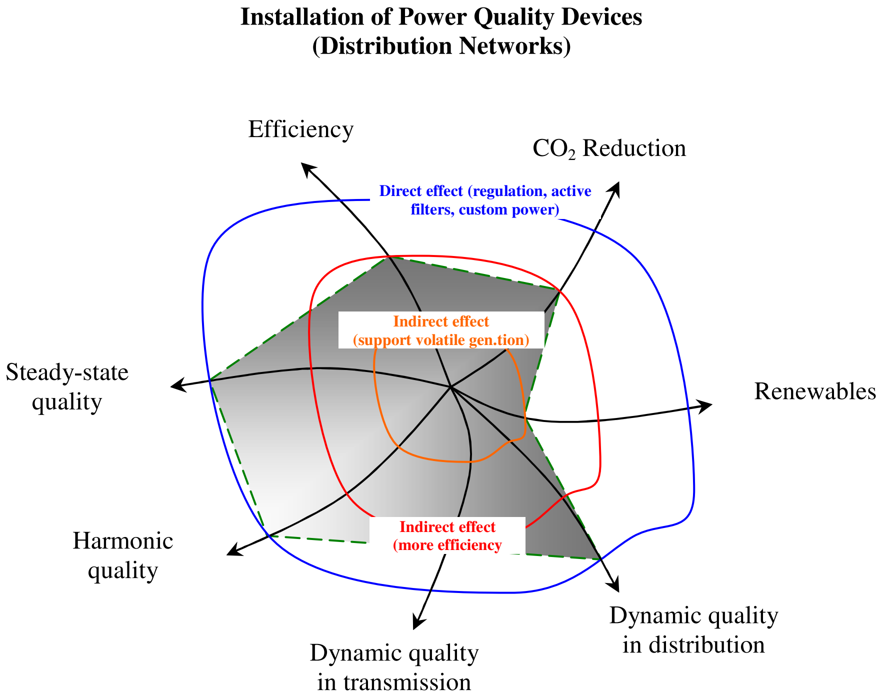

Fig. 8. Spider diagram for the effects of installation of power quality devices (Distribution Networks).

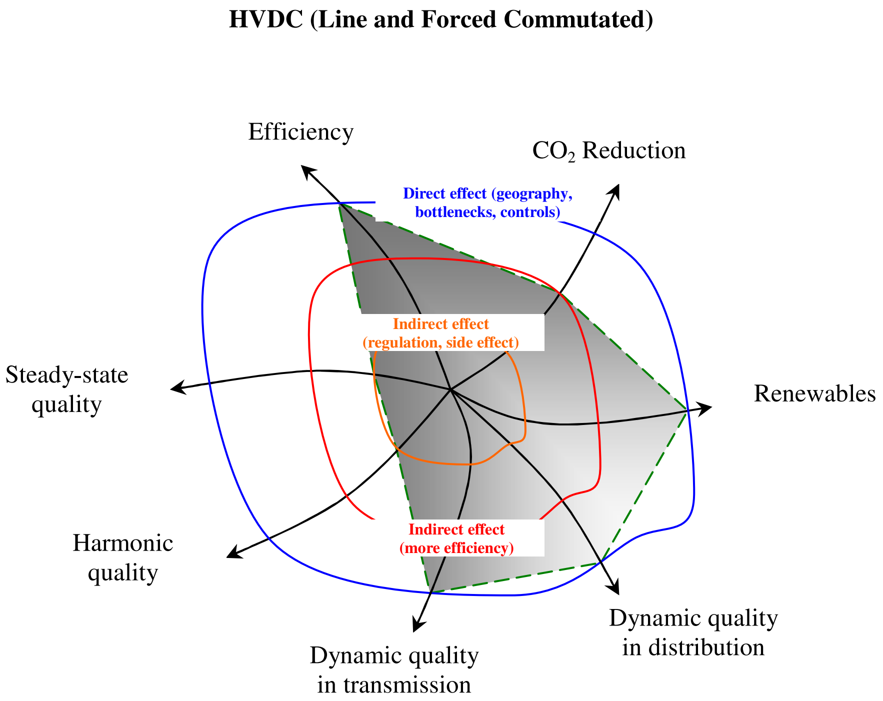

Fig. 9. Spider diagram for the effects of HVDC (line and forced commutated).

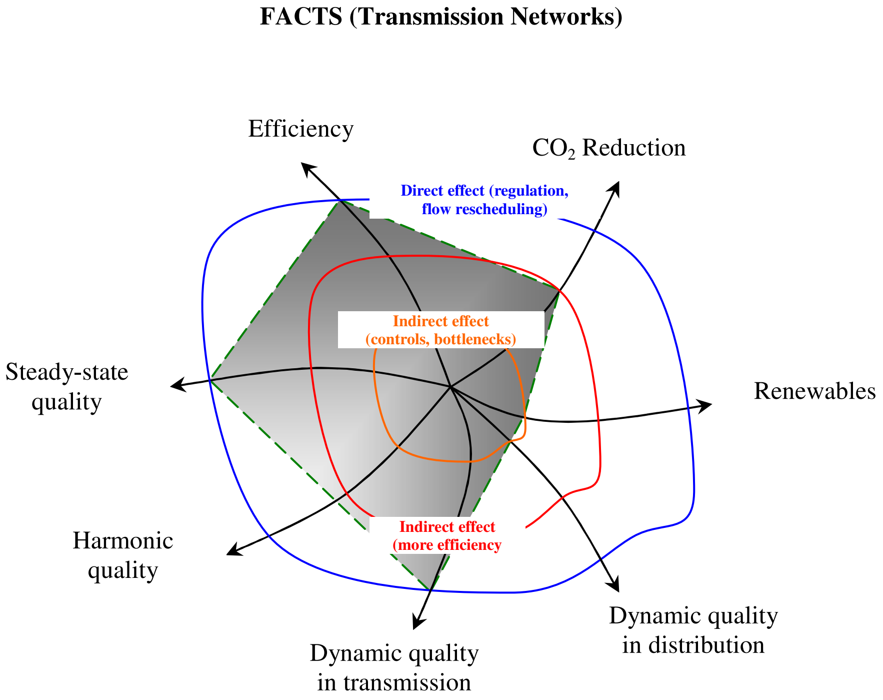

Fig. 10. Spider diagram for the effects of FACTS (Transmission Networks).

VI. CONCLUSIONS AND PERSPECTIVES OF FUTURE WORK

In this paper, a general procedure to quantify the possible environmental benefits as well as the power quality improvement provided by the application of modern T&D products and systems on the power grids has been presented. The procedure is based on the definition of suitable performance indices and suitable test networks, where to evaluate such indices. Work is now in progress to perform the identified quantitative and selective analyses to numerically express the effects of each single improving measure on T&D infrastructures. This work is presently split in multiple parallel tasks and will be performed by research teams at different European universities.

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