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Improving the energy efficiency of an islanded distribution network using classical and innovative computation methods

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A B S T R A C T

The paper presents the analysis of some potentially suitable actions for reducing the energy losses of an islanded Medium Voltage distribution network, with the aim of improving electricity distribution efficiency. For this purpose, four actions are considered: 1) increasing the network's rated voltage; 2) reactive power compensation through static capacitor banks; 3) reactive power compensation through switchable capacitor banks; 4) installation of distributed photovoltaic (PV) generation. The first two measures are typically taken into account by the distribution system operators and can be examined by means of classical design methods, whereas the latter two more innovative actions are tested here using specialized software based on the NSGA-II multi-objective optimization algorithm. The fourth action, expanding distributed PV generation, can be motivated through public or private incentives. It is investigated here using an innovative approach to the optimization problem formulation considering the perspectives of both the utility and the consumer. A case study on a small Mediterranean island real existing network is also presented.

1. Introduction

Small Mediterranean islands are characterized by the great availability of renewable sources but, at the same time, they also contribute highly to environmental pollution and fossil-fuel exploitation (Codegnoni, 2012; Nile and Lloyd, 2013). Indeed, in the past, the only way for small islands to generate electricity was to resort to low-efficiency diesel generators producing noise and harmful emissions. The electricity produced by such generators has a very high cost, while the economy of small islands is almost totally based on low remunerative activities, like fishing and tourism (the latter only in the summer periods).

For these reasons, after World War II, the Italian Government established a support funding mechanism in order to reduce the electricity costs for Italian small island inhabitants. This mechanism still exists and is currently paid by all the electricity consumers through the UC4 additional item cost (AEEGSI, Italian Authority for Electric Energy, Gas and Water, 2013). In 2011, the UC4 for small islands summed to 62 M€ (Codegnoni, 2012). Because of the existence of this support mechanism, small island generation and distribution utilities had no interest in the pursuing renewable and clean energy sources and technological solutions for improving the generation and distribution efficiency of their power plants.

In 2014, the AEEGSI began a review process of this support mechanism with the Deliberation 447/2014/R/EEL, as per the European Union (EU) and the Italian Government indications (D.L. 91/14, Law 116/2014). According to the 598/2014/R/EEL Document, beginning on 1 January 2015, small island utilities are obliged to launch a 5-year long process in order to enhance the efficiency of their generation and distribution systems.

In the last few years, the new requirements and standards for the electricity high quality (EN 50160, 2010, IEC 038, 1999) have also encouraged electricity utilities to make new investments for increasing their network efficiency. In light of that, distribution systems are rapidly changing, including increased automation (Favuzza et al., 2011a, 2011b; Cosentino et al., 2011a, 2011b, 2012; Østergaard, 2012; Ippolito et al., 2014). Moreover, the needs for energy savings and the innovative policy of "White certificates"[1] (Directive, 2003/54/EC; Directive, 2003/55/EC; Directive, 2006/32/EC; GSE, 2013) make enhancement of distribution system

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[1] In environmental policy, *white certificates* are documents certifying that a certain reduction of energy consumption has been attained.

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efficiency more imperative.

In addition, many recent initiatives are promoting the development of renewable energy sources in the EU. In 2002, the “10,000 PV roofs” initiative in Italy expanded awareness of photovoltaic (PV) technology. Furthermore, the 2003 37/2003 Legislative Decree introduced the Feed-in Tariffs funding mechanism and today, after more than 10 years, PV systems have become very competitive.

By examining all these issues, this paper presents an analysis of four different strategies that are potentially suitable for improving the energy efficiency of an islanded medium-voltage (MV) distribution by reducing real power losses in the network. The actions, analyzed in Section 5, are as follows:

ACTION 1: Increasing the network's rated voltage level.

ACTION 2: Reactive power compensation through static capacitor banks.

ACTION 3: Reactive power compensation through switchable capacitor banks.

ACTION 4: Installation of distributed photovoltaic (PV) generation.

The rated voltage increase and the reactive power compensation through static capacitor banks are regularly considered by distribution planners, since they allow to reduce the voltage drops and energy losses as well. The optimal placement of both static and switchable capacitors banks has been extensively investigated over the past several decades. The extent of the advantages conferred by the capacitors banks depends on the their size, location, and type as well as on their control settings. The design of the compensation system, including switchable elements, is an intrinsically combinatorial problem. An effective formulation of the problem includes more than one objective and constraint.

As the literature shows, different analytical, numerical programming, heuristic, and artificial intelligent based techniques have been used to address these kinds of issues (M.M. Aman et al., 2014; Tanuki Manglani and Shishodia, 2012; Ng et al., 2000; Wang and Elia, 2011; Saverio Bolognani and Zampieri, 2012; Saverio Bolognani et al., 2014). Salama and Chikhani (1997) present an interesting review of the applications of Artificial Intelligence AI to the problem of optimal capacitor placement and sizing. Various evolutionary computation-based methodologies, such as those based on genetic algorithms, have been employed (Huang, 2000; Pires et al., 2005; Fonseca et al., 2010; Carpinelli et al., 2009; Ching-Tzong and Chu-Sheng, 2002; Deb et al., 2000; Graditi et al., 2011; Mekhamer et al., 2002). Abou Jawdeh and Jabr (2012) apply a mixed integer conic programming approach to determine optimal capacitor placement; Franco et al. (2011) used a mixed-integer linear programming approach to solve the optimal fixed/switched capacitors allocation problem in radial distribution systems in presence of distributed generation.

The four actions proposed in this paper are analyzed on the basis of two network performance indices: energy losses and voltage drop. Some economic indicators (Feibel, 2003) are also considered with the aim of finding the less costly and the most feasible actions. For each action, the reduction of greenhouse gas (GHG) emissions due to power losses reduction is evaluated as well.

The first two actions are analyzed using classical design methods whereas the others are examined using an efficient multi-objective optimization genetic algorithm called NSGA-II (Deb et al., 2000). With regards to the fourth action, the paper proposes an innovative formulation of the problem of the optimal size and location of PV units considering the possibility of private incentives for expanding the role of distributed generation in the utility system. The optimization problem is solved taking into account two perspectives: the utility wants to attain the maximum installed power with the minimum expense whereas the consumers wants to obtain the maximum compensation from the utility.

In the following sections, after a brief introduction on the economic and environmental aspects of improving energy efficiency (Section 2), the proposed actions and the methodology for the analysis are presented (Sections 3 and 4). A test case for the Italian Lampedusa Island is presented (Section 5) and conclusions are given (Section 6).

2. Energy savings and energy efficiency improvements: economic and environmental aspects

Improving electric power system efficiency by reducing losses increasing the use of smart technologies, and expanding electricity production from renewable resources are some of the actions that are being implemented to increase supply-side energy efficiency and productivity and reduce CO_2 emissions. These actions are the basis of sustainable economic growth and development. Unfortunately, it can be difficult to measure the real economic value of efficiency and other energy-related improvements. Indeed, the many interactive effects at different levels of the economy are complex. The effects of some energy management actions may be indirect, or also be the product of a chain of actions.

The most comprehensive and recent monetary evaluation of the environmental impacts associated with electricity production is found in the “ExternE, Externalities of Energy” research project of the European Commission (ExternE, 2005). With regard to the considered in this paper and applied to the Lampedusa (Italy) island network, the external benefits considered are those related to: (1) reduction of electric energy losses at the grid level; (2) reduction of GHG emissions through renewable distributed resources; and (3) reduction of costs for both the utility distributor and the customers.

Distributed generation (DG) based on renewable energy sources (RES) to reduce GHG emissions can be installed at any bus of the LV and MV distribution networks, in particular near to the load centres. At the same time, the installation of DG units in a power network raises technical, environmental, and commercial issues that must be addressed in order to achieve desired benefits. One of the main problems of RES-based DG units is the variability and the uncertainty of the energetic source (Beaudin et al., 2010). Nevertheless, RES are very important resources for small islands. For example, two interesting study (Kaldellis et al., 2012 and Patlitzianas and K. Christos, 2012) two interesting studies focus on the relevance of RES-based generators for the energy autonomy of very small non-interconnected islands in Greece. Michalena et al. (2009), presents a correlation between the development of RES on a Mediterranean Island and sustainable tourism. Other studies (Bala and Siddique, 2009, Agarwal et al., 2013) proposed PV-diesel hybrid systems for the electrification of isolated islands of Bangladesh and India, respectively.

The national financing mechanisms implemented across the world for supporting RES-based DG (Campoccia et al., 2008, 2009; Fouquet and Johansson, 2008; Gutermuth, 2000; Sarasa-Maestro et al., 2013), have encouraged many private end-users to voluntarily install small DG units, in particular PV units, taking advantage of the technology as both consumer and producer. One of the most common support mechanisms in the EU for grid-connected PV systems is the feed-in tariff (FIT). With FITs, PV system owners are compensated at a price that allows them to recover the cost of their investment in a relatively short period of time. Nonetheless, the high initial installation cost of PV systems continues to discourage many potential self-producers (in particular domestic users). However, the legal frameworks introducing the FIT mechanism in the EU countries do not exclude the possibility of private capital subsidies coming from private citizens, banks, or other organizations, including utility companies.

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