Abstract of the dissertation

In recent years, progresses have been made in developing cleaner and more efficient technologies to produce, transmit and distribute energy. Pledges made in the recent summit in Paris (21°conference of the parties - COP21, Paris 2015) and Marrakech (COP22, Marrakech 2016) on climate changes promise to give new impetus to the move towards a lower-carbon and more efficient energy system. Nowadays, mandatory energy efficiency plans are expanding worldwide to cover over a quarter of the total global consumption. Furthermore, renewables represent almost half of the world's new power generation capacity.

The deepening penetration of renewable energy resources (RESs) has forced grid operators to deal with both technical and economic challenges to harness as much green energy as possible from them. Renewable plants, solar photovoltaic (PV) based and wind farms, are often small-medium scale generation plants connected at the distribution network level. The conventional distribution networks were designed to be operated as passive networks but with the continuing integration of RESs must accommodate bi-directional flows. Indeed, the implementation of the *Smart Grid* into distribution grids will bring about the effective deployment of advances in information and communication technologies (ICT) to improvements in the reliability, resiliency, flexibility and efficiency of such grids. Under the resulting new paradigm, it is possible to identify new roles that the distribution network operator (DNO) can play as well as additional activities and services that the DNO can provide to bring out marked improvements in the distribution grid management arena. The rapid changes in the distribution grid need to be accompanied by associated changes in their operations and provide the flexibility for the operators to evolve from the conventional DNO who manages passive networks to that of the distribution system operator (DSO) to run the new bi-directional flow distribution grid.

This thesis is presented within the context of the newly evolving distribution grids managed by their DSOs. The aim of the work is to investigate the feasibility and implementation of the provision of ancillary services able to support current and future DSOs to facilitate improvements in the harnessing of the energy produced by deeper penetrations of RESs into the distribution grids. To this end, specific services must be provided by resources in the distribution network (DN) to provide congestion relief, as well as various ancillary services (AS), such as frequency control, voltage regulation, spinning and non-

spinning reserves and in some cases energy services from distributed energy resources or DERs. A key contribution of the thesis is to address the potential of three DER types – distributed generations (DGs), demand response and energy storage resources – to provide such services in DNs. Proposed strategies and approaches are tested and validated on real-world DN test systems.

In detail, the thesis discusses two proposed decentralised approaches to provide voltage support from DG resources. These approaches' objective is to avoid active power curtailments or the disconnection of RESs due to rises in voltage that usually occur in periods of high generation and low demand. We take advantage of the inverter that usually interfaces a DG to the DN into which it is integrated to implement a practical control strategy to provide reactive power support, be it either via injection or absorption of vars. Capability curves define the actual operational area that defines the amount of reactive power that is possible to absorb or inject into the grid, making curtailments/disconnections the least frequent solution performed by DSO when contingencies occur. To extend the approach of this control technique, it is possible to coordinate reactive power flows coming from different DG units of an independent power producer (IPP). The idea is to maximise active power production (and, then, reduce curtailments/disconnections) of PV and wind generators by optimising reactive power injections/absorption of DG units connected to different point of the DNs. The first decentralised but coordinated approach calculates the set points of each DG units by using the coefficients of the mixed sensitivity matrix of the network. This method results to be very fast to perform but it requires the calculation of the mixed sensitivity matrix; moreover, in some conditions, it could not give the best solution in terms of reactive power. The second method is based on the solution of a non-linear optimisation problem in order to calculate the active power-reactive power set points. By solving a global problem, the method points out an optimal solution even if the number DG units involved in the control is nontrivial; anyway, a communication framework must be developed for the exchange of information between DSO and IPP. We illustrate each scheme with applications to an actual Italian distribution network and provide a comparative analysis of their performance.

To provide ancillary services by demand response resources in the DN, it is necessary to develop new load models. Two alternative formulations of the well-known ZIP model to explicitly represent the dependence of the demand on voltage changes under steady state conditions are presented. These model representations are able to provide acceptable estimates of the impacts of schemes, such as conservation voltage reduction (CVR), on the energy consumption by these loads.

More in detail, the study wants to estimate how much demand it is possible to unlock by changing voltage values along the lines. To this end, an experimental study on a next-generation home appliance (a washing machine with digital control and motor drive fed by inverter) is conducted. The time-varying behaviour of domestic appliances is represented by using a *discrete-time ZIP model* to describe each phase of the appliance operations. The proposed model is capable of modelling the active power absorption of thermostatic loads, which exhibit periodic behaviour that depends on the applied voltage as well as equipment settings and the surrounding environment. To reduce the number of loads to be modelled during a time-series simulation, a time-varying formulation of the ZIP model is presented. It allows the aggregation of ZIP parameters at a given instant in time by using a polynomial structure. This model is tested on a real UK distribution network in order to estimate the amount of demand subject to change when the voltage at the primary substation is modified via an on load tap changer (OLTC).

The deployment of energy storage resources (ESRs) for the provision of certain ancillary services is investigated. The focus of the work is specifically on battery energy storage system integrated into PV systems. Two specific situations, under which the battery energy storage system (BESS) provides voltage support at the DN level, are proposed. The BESS is integrated into a PV solar farm. In detail, two controls, in which BESSs are co-located with PV units in order to provide voltage support in DNs, are presented. The former is a sensitivity-based decentralized control approach described above reduces the reactive power needed to maintain the voltage within a specified interval when compared to the case of the same solar PV unit farm without the integrated BESS. The latter ancillary service envisages the possibility to coordinate charging/discharging periods of BESSs co-located with PV units with DSO needs. Assuming that the DSO is able to estimate generation and demand peaks during the day (when the possibility of having voltage rises and voltage drops increases), then it is possible to identify the periods of the day in which the possibility that voltage issues occur is higher. Thus, DSO can require BESSs to provide voltage support in these periods by charging/discharging according to the possibility of having voltage rises/drops. The proposed method is compared with the case in which PV/BESS are operated without supporting network operation. Energy self-consumption resulted to be comparable; moreover, the opportunity cost is estimated to associate a cost to the proposed ancillary service.

The initial design of an analytic framework to assess the deployment of ESRs within a market environment and their performance in terms of reliability, environmental and economic impacts is presented. The rather comprehensive framework

provides the capability to represent all the interactions among the embedding environment of the deployed ESR with all other players/stakeholders in the grid and in the markets. The framework has the flexibility to incorporate relevant and appropriate policy issues and policy alternatives as well as to represent new market products to effectively harness ESR capabilities. The framework is able to represent the physical grid, the ESR embedding environment, if any; all resources and loads; the communication of control signals; the broadcast of market information/forecasts/data; submission of ESR offers for provision of various services; the evaluation of all reliability, environmental and economic/financial metrics of interest; attributes and sensor measurements; the physical/financial/information flows between physical resources, market players, asset owners and resource and grid operators. The design of the framework provides an interconnected four-layer framework structure consisting of a separate layer for the physical, information, market and environmental flows with the various interactions among the layers. The four- layer structure can accommodate the consideration of all issues in the operations of ESR deployment. Despite the number of studies available in the literature, there is limited activity in the provision of services in DNs by RESs. Technical issues as well as economic considerations has been addressed in the Thesis that gives significant contributions in the field of voltage regulation by using dispersed resources for reducing the risk of curtailments and maximizing the hosting capacity. This work also contributed to the understanding that decentralised approaches can, in certain case, have similar performance of centralised ones. In addition, the role of load as an active resource in the grid has been investigated. Load models that correlate consumption and voltage have been improved and reformulated. Finally, the role of BESSs in providing ASs in DNs has been demonstrated and a preliminary framework for the assessment of their economics has been presented.