COORDINATED VOLTAGE CONTROL IN DISTRIBUTION SYSTEMS UNDER THE SMARTGRID CONCEPT

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ABSTRACT

The deployment of the smart grid concept requires more automation and control in electrical distribution systems in order to be able to accommodate Distributed Energy Resources (DER), particularly those based on Renewable Energy Sources (RES). This paper presents a hierarchical control architecture designed for electrical distribution system comprising two main control layers. This structure enables the implementation of advanced functionalities such as coordinated voltage control between the MV and LV levels, exploiting Distributed Generation (DG) capabilities together with traditional voltage control techniques. The performance of the proposed voltage control algorithm is illustrated based on simulation results using real distribution networks.

INTRODUCTION

The deployment of the smart grid paradigm involves the adoption of decentralized and smart control and communication infrastructures at various levels in order to be able to coordinate DER efficiently. The control of these resources involves not only generation sources but also actions at the demand side through special contracts with customers which must be coordinated with traditional control actions by the Distribution System Operator (DSO).

On the other hand, large scale integration of DER in electrical distribution networks requires significant changes in power system operation and planning procedures [1]. The presence of these DER, especially DG units based on RES such as wind or solar that are characterized by intermittent power generation, leads to the need for developing novel advanced control and management algorithms within the general smart grid paradigm.

In fact, one of the major concerns to the DSO is related to the voltage rise effect that can occur as a result of the massive presence of DG units in the distribution system, namely in LV networks [2]. In these systems, conventional voltage regulation methods are not suited for tackling this problem effectively as they do not address variable power injections provided by DG units. Furthermore, coordination with existing methodologies such as transformer tap regulations must be assured.

In this context, new approaches for voltage control must be developed that make full use of all resources available, especially DG and microgeneration units, taking into account the specific characteristics of distribution networks. This is particularly important in the case of LV networks that usually have very resistive lines and where both active and reactive power control is needed in order to ensure efficient voltage control. In some extreme cases, if no local storage is available, it may even be necessary to spill some local generation in order to avoid voltage rise problems [3].

Consequently, a more advanced control and management functionality for voltage control must be developed in order to support the operation of distribution networks. The implementation of these new algorithms should be done in accordance the new prospects for future distribution systems within the smart grid paradigm by exploiting hierarchical, decentralized control architectures.

DISTRIBUTION SYSTEM CONTROL ARCHITECTURE

An effective control scheme for distribution system management and operation is a key issue in order to accommodate efficiently DG in distribution grids and to exploit their potential benefits. The architecture of the decentralized control and management solution proposed is presented in Fig. 1. It is assumed that the existence of a smart metering infrastructure will support the implementation of this type of solutions, by providing communication capability between all the devices.

Nowadays, the Distribution Management System (DMS) is solely responsible for the supervision, control and management of the whole distribution system. In the future, in addition to this central DMS, there may be two additional management levels [4]:

- The HV/MV substation level, where a new management entity – the Smart Substation Controller (SSC) – will accommodate a set of local functionalities that were normally assigned to the DMS in a centralized approach.
- The LV level, where the Distribution Transformer Controller (DTC), to be housed in MV/LV substations, will be responsible for managing the distribution transformer and the microgrid (including the control of the microgenerators and responsive loads).

In the future, the operation of power systems should be shared between central generation and DG. Control of DG could be aggregated to form microgrids that operate as virtual power plants in order to facilitate their integration both in the physical system and in the market. As seen in [5], a microgrid can be regarded, within the main grid, as a controlled entity operated as a single aggregated load or generator and, given attractive remuneration, as a source of power or of ancillary services supporting the main grid.

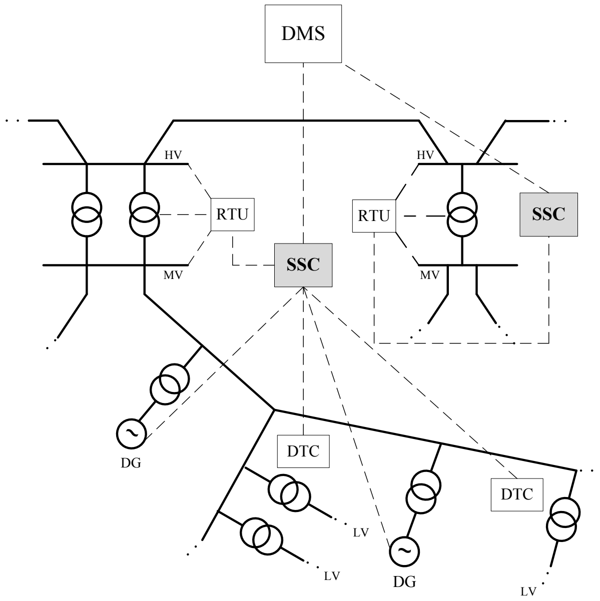

Fig. 1. Control and Management Architecture for Distribution Systems

It is important to stress that the reference architecture presented here has also been proposed in the national InovGrid project [6] which focused on the development of a fully active distribution network based on a smart metering infrastructure. In fact, some of these controllers have already been installed at a demonstration site in Évora, Portugal under the label InovCity.

COORDINATED VOLTAGE CONTROL

The algorithm presented was developed aiming at the integration in a voltage control module to support network operation, according to the control and management architecture described previously, under the smart grid paradigm. The method described here is an evolution of the one presented in [3] with a more detailed model of the LV network.

Mathematical Formulation

The voltage control problem is formulated as a non-linear optimization problem including both discrete (transformer taps) and continuous variables (active or reactive power generation).

The objective function aims at minimizing active power losses and microgeneration curtailment (that may be necessary in case of permanent overvoltages) without violating the main technical and operational constraints, namely bus voltage limits and line loading limits.

This optimization problem is addressed using a meta-heuristic approach – Evolutionary Particle Swarm Optimization (EPSO) – in order to find the solution to the problem.

MV and LV Coordination

In order to develop an efficient coordinated method for voltage support in distribution grids, involving the MV and LV levels, the specific characteristics of these MV and LV networks must be considered. Concerning the MV network, a traditional power flow routine may be used to assess the impact of DG and microgeneration. However, for a LV system comprising single-phase loads and microgeneration units that cause phase imbalance, traditional power flow routines are not suitable. For this type of systems, a three-phase power flow must be employed in order to evaluate the expected impacts in the operation of the LV grid.

On the other hand, the main problem when dealing with optimizing distribution network operation is the dimension of the distribution system. Given the size of both MV and LV real distribution networks, a full representation of an MV network (including all LV feeders located downstream) is unpractical. Since the dimension of the system may be huge, considering that an MV including the downstream LV networks can have several thousand buses, it becomes unfeasible to develop an algorithm using a full model representation of the MV and LV levels, able to operate in a real-time management environment.

Consequently, in order to speed-up the integrated control algorithm, an Artificial Neural Network (ANN) model able to emulate the behaviour of the “active” LV network (or microgrid), was adopted. This option enables the use of the optimization tool employed in real-time operation, by reducing the long simulation times that are required in order to calculate consecutive LV power flows. In fact, the ANN can be regarded as an equivalent model able to reproduce the behaviour of the LV network regarding namely voltage profiles and losses since these are the variables of major concern. Using the ANN, the computational burden and, consequently, the computational time required to run the application can be significantly reduced.

Artificial Neural Network Model

As previously mentioned, an ANN able to emulate the behaviour of an “active” LV network in terms of power flows has been developed. Therefore, each “active” LV network can be replaced by an equivalent ANN model in the global optimization procedure. In this case, ANN models for each feeder of each LV network were developed since it was observed that feeders may include different amounts of microgeneration and therefore the cause for an overvoltage may be originated from one single feeder with excessive microgeneration integration.

For this, a three-phase power flow routine was developed in order to enable the analysis of the steady-state behaviour of LV networks considering their specific characteristics, namely phase imbalances due to the connection of single-phase loads and single-phase microgeneration units exploiting different technologies.

In order to use efficiently the approach developed, it is then necessary to automate the procedure of retraining the ANNs. First of all, the main changes that trigger the need for retraining the ANNs must be identified. These changes are mostly changes in the topology of the networks due to the inclusion (or removal) of additional DG, microgeneration units or loads, the set-up (or upgrade) of a line or transformer and expansion of the LV grid.

Development of the Tool

As previously seen, the algorithm developed for voltage control is designed to be used as an online function available for the DSO. This algorithm is intended to be integrated as an independent software module that will be housed in the SSC.

The SSC, which will include several key functionalities for distribution system management and operation, is going to be installed at the HV/MV substation. The inclusion of some advanced control functionalities at the SSC allows relieving the central DMS, following a rational of decentralized operation based on partial autonomy of local controllers.

Exploiting a smart metering infrastructure, the SSC is able to collect critical information from the several devices in the network, namely data from load and RES forecast as well as results from generation dispatch, in order to assess voltage profiles, branch overload levels and active power losses. Using this information, the voltage control algorithm is run and, after it has successfully terminated, produces a set of commands in the form of set points. These commands are then sent to the several devices such as DG units, microgeneration units (via the corresponding DTC) and OLTC transformers. This procedure is intended to run cyclically and in an automated way, under the supervision of the DSO.

The topology and structure of the MV and LV distribution systems is also periodically updated in order to provide the several modules with data on the current status of the grid, including all devices such as DG units, microgenerators, loads, switches, etc.

MAIN RESULTS

In this section, results obtained from the voltage support tool designed are presented for a 24-hour time horizon, corresponding to twenty-four consecutive operating periods. The voltage control algorithm was run using ANN models for each feeder of each microgrid.

A real MV network was used to test the voltage control. This network is a typical Portuguese rural network with a radial structure with a total of 211 nodes and 212 branches. It includes an OLTC 30 kV/15 kV transformer with taps on the secondary side of the transformer.

DG units and “active” LV networks (microgrids) were added to this network in order to assess the performance of the voltage support tool in managing the MV distribution system with several different generating units and to evaluate the impact of these units on network operation. Consequently, six microgrids and three MV-connected DG units (two wind generators based on doubly-fed induction generators and a combined heat and power unit) were included. Regarding the microgrids that are included in this network, it was considered that the microgeneration units were based solely on PhotoVoltaic (PV) units since this is the most likely technology to be installed in LV networks in Portugal.

According to the objective function defined previously, active power losses minimization was one of the goals to achieve. Fig. 2 compares the base situation (without any type of voltage control – labelled Initial in the figure) and the result obtained using the voltage support tool developed (labelled Final in the figure).

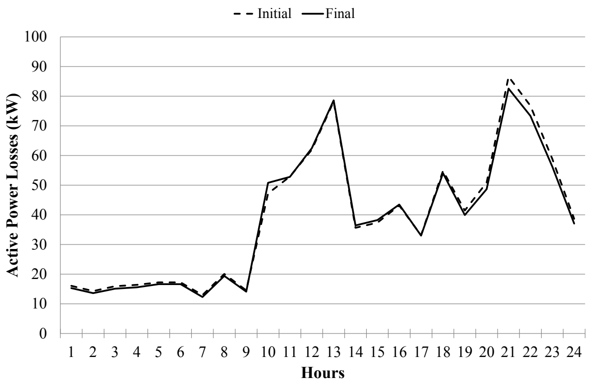

Fig. 2. Total Active Power Losses

It can be seen that total network losses were successfully decreased during night-time but have increased slightly during day-time as voltage profiles were high. Fig. 3 shows the maximum voltage value in the most problematic feeder of Microgrid 1 for each hour of the day. As can be observed, without voltage control, voltage values were above the admissible range of +5% due to the PV-based microgeneration that is generating near its peak capacity. In this case, the PV panels generate power at peak capacity around 13h, which is outside the peak demand hours and therefore force excess generation through the MV/LV transformer.

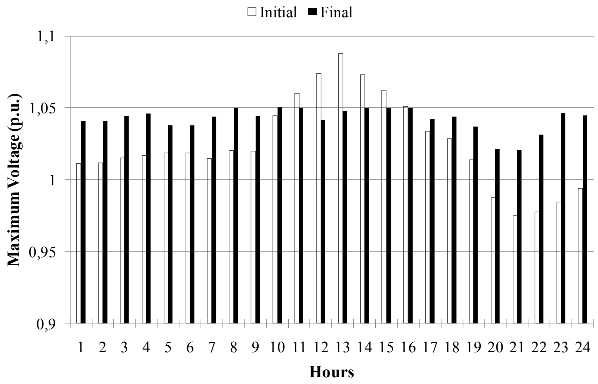

Fig. 3. Maximum Voltage in a Feeder of a Microgrid

At a first phase, changes in transformer tap settings were tested. Since they did not succeeded in bringing voltage values back to an admissible range, there was the need for curtailing excess microgeneration in feeder 3 for some critical hours of the day, as can be observed from Fig. 4.

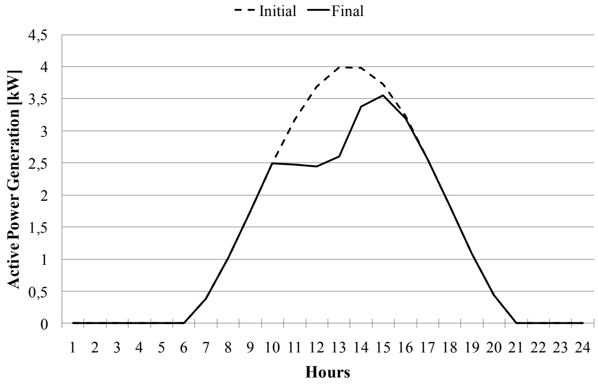

Fig. 4. Total Active Power Generation in a Feeder of a Microgrid

In this case, only one PV generator is connected to this feeder, which means that not all of the generated power can be absorbed by the LV system, which results in a spillage of renewable-based microgeneration.

CONCLUSION

Large scale integration of DG in distribution grids will require significant changes in network automation for both planning and operation. In particular, the new control architecture proposed with two management and control layers, together with the development of specific management and control tools, will allow a more efficient grid operation while avoiding operational problems that may arise.

This decentralized control approach is in line with the general vision for future distributions systems under the general smart grid paradigm and will require the development of advanced control functionalities to support distribution system operation.

In this paper, an advanced voltage control strategy was proposed, highlighting the benefits of coordinating DER (at the MV and LV levels) with the traditional voltage control techniques. In fact, it was seen that coordinating the DER present in MV and LV networks can not only reduce power losses and improve voltage profiles but also avoid the curtailment of microgeneration at the LV.

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