Voltage and Reactive Power Control in MV Networks integrating MicroGrids

A. G. Madureira[1] and J. A. Peças Lopes[1]

[1] Faculty of Engineering of Porto University and Power Systems Unit of INESC Porto
Rua Dr. Roberto Frias, 378, 4200-465 Porto, Portugal
Phone:+351 22 2094000, Fax:+ 351 22 2094050, E-mail: **agm@inescporto.pt**, **jpl@fe.up.pt**

Abstract. The main objective of this paper is to describe a strategy to deal with the voltage/reactive power problem for a MV distribution network integrating microgrids. The global problem, concerning all voltage levels, is detailed here and will imply the optimization of operating conditions by using the control capabilities of power electronic interfaces from DG sources, OLTCs and microgrids, through the application of an EPSO optimization algorithm.

Key words

MicroGrid, Voltage and Reactive Power Control, MV Networks

1. Introduction

The connection of microgeneration to Low Voltage (LV) networks, creating microgrids, is expected to be playing a key role in future power systems. Microgrids, as defined so far, comprise a LV feeder with several microsources, storage devices and controllable loads connected on the same feeder [1]. These LV microgrids may be operated in interconnected or in islanded mode, for special cases of operation [1-2] and are managed by a MicroGrid Central Controller (MGCC) that includes several key functions such as economic managing functions and control functionalities [1].

The new concept of multi-microgrids is related to a higher level structure, formed at the Medium Voltage (MV) level, consisting of LV microgrids and Distributed Generation (DG) units connected on several adjacent MV feeders. Microgrids, DG units and MV loads under Demand Side Management control can be considered in this network as active cells, for control and management purposes.

Technical operation of such a system requires the transposition of the microgrid concept to the MV level, where all these active cells, as well as MV/LV passive substations, should be controlled by a Central Autonomous Management Controller (CAMC) to be installed at the MV bus level of a HV/MV substation, serving as an interface to the Distribution Management System (DMS), and under the responsibility of the Distribution System Operator (as can be seen in Fig. 1).

At the distribution system level, microgeneration contribution in addition to the contribution of DG sources will have a significant impact. The role played by microgeneration and other DG will enable the participation of these units in providing ancillary services, such as coordinated frequency support and coordinated voltage support, for instance. In this MV network two modes of operation are also possible: a) interconnected mode and b) islanded mode.

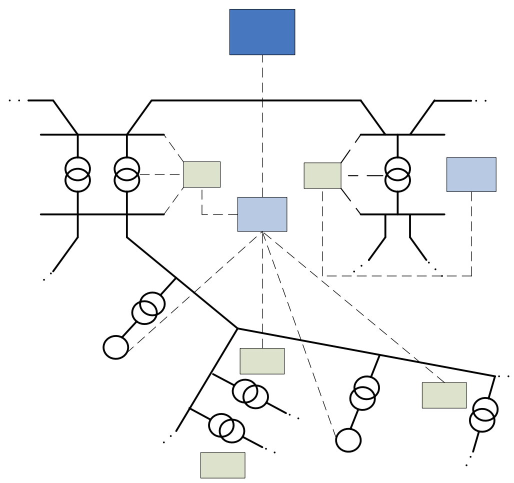

Fig. 1. Control and Management Architecture of a Multi-Microgrid System

Hence, a hierarchical control scheme should be established for voltage control, similarly to what happens in frequency control.

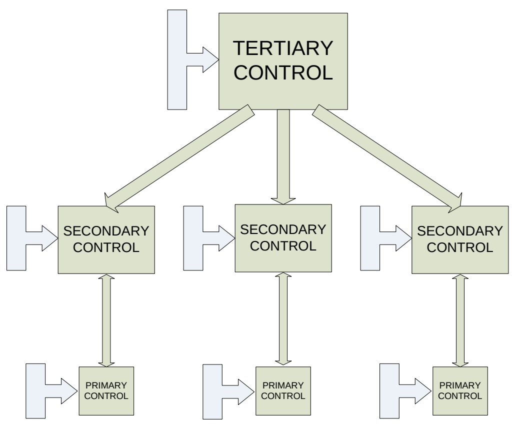

Fig. 2. Hierarchical Voltage Control

A hierarchical voltage control scheme can be divided into three control levels, according to areas of action and deployment time [3]. These three levels (for primary, secondary and tertiary control) are presented in Fig. 2.

The most common requirements for coordinated voltage/reactive power control are:

- Keeping bus voltages within specified limits
- Controlling transformer, line and feeder loading
- Minimizing active power losses
- Managing reactive power sources
- Controlling the power factor

Secondary voltage services in distribution networks integrating microgrids may be provided by microgrids operating in either grid-connected or emergency mode. Tertiary Voltage services may also be provided but only in grid-connected mode of operation.

The CAMC will have a key role in implementing these functionalities since it will have the ability to control the reactive flows of the several microgrids (through the corresponding MGCCs) and optimize global system operation of multi-microgrid systems in order to minimize reactive power flows and improve voltage profiles.

The main aim of this research is to define an optimized coordinated voltage control strategy between the several voltage levels in the distribution system.

2. Problem Characterization

One promising strategy to deal with the voltage control issue in distribution networks integrating microgrids involves the definition of voltage control areas each one with a reference bus for voltage regulation purposes.

The strategy used for the definition of voltage control areas is subject to discussion. Several methods can be found in the available scientific literature such as the method based on the definition of electrical distance [4-5]. This method has been used successfully by EDF for quite some time [5]. Nevertheless, other methods may also be used. The definition of a voltage control area per feeder is also an interesting possibility, given the structure of the distribution system and corresponding configuration.

Voltage control in distribution systems integrating microgrids is a steady-state optimization problem, with non-linear and discrete characteristics, and with a strong hierarchical structure. This fact will imply dealing with voltage control sub-areas for each voltage level. Once a solution has been found to the global problem, the sub-solutions for individual microgrids will be tested in order to evaluate their feasibility, given the characteristics of their microgenerators. The optimization procedure will require a sequence of local sub-problems solutions and global problem solutions in order to converge to a near-optimum solution.

Therefore, coordination of voltage/VAR control in MV distribution networks is addressed here with the purpose of improving system operation conditions (minimize losses and keep voltage profiles within desired levels) by exploiting, in a combined way, the control capabilities of power electronic interfaces from DG sources, On-Line Tap Changing (OLTC) transformers, Static VAR Compensators (SVC) and microgrids (that can be regarded as active cells). Specific physical and technical limitations of all controllable devices must be taken into account as well as physical limitations of network branches. Special restrictions that result from the downstream microgeneration availability and operation characteristics must also be considered here.

Some load flow analysis for typical network structures, performed in order to identify the need for voltage support by microgrids, was performed at a previous stage.

This functionality will enable the identification of the amount of ancillary services of voltage control that can be dealt with afterwards, from a market point of view.

In this work, the optimization algorithm used is a Particle Swarm Optimization (PSO) approach. In particular, a modified version – Evolutionary PSO [6-8] – is currently being used to voltage VAR control [6]. EPSO is a powerful optimization algorithm developed at INESC Porto, based on a combination between traditional PSO strategies by Kennedy and Eberhardt [9] and Genetic Algorithms by Holland [10]. Thus, it combines the benefits from both PSO and Evolutionary Strategies, creating a very robust algorithm.

It should be stressed that this algorithm has been extensively tested in recent years, applied to optimization problems in power systems [7].

3. Mathematical Formulation

The characteristics and the formulation for the voltage/VAR control problem at MV level are presented next:

- Type of Problem: Mixed (combining integer and continuous variables), Non-linear Minimization Problem
- Control Variables: Reactive Power generation in each active cell (such as microgrids, DG units), Transformer Taps values (discrete variable) and Capacitor Banks (discrete variable)
- Objective Function: Minimization of Active Power Losses, subject to a set of functional and technical constraints
- Constraints: Technical (represent operational limits of equipments and other physical limits imposed to system operation)
    - ✓ Voltage limits in all buses
    - ✓ Power flow limits in lines and transformers
    - ✓ Capacitor steps limits

- ✓ Reactive power generation limits for active cells and DG units, as well as Transformer tap ratio limits

Mathematically, this can be described as follows:

$$\min\ OF(\underline{X}) = P_{LOSSES}$$

subject to:

$$V_i^{\min} \le V_i \le V_i^{\max}$$
$$S_{ik}^{\min} \le S_{ik} \le S_{ik}^{\max}$$
$$t_i^{\min} \le t_i \le t_i^{\max}$$
$$Q_i^{\min} \le Q_i \le Q_i^{\max}$$

where:
OF – Objective Function
$\underline{X}$ – Control variables
P_{LOSSES} – Active Power Losses
V_i – Voltage at Bus i
V_i^{min}, V_i^{max} – Minimum and maximum voltage at bus i
S_{ik} – Power Flow in Branch ik
S_{ik}^{min}, S_{ik}^{max} – Minimum and maximum power flows in Branch ik
t_i – Transformer tap of or capacitor step position
t_i^{min}, t_i^{max} – Minimum and maximum tap

Concerning LV microgrid modelling, the main assumptions considered are presented next:

- Simulations were made for assessing reactive power flow between the LV microgrid and the upstream MV network
- Each LV microgrid was considered as a single bus with an equivalent generator (sum of all microsource generations) and equivalent load (sum of all LV loads)
- Q limits for each microgrid consider a tan(φ) = 0.25 based on the microgrid nominal active power generation

4. Test Network Characterization

In order to test the algorithm at the MV level, a MV test network was used. This is a 15 kV network that has two distinct zones: an urban zone (the part on the left-hand side of Fig. 3, corresponding to an electrical “ring”) and a rural zone (the part on the right-hand side of the figure, corresponding to a radial network). There are some DG units connected to the MV level, namely:

- A Diesel unit (1.5 MVA)
- A Double-Fed Induction Machine corresponding to a Wind Park (9 MVA)
- A Combined Heat and Power (CHP) unit (2.2 MVA)
- A Hydro unit (2.8 MVA)

There are also 5 LV microgrids connected to the MV grid and 2 capacitor banks (0.5 MVAR each) also directly connected to the MV network.

Besides, two load and generation scenarios were developed. These scenarios correspond to peak and valley hours. It was considered that in peak hours the MV network is importing active power from the upstream HV network and in valley hours the MV network is exporting active power to the HV network. The amount of active and reactive power generation levels is defined in Table I.

TABLE I. – Load and Generation Scenarios

	Peak Hours		Valley Hours	
	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
Total Load	9.78	3.65	3.67	1.37
Total Generation	8.54	3.42	5.20	1.48

It must be stressed that, initially, reactive power flow was defined to be near-zero in the HV/MV transformer for both scenarios.

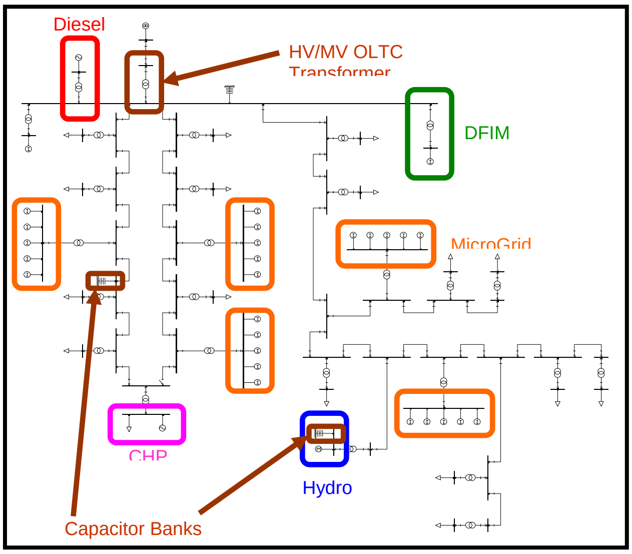

Fig. 3. MV Test Network

5. Main Results

The start point considered for the start of the optimization procedure was a flat case based on a simple power flow result. For the studied scenarios, 20 particles (solutions), 3 replicates and 500 generations were used.

The particle structure, containing the control variables, is presented next:

$$Q_{MG1} \ldots Q_{MG5} \mid Q_{CHP} \mid Q_{HYDRO} \mid Q_{DFIM} \mid Q_{DIESEL} \mid t_{tap} \mid CAP_1 \ldots CAP_2$$

where:
Q_{MGi} – Reactive power provided by microgrid i
Q_{CHP} – Reactive power provided by the CHP unit
Q_{HYDRO} – Reactive power provided by the Hydro unit
Q_{DFIM} – Reactive power provided by the DFIM unit
Q_{DIESEL} – Reactive power provided by the Diesel unit
t_{tap} – OLTC transformer tap position
CAP_i – Reactive power provided by capacitor bank i

The main results obtained are presented in this section, considering the two load scenarios and the test network presented previously.

For peak hours, a loss reduction of 3.38% (corresponding to 1.8 kW) is achieved, with no reactive power generation limits violated and no branch limits exceeded. A summary of the results obtained is presented in Table II. A comparison between the final values of the EPSO algorithm (EPSO Losses) and a base case from a simple power flow routine (PF Losses) is presented in Fig. 4.

TABLE II. – Loss Reduction achieved

	Loss Reduction (%)	Loss Reduction (kW)
Peak Hours	3,38%	1,80
Valley Hours	39,13%	1,80

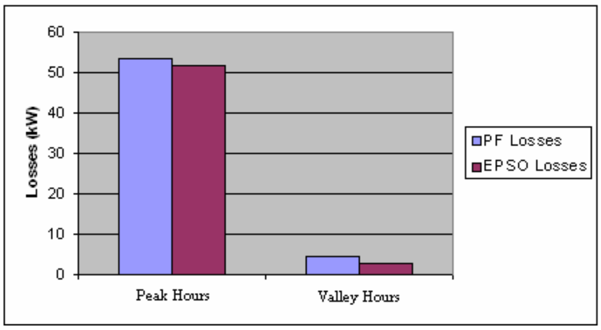

Fig. 4. Comparison between Losses Before and After the run of the EPSO Algorithm

The behaviour of the optimization procedure regarding fitness, for peak hours is presented in Fig. 5. The final values of the EPSO algorithm for the control variables (EPSO particle) compared to a base case from a simple power flow routine (PF particle) are presented in Fig. 6.

Concerning valley hours, a loss reduction of 39.1% (corresponding to 1.8 kW) is achieved, with no reactive power generation limits violated and no branch limits exceeded. A typical algorithm run for peak hours is presented in Fig. 7. The final values of the EPSO algorithm for the control variables (EPSO particle) compared to a base case from a simple power flow routine (PF particle) are presented in Fig. 8.

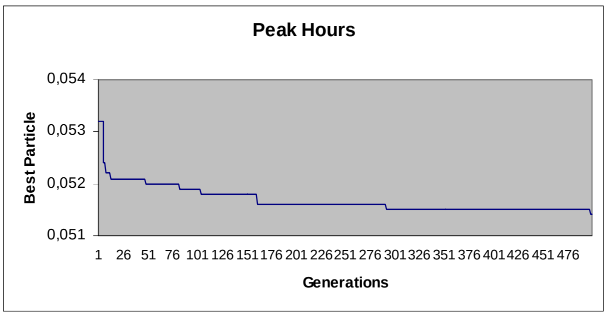

Fig. 5. Active Power Losses (MW) in each iteration for Peak Hours

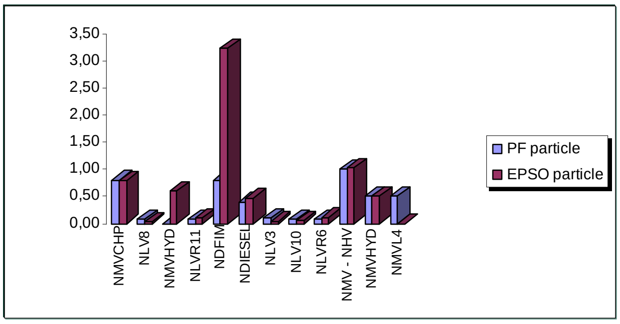

Fig. 6. Control Variables (in MVAR, except for the transformer tap) for Peak Hours

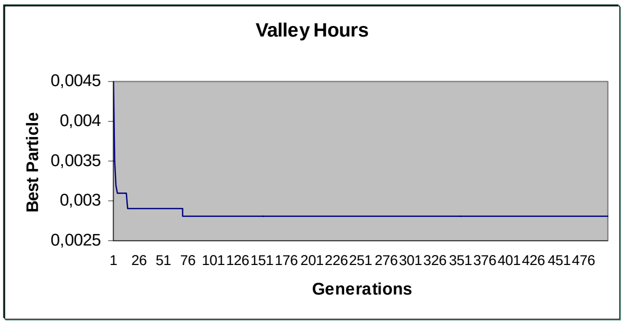

Fig. 7. Active Power Losses (MW) in each iteration for Valley Hours

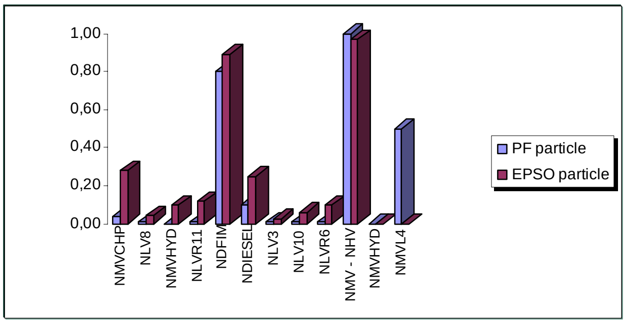

Fig. 8. Control Variables (in MVAR, except for the transformer tap) for Valley Hours

The allocation of reactive power generation inside each microgrid (splitting it through the local microsources) needs to be decided afterwards by the MGCC. A similar procedure can be used for this purpose.

6. Conclusion

In conclusion, voltage/VAR control in distribution systems integrating microgrids is a hierarchical optimization problem that must be analysed in a coordinated way between LV, MV and HV levels.

An EPSO approach was adopted in order to deal with the voltage/VAR control problem at the MV level and the algorithm has proved to be efficient in order to achieve the main objective function: Active Power Loss Minimization.

Currently, more developments on the algorithm are being implemented and tested, namely concerning the coordinated operation between LV and MV levels and using different objective functions.

Acknowledgement

The authors would like to thank Nuno Fonseca for developing the basis for the EPSO algorithm used in this work.

The authors also want to acknowledge the financial support from FCT (PhD grant SFRH/BD/29459/2006) and from the EU within the framework of the More MicroGrids project (Contract no. PL019864).

References

[1] J. A. P. Lopes, C. L. Moreira, A. G. Madureira, "Defining Control Strategies for MicroGrids Islanded Operation", Proceedings IEEE Transactions on Power Systems, Vol. 21, Issue 2, pp. 916-924, May 2006.

[2] J. A. P. Lopes, C. L. Moreira, A. G. Madureira, *et al*, "Control Strategies for MicroGrids Emergency Operation", Proceedings 2005 International Conference on Future Power Systems, Amsterdam, The Netherlands, November 2005.

[3] Wilson Feijó Júnior, "Um Estudo sobre Coordenação e Ajuste de Transformadores com Mudança de Tap sob Carga e de Bancos de Capacitores para Suporte das Acções de Controle Coordenado de Tensão e Potência Reactiva" (in portuguese), M.Sc. Thesis, October 2002.

[4] J. Zhong, E. Nobile, A. Bose, K. Bhattacharya, "Localized Reactive Power Markets Using the Concept of Voltage Control Areas", IEEE Transactions on Power Systems, vol. 19, no. 3, August 2004.

[5] P. Lagonotte, J. Sabonnadière, J. Léost, J. Paul, "Structural Analysis of the Electrical System: Application to Secondary Voltage Control in France", IEEE Transactions on Power Systems, vol. 4, no. 2, May 1989.

[6] J. A. Peças Lopes, Â. Mendonça, N. Fonseca, L. Seca, "Voltage and Reactive Power Control Provided by DG Units", CIGRE Symposium: Power Systems with Dispersed Generation, Athens, Greece, April 2005.

[7] V. Miranda, N. Fonseca, "EPSO – Evolutionary particle swarm optimization, a new algorithm with applications in power systems", Proceedings IEEE/PES Transmission & Distribution Conference and Exhibition: Asia Pacific, pp. 745–750, 2002.

[8] V. Miranda, N. Fonseca, "New evolutionary particle swarm algorithm (EPSO) applied to voltage/VAR control", 14th Power Systems Computation Conference (PSCC'02), Seville, Spain, June 2002.

[9] J. Kennedy, R.C. Eberhart, "Particle Swarm Optimization", IEEE International Conference on Neural Networks, Pert, Australia, IEEE Service Center, Piscataway, NJ, 1995.

[10] J. H. Holland, "Adaption in Natural and Artificial Systems", The University of Michigan Press, 1975 Ann Arbor