OBJECT-ORIENTED MODELING OF A POWER NETWORK FOR MODEL-BASED VOLTAGE CONTROL

Francesco PETRONE
Politecnico di Milano – Italy
petrone.fr@gmail.com

Marcello FARINA
Politecnico di Milano – Italy
farina@elet.polimi.it

Antonio GUAGLIARDI
RSE, Italy
guagliardi@rse-web.it

Carlo SANDRONI
RSE - Italy
carlo.sandroni@rse-web.it

Riccardo SCATTOLINI
Politecnico di Milano – Italy
scattoli@elet.polimi.it

Anna VENERONI
Politecnico di Milano, Italy
annaveneroni87@hotmail.com

ABSTRACT

This paper deals with the design of dynamic regulators for voltage control in Medium Voltage feeders with Distributed Generators, which can be used as active control elements. A modular object-oriented simulation environment has been developed in Matlab® /Simulink/Simscape. This tool has been used for the design and validation of a control structure made by control loops acting at different levels. Specifically, two control structures are synthetized: the first one is made by standard PI-PID regulators, while the second one relies on the Model Predictive Control (MPC) approach.

INTRODUCTION

The liberalization of the energy market and the widespread diffusion of distributed generation rise new problems in the management and control of medium voltage (MV) distribution networks. In fact, the high variability of renewable energy generation can result in significant modifications of the voltage profiles along the open-ended radial feeders typical of distribution networks. In turn, this can produce unexpected bi-directional variations in network power flows, with severe consequences on the quality of supply. For these reasons, coordinated voltage control in distribution systems is becoming of paramount importance and has stimulated many research efforts, see e.g. [1]-[3], just to mention a few.

Voltage control usually relies on the use of on-load tap changer and switched shunt capacitors, operated in a decentralized setting, i.e. with local control laws without high level global coordination. More innovative approaches are based on the direct use of distributed generation by directly exploiting the possibility of synchronous distributed generators to control their terminal voltage by adjusting their reactive power, see again [3] and the references quoted there. The corresponding control structures can be either fully decentralized, i.e. any distributed generator is controlled by a local control law, or designed according to a centralized structure.

In any case, i.e. either for centralized or distributed control structures, the common assumption of sinusoidal regime cannot be advocated, and a rational controller design requires the knowledge of a (linearized) dynamic model of the system.

In view of these considerations, the research activity described in this paper is aimed at developing new model-based distributed control methods for voltage control in MV feeders. The overall control system is composed by the joint use of a centralized regulator, which defines the proper settings of the reactive power along the feeders and of local decentralized regulators, one for every controlled distributed generator.

In order to compute the required linearized models of the system and to test the control scheme in dynamic conditions, the first step of the research activity has concerned the development, in the Matlab®/Simulink/ Simscape environment, of a modular dynamic modeling and simulation environment allowing for the definition and simulation of feeders with arbitrary configuration. This simulation environment and the computed linearized model are first used to design a control system made by standard PI-type regulators where the dynamics is explicitly accounted for. Then, a Model Predictive Control (MPC) regulator is used to provide more flexibility to the control scheme and to improve the overall control performances.

THE OBJECT-ORIENTED SIMULATION TOOL

The typical elements of the feeder, i.e. synchronous generators, passive loads, transformers, transmission lines, asynchronous motors, have been modeled by means of the Park's transformation, see [4]. The corresponding simulation blocks have been developed in the object-oriented simulation environment Simscape, a toolbox of Matlab®/Simulink for a-causal modeling and simulation. This choice stems for the need to consider systems described by DAE (Differential Algebraic Equations), and to connect them according to an a-causal configuration, typical of electrical networks. In the proposed simulation environment one can fully take advantage of the many features of Matlab/Simulink, such as the possibility to automatically derive the linearized models to be used in the control synthesis phase. Moreover, it is possible to link Simscape and Simulink models, so as to validate in

simulation the overall control system.
and validated by comparing its performances to those of more complex and highly reliable simulation codes, such as DIgSILENT PowerFactory® and LEGO. In the validation phase, a system composed by two feeders has been analyzed, see Figure 1. The first feeder includes passive loads, an asynchronous motor and two distributed generators, besides transformers and transmission lines, modeled as static elements.

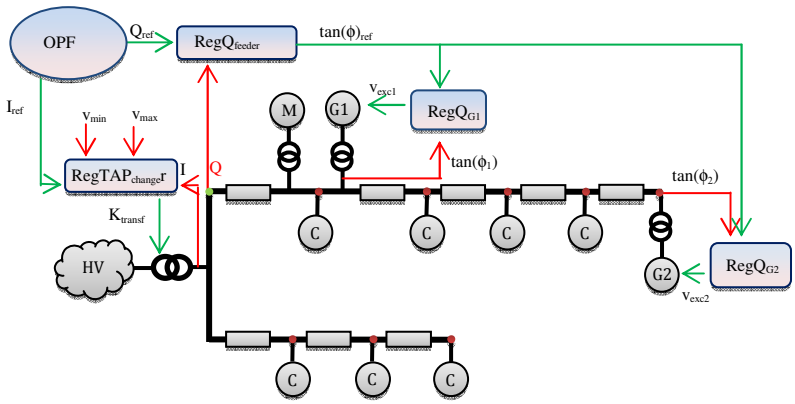

Figure 1: Sketch of the MV system and of the adopted traditional control scheme.

THE CONTROL SYSTEM

The adopted control scheme combines a direct action on the position of the tap changer with coordinated control along each feeder, providing the reference value of the power factor for local reactive power control of the distributed generators, see also [5].
More specifically, a control loop, made by a proportional regulator ($RegTAP_{changer}$ in Figure 1), computes the tap changer position based on the error between the current flowing from the High Voltage (HV) and a prescribed reference value. Corrective actions, not represented in the scheme of Figure 1, are also added to maintain the voltage along the feeders inside some prescribed ranges. This requires the knowledge, or the estimation, of the voltage profiles, which can be done according to the approach proposed in [6].
Additional control loops, one for any feeder with DGs, are made by PI-PID type regulators ($RegQ_{feeder}$ in Figure 1), computing the required value of the feeder power factor based on the error between the reactive power flow at the beginning of the feeder and a given reference value. The output of these regulators are used as the reference signals for the local regulators of the DG, also made by PI-PID elements ($RegQ_{Gi}$ in Figure 1).
All the reference values for the high level regulators $RegTAP_{changer}$ and $RegQ_{feeder}$ can be determined though the solution of an Optimal Power Flow (OPF in Figure 1) problem.
The implementation, tuning and testing of this control structure can be easily performed with the simulation tool described in the previous Section. Since the local feedback loops are usually much faster than the control loops used for coordination, the local regulators $RegQ_{Gi}$ can be tuned neglecting cross-coupling effects and starting from the knowledge of the DGs transfer functions between the excitation voltage and the reactive power flow of the DGs. In the test case of Figure 1, the Bode diagrams of the four transfer functions between the excitation voltages of the two DGs and the corresponding reactive power flows are reported in Figure 2. The availability of the linearized model also allows one to compute the Relative Gain Array (RGA) matrix [8]:

$$RGA = \begin{bmatrix} 0.9999 & 0.0001 \\ 0.0001 & 0.9999 \end{bmatrix}$$

which confirms the feasibility of a decentralized approach, in view of the weak static couplings between the two DGs. Once the local feedback loops have been tuned and included into the overall dynamic simulator, a similar approach can be followed, for any feeder, for the synthesis of the coordinating regulators $RegQ_{feeder}$, as well as of the regulator acting on the tap changer.
With reference again to the system of Figure 1, and in order to test the performances of the control scheme, a simulation has been made by imposing a 20kW step variation of the motor load at time t=40s. The system was in initial stationary conditions, the computed transients of the voltages at the loads and of the reference and controlled power factors at the DGs are reported in Figures 3-4, while Figure 5 shows the reactive power at the beginning of the first feeder.

THE MPC APPROACH

In the scheme of Fig. 1, only one reference value of the power factor, to be sent to the local control loops of the

DGs as the reference signal, is computed for any feeder by the PI-type regulator $RegQ_{feeder}$. In order to gain flexibility, and to exploit the possibilities offered by the knowledge of a dynamic mathematical model of the system, the regulator $RegQ_{feeder}$ can be designed according to the Model Predictive Control (MPC) approach, see e.g. [9]. This solution has the following advantages: (i) a different reference power factor can be computed for any DG of the feeder; (ii) constraints on the predicted voltages along the feeder can be explicitly considered in the computation of the optimal control law; (iii) future predicted variations of the loads and of the power produced by the DGs can be accounted for.

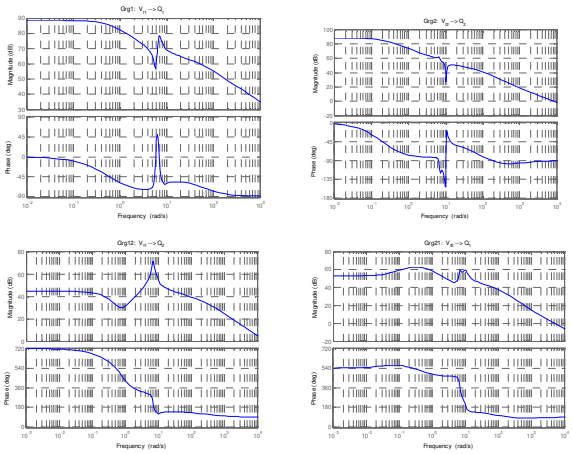

Figure 2: Bode diagrams of the transfer functions between the excitation voltages of the DGs and the reactive power flows.

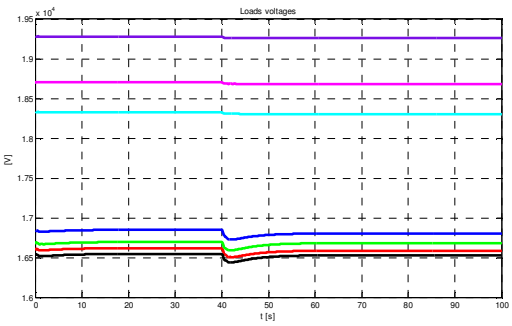

Figure 3: voltages at the loads after a step variation of the motor load at time t=40s.

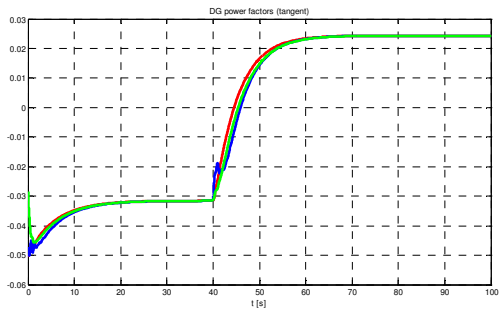

Figure 4: DG power factors (tangent): the red curve is the reference signal computed by $RegQ_{feeder}$, the green and blue curves are the power factors controlled by the DGs local regulators.

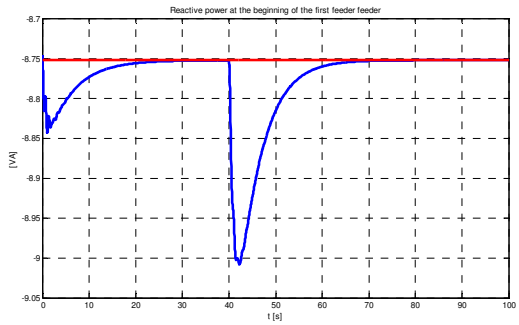

Figure 5: Reactive power at the beginning of the first feeder (the red line is the reference).

The MPC control problem can be stated as follows. Consider the linearized model of a feeder, with the local control loops already implemented, described by

$$\begin{aligned} \dot{x}(t) &= A_c x(t) + B_c u(t) + M_c d(t) \\ y_c(t) &= C_c x(t) \\ y_m(t) &= C_m x(t) \end{aligned} \qquad (1)$$

where u is the vector of the reference power factors $tan(\phi_i)_{ref}$ for the *i-th* DG along the feeder, y_c (controlled variables) is the vector of the measured power factors $tan(\phi_i)$, d (disturbances) is the vector of the power produced by generators and absorbed by the loads, y_m (measured variables) is the vector of the measured voltages and reactive powers along the feeder. All these signals are referred to variations with respect to the considered nominal operating point. System (1), discretized and transformed in velocity form, can be written as

$$\begin{bmatrix} \Delta x(k+1) \\ e(k+1) \end{bmatrix} = \begin{bmatrix} A_d & 0 \\ -C_c A_d & I \end{bmatrix} \begin{bmatrix} \Delta x(k) \\ e(k) \end{bmatrix} + \begin{bmatrix} B_d \\ -C_c B_d \end{bmatrix} \Delta u(k) + \\ + \begin{bmatrix} M_d \\ -C_c M_d \end{bmatrix} \Delta d(k)$$

$$y_c(k) = y_c(k-1) + \begin{bmatrix} C_c & 0 \end{bmatrix} \begin{bmatrix} \Delta x(k) \\ e(k) \end{bmatrix}$$

$$y_m(k) = y_m(k-1) + \begin{bmatrix} C_m & 0 \end{bmatrix} \begin{bmatrix} \Delta x(k) \\ e(k) \end{bmatrix}$$

where k is the discrete time index and, with reference to the generic signal ξ, $\Delta\xi(\kappa)=\xi(\kappa)-\xi(\kappa-1)$, $e(k)=y^o-y_c(k)$, and y^o is the reference signal. The velocity form is adopted here to include in the control system an integral action, so as to guarantee steady-state zero error regulation for constant references.

Letting $\gamma(k) = \begin{bmatrix} \Delta x(k) \\ e(k) \end{bmatrix}$, at any time instant the future control increments $\Delta u(k), \ldots, \Delta u(k+N-1)$ are computed as

the solution of the following finite horizon optimization problem, where $N>0$ is the adopted prediction horizon

$$\min_{\Delta u(k),\ldots,\Delta u(k+N-1)} \sum_{i=0}^{N-1} \left(\gamma(k+i)'Q\gamma(k+i) + \Delta u(k+i)'R\Delta u(k+i)\right) + \\ + \gamma(k+N)'Q\gamma(k+N)$$

subject to the constraints

$$u_{\min} \le u(k+i) \le u_{\max} \ , \ k = 0,\ldots,N-1$$
$$y_{m\min} \le y_m(k+i) \le y_{m\max} \ , \ k = 1,\ldots,N$$
$$y_{c\min} \le y_c(k+i) \le y_{c\max} \ , \ k = 1,\ldots,N$$

The limits u_{min}, u_{max}, y_{mmin}, y_{mmax}, y_{cmin}, y_{cmax} must be chosen to represent physical constrains on the corresponding quantities. Analogous constraints could be imposed on the increments of the control and controlled variables. Some comments are in order:

1. according to the well known *Receding* Horizon approach, at any time instant only the first value $\Delta u(k)$, of the optimal control sequence is effectively used to compute the current control signal $u(k)$.
2. The optimization problem is quadratic, so that standard and efficient methods can be used for its on-line solution even for small sampling times.
3. The solution of the optimization problem requires the knowledge of the future variations of the loads and of the DGs power variations. If these quantities are known in advance, their inclusion can significantly improve the control performances. In other cases, it is usually assumed $\Delta d(k+i)=0$, $i>0$.
4. The proposed MPC requires the knowledge of the state of the overall system. In general, this information is not available, so that a dynamic estimator must be used, such as the well known Kalman filter.

In order to test the performances of the proposed control scheme with MPC, the same experiment previously considered has been used, i.e. a step variation at $t=40s$ of the motor load. The results achieved are shown in Figures 5-6. Note that in this case an Optimal Power Flow has been used to compute one reference value for each DG power factor, while the MPC algorithm computes its transient deviations in order to improve the overall performances.

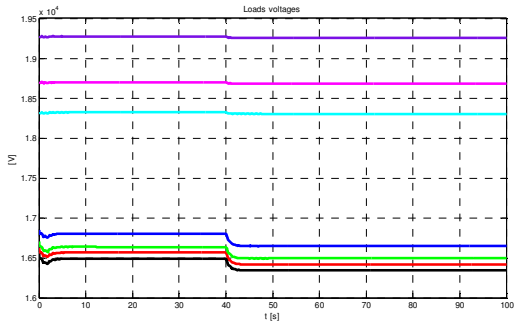

Figure 5: voltages at the loads after a step variation of the motor load at time t=40s (MPC control).

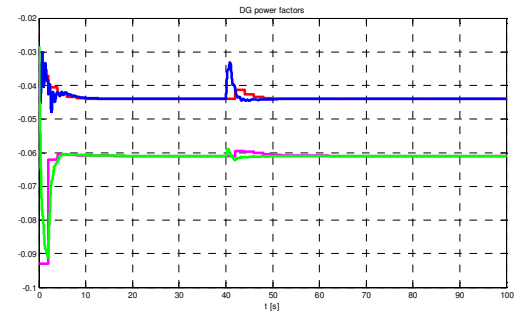

Figure 6: DGs power factors (tangent): the red and pink curves computed by MPC, the blue and green curves are the power factors controlled by the local regulators (MPC control).

REFERENCES

[1] Kiprakis A.E. and A.R. Wallace: "Hybrid control of distributed generators connected to weak rural networks to mitigate voltage variation", 17th Int. Conf. on Electricity Distribution, *CIRED*, paper n. 44, Barcelona, 2003.

[2] Viawan F.A. and D. Karlsson: "Coordinated voltage and reactive power control in the presence of distributed generation", *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, IEEE*, 2008.

[3] Vovos P.N., A.E. Kiprakis, A.R. Wallace and G.P. Harrison: "Centralized and distributed voltage control: impact on distributed generation penetration", *IEEE Trans. on Power Systems*, Vol. 22, pp. 476-483, 2007.

[4] Marconato, R., 2004, *Electric Power Systems*, CEI.

[5] Guagliardi G.A. , C. Sandroni, S. Spelta. "Il controllo della tensione nelle reti MT in presenza di generazione diffusa". *Convegno Nazionale AEIT 2011*, Milan, 27-29 June, 2011 (in Italian).

[6] Elkhatib M.E., R. El-Shatshat, M.M.A. Salama. "Nover coordinated voltage control for smart distribution networks with DG", *IEEE Trans. on Smart* Grid, Vol. 2, pp. 598-605, 2011.

[7] Skogestad S., I. Postlethwaite: *Multivariable Feedback Control*, Wiley, 1996.

[8] Camacho E., C. Bordons: *Model Predictive Control*, Springer, 2007.