DECENTRALIZED AND CENTRALIZED APPROACH IN THE ACTIVE MANAGEMENT OF DISTRIBUTION NETWORKS: A COMPARISON THROUGH BUSINESS CASES

Susanna MOCCI, Nicola NATALE, Fabrizio PILO, Simona RUGGERI
University of Cagliari – Italy
susanna.mocci@diee.unica.it, nicola.natale@diee.unica.it, pilo@diee.unica.it, simona.ruggeri@diee.unica.it

ABSTRACT

In the modern distribution systems more attention is paid to operation strategies that bridge the transition of passive into active/smart network. By exploiting the active demand, the Distribution System Operator (DSO) may reduce technical barriers to renewable integration and increase the hosting capacity of the network. If suitable control strategies are available, Active Demand provides benefits to the customers, utility, and society as a whole. In the last years the authors proposed both centralized and decentralized control systems in order to increase the hosting capacity of Smart Grids. The aim of this paper is to highlight the effectiveness of the proposed control systems, by comparing the outcomes of the centralized and the distributed approach in the active management, respectively.

INTRODUCTION

Active management enables the DSO to maximize the use of the existing networks by taking full advantage of generator dispatch, demand side integration, and system reconfiguration in an integrated manner. All these ways to control and integrate Distributed Energy Resources (DERs) affect the system operation, but they also have a significant role even in the optimal development of the system. The coordination of Active Demand (AD), included the plug-in electric vehicles, distributed generation and distribution storage devices is essential to make the distribution system capable to offer services that increase security and quality of supply of power systems, improve energy efficiency and reduce the cost for energy [1], [2]. Different methods and tools for the active management can be applied in the distribution networks: centralized or decentralized approaches are both valid options, with different actors involved [3].

In the last years the authors proposed both centralized and decentralized control systems in order to increase the hosting capacity of Smart Grids. The main distinction is where decisions are taken: the Centralized Approach implies that a Central Processing Unit, located at HV/MV or MV/LV substation level, collects all the measurement and decides next actions; the Decentralized Approach implies that advanced controllers are installed in each LV node forming a distributed control system.

In [4] a centralized DMS (Distribution Management System) for the operation of active distribution networks is developed within the framework of the ATLANTIDE project [5]-[7]. The algorithm is capable to find solutions that allow increasing the network hosting capacity and improving the efficiency of power delivery. It relieves power flow congestions at MV or LV level, improves voltage regulation and allows fast reconfiguration, by sending signals to the DER local controllers. When there are a lot of resources involved in the optimization and there is a huge amount of information to handle, the centralized control system is not a suitable solution, because it needs significant computational resources and expensive data communication infrastructure.

Moreover, active management involve the participation of demand in several ways; one of them is the direct control of loads. The direct control of demand through an intermediate player, the Aggregator, permits DSO to reduce the impact on the systems of highly demanding loads (e.g., Electric Vehicles), or not predictable small generation, and can be used by DSO as a resource for active management. At LV level, decentralized control systems have the merit to allow the operation of many small customers with a reduced information flow by exploiting local information gathered from the field with intelligent meters.

In [8], [9] authors proposed a Multi-Agent System (MAS) for the control of LV networks with active loads and EV, with a Master-Slave interaction that allows finding a global optimum without a direct control of each resource. The MAS operates without a centralized optimization system as well as the definition of network constraints that allow following specific DSO requests. The general structure of the control is based on autonomous agents that exchange information about the state of the system to develop strategies that enable the achievement of both local targets and global objectives.

The aim of this paper is to highlight the effectiveness of the proposed control systems, by comparing through business cases the outcomes of the centralized and the distributed one, respectively. The optimization algorithms proposed allow designing valid and effective demand response program, able to analyse and meet the load needs to contribute to the voltage control of the distribution network. Application examples are presented in order to illustrate the algorithm effectiveness. The operational costs of the different control strategies are evaluated and compared.

CENTRALIZED DMS (DISTRIBUTION MANAGEMENT SYSTEM)

In the centralized approach, the core of the active management is the DMS, which relieves power flow congestions at MV or LV level, improves voltage regulation, by sending signals to the DER local controllers (Fig. **1**). The DMS is based on an Optimal Power Flow (OPF) algorithm, run by the DSO in order to minimize the operational costs of the system by making all technical constraints (line thermal limits, nodal voltage, etc.) complied with.

DMS Optimization Problem

The DMS optimization function allows increasing the hosting capacity of the system with less capital expenditures (e.g., deferment of investments for the addition of a second transformer in the substation) by exploiting the opportunities from demand side integration, modifying the consumer's load to meet the network constraints. According to the main European project, the AD is expressed as a variation of load with respect to a reference profile representing the load without any participation to demand side any integration. The Objective Function (OF) to be minimised by the network operator is the sum of the costs of active management alternatives C_i (1).

$$\min J = \{\sum_i C_i = C_{losses} + C_{AD}\} \quad (1)$$

where C_{losses} is the cost of energy losses and C_{AD} is the cost of demand side integration. The cost function J is subject to power flow equations, technical and commercial constraints that can be formulated either as equality or inequality constraints. The technical constraints concern node voltages and branch power flows, and they are analysed in details in [4]-[6]. In the ATLANTIDE project the DSM model and the optimal active loads programme are evaluated with a load flow calculation with MATLAB® and OpenDSS (OpenSource Distribution System Simulator developed by EPRI) [10].

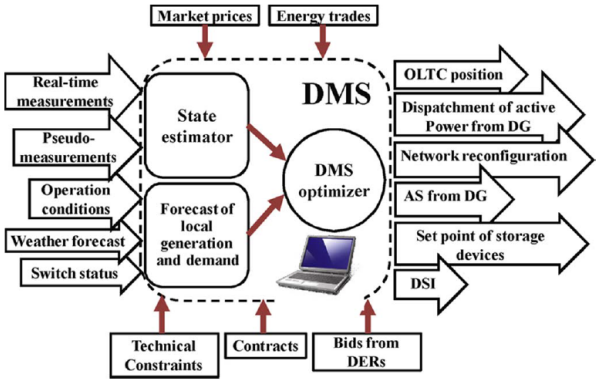

Fig. 1: DMS Centralized control.

Basing on the concept of flexibility, the DMS sends the request of AD to the final customers expressed in terms of power. Usually, the response of the loads involved in AD does not perfectly match the request because customers are free to decide if and how much contribute to the operation strategy.

Payback Effect, PB

The *payback effect* (the user to the active demand program) considers the fact that a demand modification may be followed by an opposite sign modification, and it has been properly included in both the models, centralized and decentralized.

The active demand ad is expressed as the variation of the load demand in comparison with the reference load profile, which is the scheduled power without AD, and it is representative of the involvement of the customers. In fact, the load models must include some kind of mechanism describing how ad is "transformed" into ad^{true}.

$$P_{AD}(t) = P_{sched}(t) + ad^{true}(t) \quad (2)$$

The total demand P_{AD} of each AD agent at time t is the sum of the scheduled power P_{sched} (without AD program) and the actual AD contribution of the Agent ad^{true} in the same interval, as in (2). Such a model is based on realistic considerations about the consumers' behavior: the consumers may not comply exactly with the AD programs. This results into a delayed and/or partial response with respect to the requested AD profile. If the model of the consumers' response is assumed linear and time-invariant, a simple Finite Impulse Response (FIR) model is appropriate (3).

$$ad^{true}(t) = f_0 \mathrm{ad}(t) + f_1 ad^{true}(t-1) + f_2 ad^{true}(t-2) + \mathrm{n}(t) \quad (3)$$

Where t is the time interval, *n(t)* is a zero-mean white error process, modelling the random perturbations, and f_0, f_1, f_2 are the parameters of the model, that can be interpreted as the steady-state "responsiveness" of the consumers. If f is less than 1, it means that the consumers are not fully compliant with the AD availability. Coefficients f_i (i = 0, 1, 2) take into account the customer's level of willingness to accept the request to curtail the consumption (f_0), and the effect of precedent curtailments (f_1, and f_2) that can reduce the amplitude of the true action (*payback*).

MAS FOR DEMAND SIDE INTEGRATION

MAS realize decentralized control systems in an effective way with a simple Master-Slave interaction that allows finding a global optimum without a direct control of each resource (Fig. 2). The general structure of the control is based on autonomous agents that exchange information about the state of the system to develop strategies that enable the achievement of both local targets and global objectives. The methodology consists in an iterative exchange of information between a Master Agent (MA) and Agents that control AD customers connected to the

LV network.

In the proposed MAS control system, the Agents responsible for the AD communicate directly with the MA, through a vertical communication.

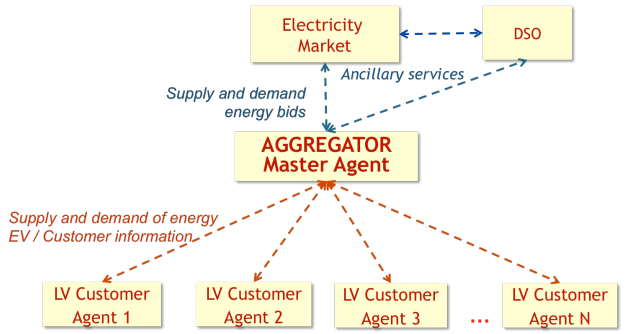

Fig. 2: MAS Decentralized control (MV/LV level).

MAS Optimization Problem

Each agent optimizes an OF using local information about its state and global information, i.e., the pricing strategy, the average behaviour of the other agents and the technical constraints. The DSI strategy is based on the virtual cost, $p(t, P_t)$, expressed by (4). The virtual cost is a linear function of the ratio between the total demand and the nominal power of the MV/LV transformer. Eq. (4) shows that the highest virtual prices are expected at peak hours.

$$p(t, P_t) = f\left(\frac{D(t) + \sum_{i=1}^{N}(P_{AD,i}(t))}{P_{tr}}\right) \quad (4)$$

$$P_t(t) = \sum_{i=1}^{N} P_{AD,i}(t) \quad (5)$$

where:

- $D(t)$ is the forecasted demand of the MV/LV transformer at time t;
- $P_{AD,i}(t)$ is the i-th AD power at time t;
- $P_t(t)$ is the total AD power of the Agents at time t;
- P_{tr} is the nominal power of the MV/LV transformer;
- t is the time interval (1 hour);
- N: AD Agents involved in the MAS control system.

The MA evaluates (4) and (5) and sends the value of the virtual cost $p(t,P_t)$ and $P_t(t)$ to Agents that execute the mono-dimensional constrained optimizations expressed in equation (6).

$$\min J_i(P_i, P_{-i}) = \sum_{t=0}^{T-1}\{p(t, P_t) \cdot P_i(t) + \delta[P_i(t) - avg(P_t)]^2\} \quad (6)$$

s. t. technical constraints

where:

$$avg(P_t) = \frac{1}{N}\sum_{i=1}^{N} P_i(t) \quad (7)$$

is the average of the power of the AD agents, and δ is a tracking parameter with non-negative constant value, which links the linear term with the quadratic one of the OF [8], [9]. A quadratic optimization function available in MATLAB Simulink has been used to perform the optimization. Since each local minimum is not a global minimum for the system, a global optimization is necessary. This result is achieved through a single-objective, non-cooperative, dynamic game, which converges to Nash equilibrium under the condition of weakly coupled Agents. The feasible set P_i that minimizes the AD agent's objective function is the best AD agent's response to the Master Agent strategy, answering to the DSO requirements.

CASE STUDY

The proposed control systems, DMS and MAS, have been applied to the radial LV network depicted in Fig. **3**, representative of urban Italian distribution networks. The test network is supplied by one MV/LV secondary substation with a 15/0.4 kV 630 kVA transformer. Six feeders, with 53 LV buses and 173 urban loads, constitute the network. Each feeder is constituted by 4 wires (neutral + 3 conductors) and the loads are both single-phase (150) and three-phase (23). There are residential loads and tertiary loads (commercial, offices, bars, garages etc.), characterized by different daily load curves. The number of residential loads that have the chance of active participation to the control is 150, with different percentages offered for varying their scheduled load demand, as described above. In the AD programs, the hourly energy price [€/kWh] is subdivided into three time bands during the day to take into account the peak and off-peak hours. The active customers, depending on their contract and according with the tariff model, offer different percentages for varying their scheduled load demand (following the ADDRESS tariff model [1]).

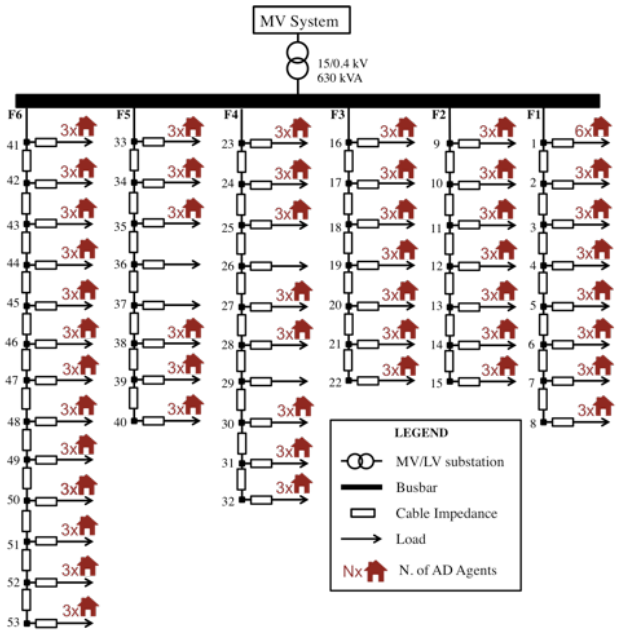

Fig. 3: LV Test network.

The average voltage threshold is required to be equal to 0.95 p.u., in order to satisfy the power quality service

imposed by DSO (ΔV_{TH} =5%). The time granularity for simulations and for the load profiles is 1 hour; the time window is 24 hours wide since all simulations are devoted to day-ahead markets.

RESULTS AND DISCUSSION

Different cases have been studied to show the DMS and MAS systems effectiveness to control loads and to achieve improvement from its usage. The results of simulations show that for the studied urban distribution system with the considered load, excessive voltage drop and overloads occur. Both methodologies performances are studied by observing the daily load curve (Fig. **4**) and the average voltage profiles in the different analysed cases. If there are no AD-based services in the distribution system, the load profile is the represented by the light blue curve in Fig. **4**., Critical feeder F3 can pose the DSO in a difficult situation, being the voltage below the contractual limits (Fig. **5**).

By considering the DMS centralized control and disregarding the payback effect (f_0 = 1.0; f_1 = 0.0; f_2 = 0.0) the Agents obtain the goal of consuming the power with a more suitable profile, with a significant improvement during the peak hours (orange line in Fig. **4**). The same result has been reached by considering the MAS control (yellow line in Fig. **4**). At the same time, voltage remains within the regulation range imposed by DSO with a positive effect in the feeder F3 (orange and yellow lines in Fig. **5**).

Nevertheless, the customer's level of participation and the PB effect should be considered for a proper estimate and comparison of both control systems when AD is considered. For this reason, the FIR model in (3) is implemented in both control systems, with AD model parameters assumed equal to: f_0 = 0.55; f_1 = 0.3; f_2 = -0.05. It can be noticed a load profile variation compared with previous cases, and a reduction of the positive effect on voltage profiles in the feeder F3 (grey and violet curves in Fig. **4** and in Fig. **5**), but the voltage still remains above the contractual limits.

The control strategies obtained through the DMS and MAS methodologies proposed allow to offer the AD-based service to the DSO.

In Table I the average annual system costs concerning the implemented control systems are reported. The cost of AD programs (following the AD tariff model) and the cost of Joule losses have been considered. Since the costs in different strategies are comparable, the DMS presents lower total costs than the decentralized MAS. On the other hand, it is important to notice that the MAS direct control considerably reduces the flow of data and information and can be better suited than centralized control systems for LV applications.

CONCLUSIONS

The paper highlights the effectiveness of two different control systems, by comparing the outcomes of the centralized and the distributed one, respectively. An intelligent and decentralized Multi-Agent System for handling AD implementation based on direct control of loads in the LV distribution networks is compared with a centralized DMS. The main distinction is where decisions are taken. The optimization algorithms proposed allow designing valid and effective demand response program, able to analyse and meet the load needs to contribute to the voltage control of the distribution network. The outcome is the difference between the solutions obtained with the two different control systems and a comparison between the system costs in both cases, with particular reference to LV systems.

ACKNOWLEDGMENTS

The work is one of the topics in the project **e-visiØn** (electric-vehicle integration for smart innovative 0-CO_2 networks), financially supported by the Sardinian Regional Government (L.R. 7/2007). Progress of this project can be found at http://evision.diee.unica.it.

REFERENCES

[1] ADDRESS Project. [Online]. Available: http://www.addressfp7.org

[2] E. Peeters, D. Six, et Al., 2009, "The ADDRESS Project: An Architecture and Markets to Enable Active Demand", *Proceedings 6th International Conference EEM 2009*, 27-29 May 2009.

[3] "Planning and Optimization Methods for Active Distribution Systems", *CIGRÈ Technical Brochure 591*, 2014Working Group C6.19. 2014.

[4] F. Pilo, G. Pisano, G. G. Soma, "Optimal Coordination of Energy Resources with a Two-stage on-line Active Management", *IEEE Trans. on Industrial Electronics*, Oct 2011, vol. 58, n. 10.

[5] ATLANTIDE Project [Online]. Available: www.progettoatlantide.it

[6] F. Pilo, G. Pisano, S. Ruggeri et al., "Active Management of Distribution Networks with the ATLANTIDE models", *Proceedings MEDPOWER 2012*, Cagliari, 1-3 Oct 2012.

[7] A. Bracale, R. Caldon, M. Coppo, et al., 2013, "Applications of DMS in the ATLANTIDE Project: models and tools", *Proceedings CIRED Conference*, Stockholm, 10-13 June 2013.

[8] S. Mocci, N. Natale, S. Ruggeri, F. Pilo, 2014, "Multi-Agent Control System for increasing hosting capacity in Active Distribution Networks with EV", *Proceedings IEEE Energycon Conference*, Dubrovnik, 13-16 May 2014.

[9] S. Mocci, N. Natale, S. Ruggeri, F. Pilo, 2014, "Multi-Agent Control System to Coordinate Optimal

Demand Response Actions in Active Distribution Networks", *Proceedings MEDPOWER 2014*, Athens, 2-5 November 2014.

[10] Available on: http://sourceforge.net/projects/electricdss

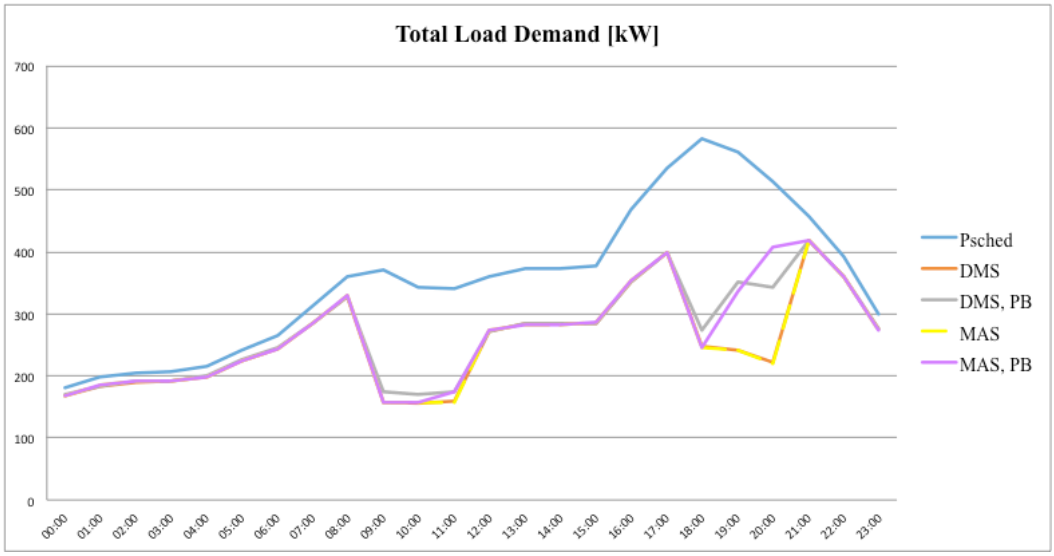

Fig. 4: Load profiles in the test network.

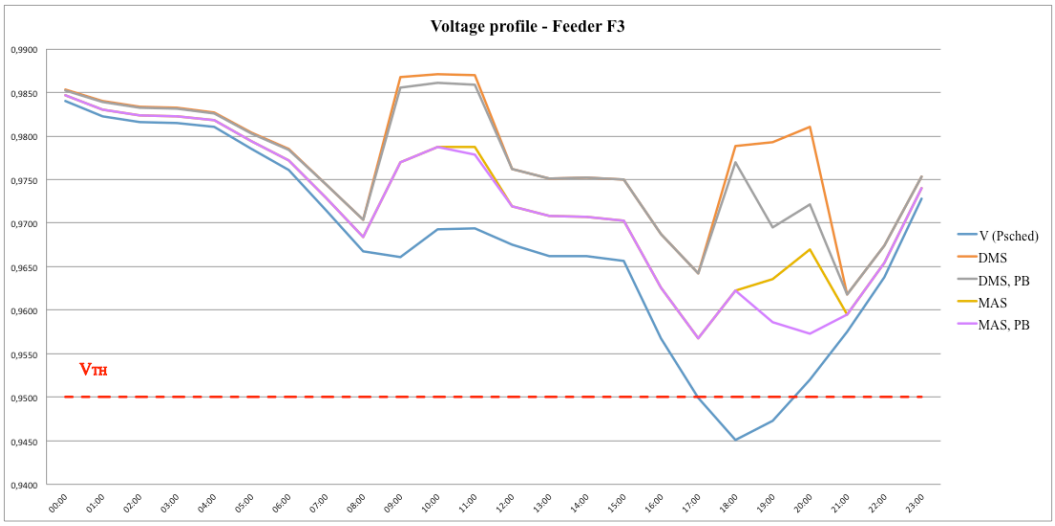

Fig. 5: Average Voltage Profiles in Feeder F3.

Table I. Evaluation of average annual costs in the different implemented control systems [€/year].

Costs	Control System			
	DMS	**DMS, PB**	**MAS**	**MAS, PB**
AD program	€ 28.548,92	€ 24.411,44	€ 28.563,72	€ 24.582,73
Joule Losses	€ 844,43	€ 912,83	€ 1.583,09	€ 1.619,04
Total cost	**€ 29.393,35**	**€ 25.324,28**	**€ 30.146,81**	**€ 26.201,77**