Decentralized Distribution System Operation Techniques: Results from the Meltemi Community Smart Grids Pilot Site

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ABSTRACT

In this paper, results from the testing procedures of the decentralized techniques developed within the FP7 project DREAM are presented. The techniques are developed for the decentralized distribution system operation. More specifically, for the settlement of short-term energy imbalances at the distribution level in an intra-day market based procedure, the mitigation of voltage deviations and congestion management in the real-time operation domain. The demonstrations were performed in the Meltemi community smart grid pilot site.

INTRODUCTION

The future Distribution Grid is envisioned capable of managing efficiently the new energy profiles and simultaneously accommodating different types of users and DERs. In this direction, the Smart Grid paradigm can break new ground delivering the flexibility from DERs and active customers in order to locally address the newly raised problems introduced by the high penetration of intermittent power sources into their grids. In order to reduce the complexity of the optimization problem and avoid centralized data collection and processing, the decentralized control scheme is adopted and evaluated. In a decentralized architecture, the intelligence is dispersed in the various active components of the grid solving the problems that arise locally, where possible, as well as increasing the robustness of the coordination algorithms in case of telecommunication failures. The tests were conducted in the Meltemi Community Smart Grids Pilot Site, part of the European FP7 DREAM project demonstration sites.

PREPARATION OF THE TEST SITE

Meltemi: a smart grids pilot site

Meltemi is a seaside holiday camp near Rafina, a town located on the eastern coast of Attica in Greece. The settlement comprises a number of holiday cottages which are fully inhabited in the summer (from May to September) and mostly empty in winter. The field site presents certain functionalities making it ideal for testing scenarios related to real-time operation, critical and emergency situations of the power grid.

Development of distributed algorithms

The developed decentralized techniques are based on distributed optimization algorithms that are employed to solve resource allocation problems. For each tested functionality, the corresponding optimization problem is formulated and solved in a decentralized manner, i.e.: requiring only peer-to-peer exchange of information. More specifically, the algorithms are adapted to the needs of the pilot site and handle a variety of test scenarios such as: energy imbalances at the distribution level, voltage deviation mitigation and congestion management. The resource that is used to cope with the aforementioned problems is the end-users' active power flexibility, that is introduced in a market based context. More details for the developed techniques and Multi-Agent platform can be found in [1]. In Figure 1, the tested communication topology of the houses that participate in the tests is presented. The total consumption of the settlement is measured from the single MV/LV transformer that is feeding it (shown in Figure 1 with a blue square).

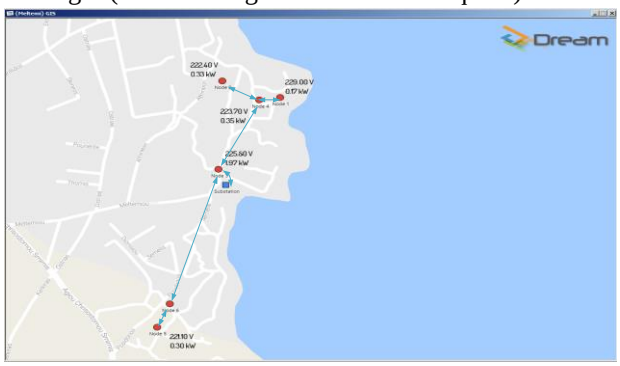

Figure 1 – Households equipped with MAGIC controllers and the P2P communication network topology.

The Intelligent Load Controller

The core of the demonstration activities is the communicating intelligent load controller (MAGIC -

Microgrid AGent Intelligent Control) that accommodates the end-users' flexibility mediating for the support of the grid's operation. The flexibility essentially constitutes the possibility and willingness of the grid users to alter their consumption, in order to participate in the optimization of the grid operation. For the test procedures, 6 households were equipped with controllers (Figure 1), which measure the households' consumption and control their flexible loads taking into account the goals set by their owners. A detailed description of the MAGIC controller can be found in [2]. The controller connects with the Wi-Fi router that is installed in the customers' premises corresponding to the internet gateway. A Virtual Private Network (VPN) is then used to enable the peer-to-peer connectivity of the neighboring houses as well as handle cyber security and privacy issues.

Monitoring of the substation and the households

The DSO agent, responsible for monitoring of the total consumption of the substation and for the provision of the imbalance signals is executed in the Advanced RTU (model: SM_CPU886e) provided by Schneider Electric. In Figure 2, a screenshot of the Human Machine Interface (HMI) of the Advanced RTU, developed by Schneider Electric is shown.

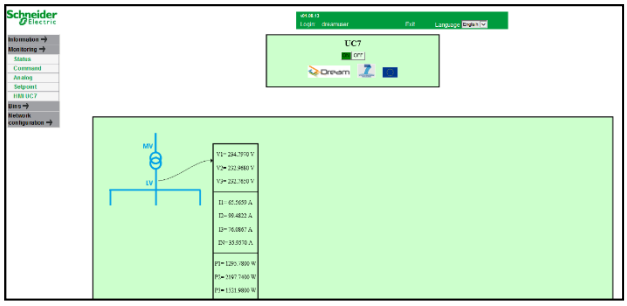

Figure 2 – The web HMI deployed in the ARTU in Meltemi substation.

In the following figure, the monitoring dashboard of the SCADA of the Meltemi settlement is given (implemented in the NTUA laboratory), that presents real-time measurements from the households' consumption and voltage profiles.

Figure 3 – The real-time monitoring dashboard of the houses.

Mapping of the customers' flexibility

In order to model the customer's willingness to alter his consumption profile in a simplified way, the value of a parameter corresponding to the impact of activating his flexibility is set. The distributed optimization technique could aim at the least discomforting decision for all the customers that took part in the tests. The three levels of load shedding priorities that the customers can choose from are shown in Table 1.

Table 1 – Classification of load shedding priorities

User Defined Priority:	Interpretation by the algorithm:
High	The load should not be shed except in case of grid emergency.
Medium	The load could be shed in case that lower priority loads are not sufficient to solve the problem.
Low	The load can be shed in order to facilitate the energy balancing of the grid.

In the next table, the types of controllable loads are given along with their available active power flexibility, for each house that participated in the tests.

Table 2 – Type of loads and amount of flexibility per household

Number of Household	Type of controllable load	Active Power Flexibility (kW)
1	Water Heater Oven	2 2.5
2	Water Heater	2
3	A/C	3
4	Water Heater	2
5	Water Heater	2.5
6	Water Heater	2

TESTING OF THE DECENTRALIZED COORDINATION ALGORITHMS

The distributed resource allocation problems that were formulated and tested, integrate the grid and end-user constraints while simultaneously minimize the total cost of the procedure. The procedure must be performed in an economically efficient way since all the participating prosumers are assumed to be reimbursed for their contribution to solve the problem of the grid depending on their willingness to alter their loads. The solution is calculated using distributed constrained optimization techniques that enable the problem to be optimally solved in a distributed manner [1]. Voltage control and congestion management are handled using the same idea,

by appropriately adjusting the active power of the controllable loads. The applicability and efficiency of the developed decentralized techniques is evaluated through the various testing scenarios conducted in Meltemi field site.

Short-term imbalances settlement

The short-term energy imbalance settlement algorithm, assumes inputs of a 24-hour load curve corresponding to the day before scheduling and the short-term load and RES production prediction (i.e. for the following hour). The triggering event is a deviation from the initially scheduled aggregated demand curve. In order to activate the algorithm and proceed with the tests, the triggering is provided manually by assuming a deviation that would trigger the algorithm. Hence, the DSO actor (i.e. the agent corresponding to the DSO, that is located in the substation's RTU) informs the customer agents (at least one of them), to proceed to a reduction of power in the corresponding time-frame following their declared flexibilities. The declared flexibilities of the customers are presented in Figure 4. The participating entities negotiate next, in order to arrive at an agreement regarding the amount of power to be altered, along with their respective reimbursement. The first campaign of tests started in the summer months (June-July and August) when the residents were more likely to be in their houses. For two timeslots that the algorithm was in operation and specifically for the hours 06.00 PM – 7 PM and 10.00 AM – 11.00 AM an imbalance was assumed of 9.0kW and 12.0kW respectively. The triggering was provided by the coordinator to settle the imbalance and the negotiation provided the schedule for the next hour of operation for each participating customer. The rule based upon the load controllers decide whether to curtail their loads or not, is when the decision variable (calculated in a distributed manner) converges to a value greater than a predefined limit. The algorithm terminates when convergence is detected, meaning that all agents reach the same value in the synchronization signal. In Figure 6, the results for the two timeslots are presented. The active power flexibility that was used is shown in Figure 5.

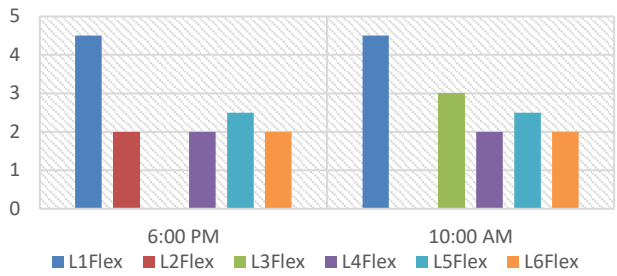

Figure 4 – Available flexibility per customer for the two timeslots

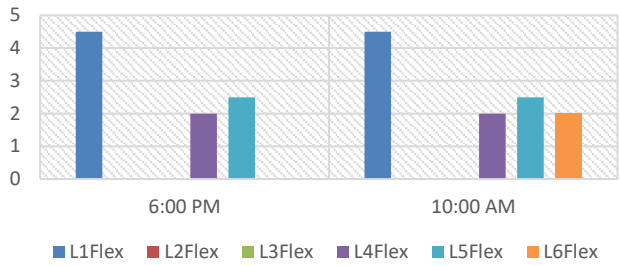

Figure 5 – Flexibility that was finally activated by the algorithm

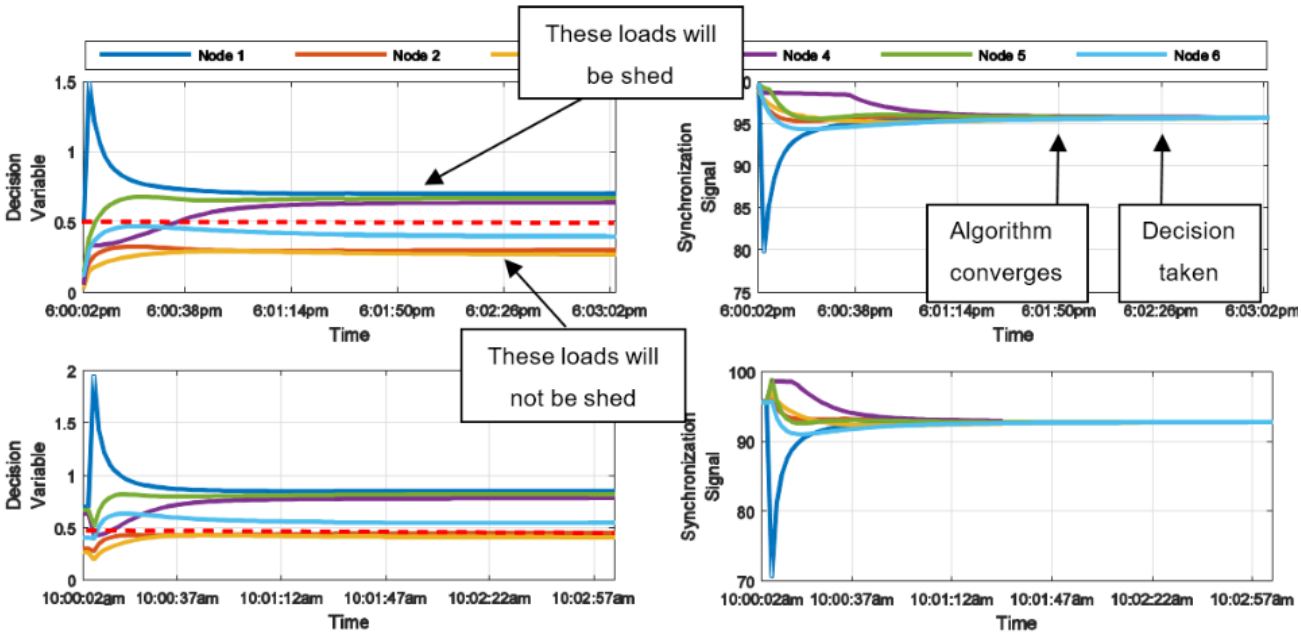

Figure 6 – Results of the distributed optimization algorithm for the application of Short term imbalance settlement algorithm

Decentralized Voltage control

The algorithm for decentralized voltage control allocates the amount of active power to be altered per participating entity in order to cope with voltage violations. In this case, the voltage margin of node 5 is violated, an event that triggers the voltage control algorithm. The distributed algorithm is triggered having as inputs the available flexibility per household and their voltage sensitivities and iterates exchanging peer-to-peer messages, until convergence is reached (Figure 7). The decision whether to curtail or not each controllable load is taken as in the previous case, if the corresponding decision variable of each controller exceeds a certain threshold. The algorithm is terminated when the synchronization signals of all participating agents converge to the same value.

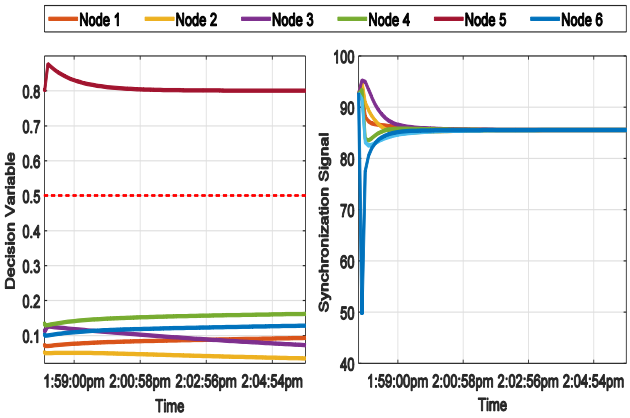

Figure 7 – Distributed solution of the voltage control problem

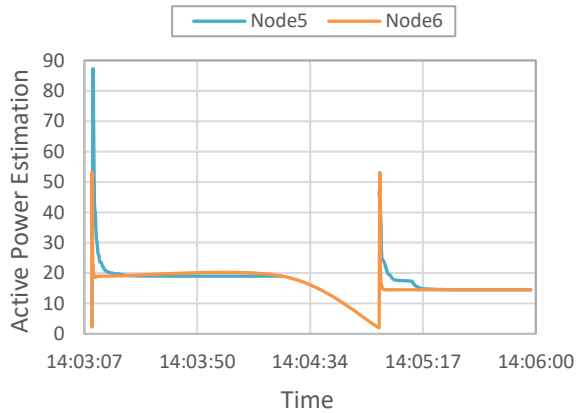

Figure 8 – Gossiping to address voltage violation among nodes 5 and 6

For illustration purposes, we are showing also a second instance (Figure 8) when node 5 detects a voltage violation. However, the available flexibility within node 5 is not enough and therefore the available flexibility in node 6 is exploited. It should be noted here that there was also available flexibility at node 1, which has not been used, since the utility function associating this flexibility to voltage violation in node 5 expresses also the efficiency of this measure. Thus, node 1 is very loosely correlated to voltage deviation of node 5 due to the grid topology. The active power flexibility that was finally used is shown in Figure 9.

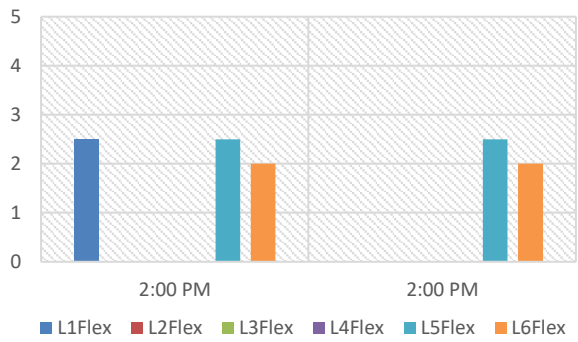

Figure 9 – Available flexibility (in kW) during the illustrative voltage control and the flexibility exploited (left and right figure respectively)

Decentralized Congestion Management

Congestion management copes with situations where the electricity supply exceeds the available capacity of the grid regarding a specific part of the grid. The excess active power is curtailed in order to resolve the congestion. The goal of the developed algorithm is to optimally allocate the amounts of active power to be altered per prosumer, taking into account the priority of the loads and their flexibility. A set of scenarios has been deployed, in which the substation has been assumed to be congested, in a sense that the aggregated net demand of the prosumers in a specific timeslot is larger than the thermal limit of the substation. The households are participating in the congestion management scenario by offering their available active power flexibility. First of all, they participate in gossiping to obtain a global consensus regarding the total active power. This means, that after a certain number of rounds they are acknowledging the trespassing of the thermal threshold and they trigger iteratively the shedding according to their flexibility on their own. An indicative snapshot of the results of the distributed algorithm is shown in Figure 10 where the nodes estimate the excess power in kW in the congested substation. The specific moment has been captured during the first campaign of tests. After few seconds (~80 sec) and two triggers of the algorithm all the households confirm that the algorithm has converged in the final solution. In a busy evening (at 20:50), the total active power flexibility among the households was 9.5 kW. While several households where using their flexible loads at the time, as shown in Figure 11, the final decision for curtailment included only a subset of those, according to the goals that were set by the customers.

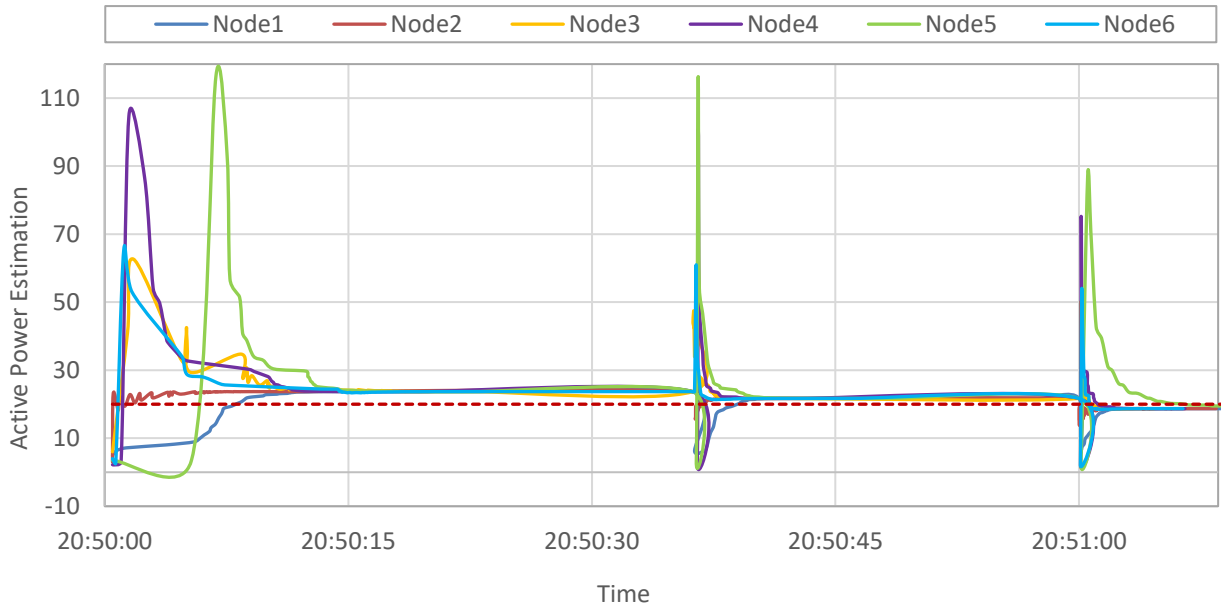

Figure 10 – Congestion management via gossiping

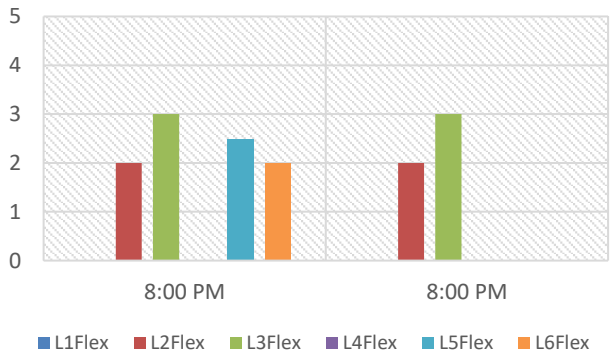

Figure 11 – Available flexibility (left subfigure) during the illustrative congestion management scenario and the flexibility exploited (right subfigure)

CONCLUSIONS

A number of conclusion are drawn from the testing scenarios conducted in Meltemi pilot site. The advantages of the decentralized architecture were highlighted, such as the easy deployment and scalability (plug and play capability). The Java based implementation of the MAS platform simplified the interoperability of the different systems. Another issue was the communication availability, which was proven to play a significant role during the tests. Especially, non-availability of a number of controllers (suppose they are not reachable) has caused several problems and delays. The communication speed has not considerably affected the convergence of the distributed algorithms. To sum up, the demonstrations showed that even though a small number of houses participated in the experiments, the algorithms were in most cases able to fulfill satisfactorily the objectives set by the distribution grid. In order to draw definite conclusions for a large-scale implementation of the tested algorithms however, experiments with a bigger sample of intelligent load controllers and participating households should be performed.

ACKNOWLEDGMENTS

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