OVERVIEW OF DECENTRALIZED DISTRIBUTION SYSTEM OPERATION TECHNIQUES

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ABSTRACT

The scope of this paper is the provision of an overview of the decentralized techniques for the operation of the distribution grid that are developed within the FP7 project DREAM. The solution provided is threefold and copes with the energy imbalances at the distribution level in an intra-day market based procedure, voltage deviation mitigation and congestion management in the real-time operation of the distribution grid. Moreover, the use cases are integrated in a general unified architecture, the DREAM platform, as components of a multi-agent system.

INTRODUCTION

The Smart Grid paradigm leads the way towards active, flexible and self-healing distribution systems. The DSOs exploit the hidden flexibilities of intermittent power sources and end-users, not only to fulfil TSOs' requirements but also to address locally the newly raised problems introduced by the higher penetration of renewables into their grid [1]. The DREAM project contributes in this direction, developing an innovative solution that allows the increased penetration of distributed energy resources (DERs), through an active distribution system management and having as a concrete goal to deliver sustainable, economic and secure electricity to the end-user. The proposed integrated architecture establishes marketplaces at the distribution level of the power system in different timeframes, i.e. the day ahead market that copes with the larger quantity of electricity trading and the hour ahead balancing market that handles deviations near the real-time operation. Furthermore, real-time constraint violations that may occur unexpectedly, are solved primarily locally based on the concept of traded customer flexibility, while in cases of emergency, the DSO is able to take additional measures in a centralized way. The technical solution uses decentralized agent-based systems (MAS), implementing algorithms for each function as described above, in order to ensure the optimized and stable operation of the distribution grid.

DECENTRALIZED COORDINATION

The decentralized control scheme, derives from the necessity to disperse the intelligence of the various controllable entities of the power grid in order to reduce the complexity of the optimization of the operation of the distribution system. Thus, a central data fusion center is no longer required and the robustness of the grid is increased since the control decisions are calculated using local interactions following strategies that lead to globally optimal solutions. The motivation for such a scope for the grid operation has numerous advantages such as avoidance of the single point-of-failure, reduced computation and communication cost, privacy of the end-user, and most importantly scalability ("Plug-and-Play" capability).

The MAS Architecture

The scope of the implemented MAS is to accommodate the end-users' flexibility facilitating their participation in the hour ahead balancing market and supporting the real-time operation of distribution grids. The traded flexibility constitutes the willingness of the grid users to alter both the timing and/or quantity of their consumption or production of electricity and at the same be reimbursed for those actions for the ancillary services provision at the distribution level. The end-users of the distribution grid are assumed to be equipped with Intelligent Electronic Devices (IEDs) that have the capability to monitor and control the power consumption of loads and generation of the distributed generation units. Another actor that is involved in the DREAM marketplaces, apart from the prosumer and DSO actors, is the aggregator entity that has as an objective to aggregate grid users and trade energy and flexibility, either for imbalances settlement in the hour ahead domain, or in the real-time relief of constraint violation. The DSO and the aggregators are respectively equipped with IEDs that interact in various coordination

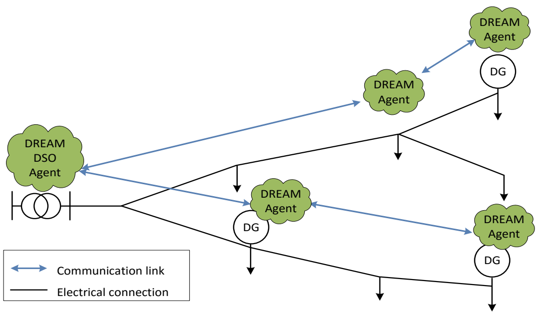

Figure 1 – The proposed architecture, communicating agents control DGs and controllable loads.

schemes depending on the severity of the problem that is handled at the time, as discussed previously. In the general case and especially in “normal” or near “normal” operating states, decentralized coordination is employed. This way, the grid is driven to a more self-organized structure, where every entity actively participates in the global optimization of the grid operation and simultaneously takes into account the grid constraints, as they are posed by the operator. In order to achieve the decentralized coordination scheme, distributed optimization techniques are used to solve the imbalances and the violations that demand only local interaction between the participating entities. In Fig. 1, the MAS infrastructure is presented in a sample distribution feeder.

DECENTRALIZED SOLUTIONS FOR GRID MANAGEMENT

The applications presented in this paper are formulated as distributed resource allocation problems incorporating all the grid and end-user constraints and at the same time minimizing the total cost of the operation. The applicability and efficiency of the distributed algorithms presented is evaluated through simulations in a part of the Greek distribution system, in the Meltemi Smart Grid pilot site that constitutes a demonstration site for DREAM project. The controllable DG units and loads are assumed to be equipped with intelligent controllers that communicate through a Power Line Communication (PLC) infrastructure in a peer-to-peer scheme.

<u>Short-term imbalances settlement</u>

The Short-term scheduling is integrated in the balancing market. As presented in Fig.2, the algorithm is based on the idea that it is possible to aggregate distributed energy resources and provide flexibility to the DSO according to economic incentives, in order to compensate short-term power imbalances.

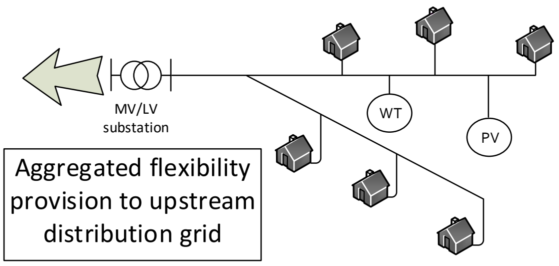

Figure 2 – Aggregation of loads and generation in order to provide ancillary services to the DSO.

The short-term energy balance procedure assumes inputs of a 24-hour load curve corresponding to the day before scheduling (produced from a long-term forecast functionality, possibly from the DMS) and short-term load and RES production prediction, e.g. for the following hour that a more accurate forecast is available. As depicted in Fig. 3, the triggering event of the algorithm is a deviation from the initially scheduled aggregated demand curve. The DSO informs a number of aggregators and/or LV/MV customers (at least one is enough for the distributed negotiation to initiate), to proceed to a reduction/increase of power in the corresponding time-frame following their declared flexibilities. The participating entities negotiate next, in order to arrive to an agreement regarding the amount of power to be altered, along with their respective reimbursement. The solution is calculated using distributed constrained optimization techniques that enable the problem to be solved in a distributed manner with optimality guarantees [2]. The proposed method is scalable and fully decentralized.

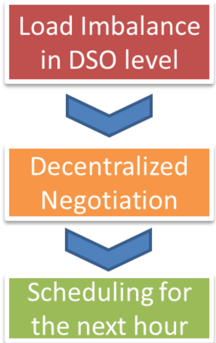

Figure 3 – Flow chart of the Short-term imbalance algorithm.

In more detail, each node is assumed to exchange only locally available information in turns with its neighbouring nodes, it processes the available and received information to converge on a consensus estimate of a global state variable and finally a decision is taken, that solves the problem of deviation between scheduled net demand and the current demand. The application of gossip algorithms assumes the implementation of peer-to-peer communications over the existing telecommunication infrastructure as an overlay network [2]. Gossip algorithms constitute a large family of distributed algorithms that are mainly used for information dissemination. During each round, every node selects and contacts one or more of its neighbouring nodes and exchanges information with them. Before the beginning of the next round, the information is processed locally and enhanced with local measurements to create the estimate of information to be exchanged.

Simulation Results

In our application, each node having an internal information (e.g. apparent power), tries to calculate, as fast as possible, a good estimate of a global variable (e.g. nodal voltage) by a function of interest via a gossip algorithm. The algorithm takes into account a scheduled profile for net demand (demand minus production) within a grid section for a few hours ahead. For every hour, each node participates in gossiping to calculate the total demand and total production from DGs within this grid section. Thus, the aggregated net demand is known to every node along with the information on possible deviation. If there is an excess in DER generation, each prosumer decides on its own to provide production curtailment for the next few hours to alleviate the deviation. The curtailment is proportional to the generated power. If there is an excess in consumption, each prosumer with demand decides to participate in a bidding round by transmitting to its peers its internal price for the demand curtailment, based on its only locally known utility function. The gossiping function contains a subset of other procedures and needs a set of rounds to converge to the desired values. In the following figure, the deviations and their solution are illustrated. There is a deviation between 10.00 and 14.00 (excess in consumption) and between 18.00 and 21.00 (excess in production).

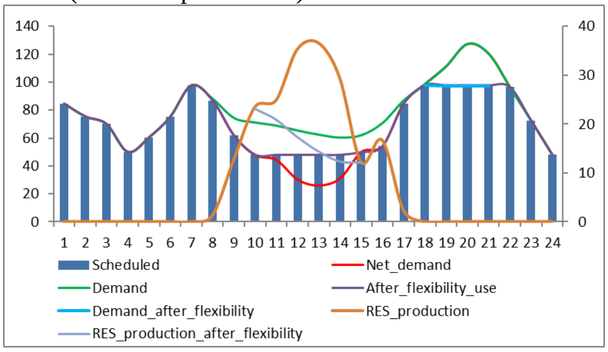

Figure 4 - Inputs and results of the sort-term scheduling algorithm.

For example, at 10.00 am there is the first deviation, which is addressed as a production excess deviation. Every node of the grid participates in the gossiping to determine the problem and the deviation that should be allocated among the generating prosumers.

Decentralized Voltage control

Voltage control is handled in the same way by appropriately adjusting the active power of the controllable entities. This function is performed in an economically efficient way, since all participating prosumers are assumed to be reimbursed for their contribution to solve the problem of the grid. The developed algorithm allocates the amounts of active power to be altered per participating entity. The basic gossip algorithm for calculation of summation includes local exchange of information between neighbouring nodes of the grid, which elaborate the received information in an appropriate manner before sending it again in the next gossip round to their neighbours. The convergence into a global variable is ensured and accelerated by the appropriate selection of the weights' matrix [2]. The algorithm utilizes a gossiping method, in order to calculate in a distributed manner all the necessary information and moreover to communicate parameters and decisions to all participating nodes. The basic gossip algorithm has been used to calculate periodically the nodal voltage as an aggregate of the active and reactive power injections of the neighbouring nodes, by using the following linearized power flow equation:

$$V_i = V_{feeder} - \sum_{j=1}^{n} z_{ij} \cdot \frac{S_j^*}{\left(V_j^{t_0}\right)^*},$$

where S_j is the apparent power injection in node j.

The following procedure is performed by each node that participates in negotiation periodically and is triggered in cases of voltage violation detection.

- Each node calculates periodically V_i using as an update function within gossiping the linearized power flow equation.
- If V_i of some node is found to be out of limits, each node calculates $(V_i - V_{limit})$ and $max(\Delta V)$ is calculated through gossiping.
- The active power injection sensitivity factors corresponding to the common path are then used, so as every node having a common path with the one having the $max(\Delta V)$ (let it be the node j) calculates the appropriate curtailment as $\Delta P_i = \max(\Delta V) \cdot {z_{ij}}^{-1}$.
- $max\ (\Delta P)$ is calculated through gossiping.
- The node with the $max(\Delta P)$ curtails the excess P, without violating its internal restrictions $(P - \Delta P > P_{min})$.
- If the voltage problem is not solved the algorithm iterates through the previous steps until the voltage of all nodes lies within limits.

Simulation Results

The algorithm is simulated in the Meltemi test distribution network. The loads and the DERs are appropriately modified in order to technically cause voltage problems. The algorithm is triggered and all participating nodes that have detected the problem negotiate, in order to calculate the active power curtailment. The threshold for voltage violation is assumed lower than the normal limits defined in EN50160. This way, a preventive control scheme is applied, so that nodal voltages are maintained into a

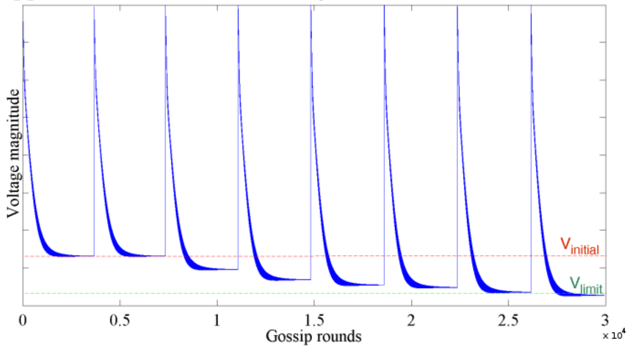

Figure 5 - Convergence of the gossiping algorithm for Voltage Control

narrower band. In Fig. 5, iterative runs of the algorithm calculating the voltage of a specific node are presented along with the voltage violation mitigation.

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. This process should be performed in an economically efficient way, since all participating prosumers are assumed to be reimbursed for their contribution to solve the problem. The goal of the developed algorithm is to optimally allocate the amounts of active power to be altered per prosumer. The negotiation is performed between the prosumers in a distributed communication scheme and without the need of a centralized coordination entity. This problem can be cast as a distributed resource allocation problem, since it allocates active power among the participating entities aiming to minimize the total cost of this operation. At this point, it should be clarified that there are two different possibilities that require the curtailment of active power in a distribution grid. In the first case, the demand is higher than the system is able to supply (downstream active power flow), while in the second, the production of distributed generation exceeds the capacity of the upstream active power flow for specific parts of the grid. The aforementioned parts can be either a distribution line or a distribution transformer or a feeder. The algorithm minimizes the total cost of the power to be altered and hence the objective function of the problem is given by:

$$\min C_{total}(\boldsymbol{p}) = \min \sum_{i \in V} C_i(p_i)$$

Subject to:

$$P_{total} = \sum_{i \in V} p_i$$

Where P_{total} denotes the total active power to be altered, p_i the power of customer i, $C_i(p_i)$ is the cost function corresponding to the financial reimbursement of the customer for curtailing load or production respectively and $V = \{1, \dots, N_{nodes}\}$ defines the set containing the participating nodes. The active power to be altered by each node is within predetermined limits according to the end-user's objectives and ability to alter its electricity usage. In order to solve the distributed resource allocation problem, the distributed method presented in [3] is implemented.

Simulation Results

The algorithm is simulated in the same distribution network as in the previous case and the single MV/LV substation feeding the test site is assumed congested. More specifically, the DSO triggers the algorithm requesting the curtailment of 1kW of renewable generation. In this simplified scenario, 5 DG units are participating in the negotiation calculating in a distributed way the active power curtailment of each one, in order to minimize the cost of the total curtailment. In Fig. 6 the results of the algorithm are presented. After the trigger (at iteration 0, with a random initialization), a number of iterations are performed. At each iteration peer-to-peer messages are exchanged and local computations are executed. Eventually, the convergence to the optimal solution is reached (optimizing the given cost function of each node). Afterwards, each node performs the curtailment and the congestion is resolved.

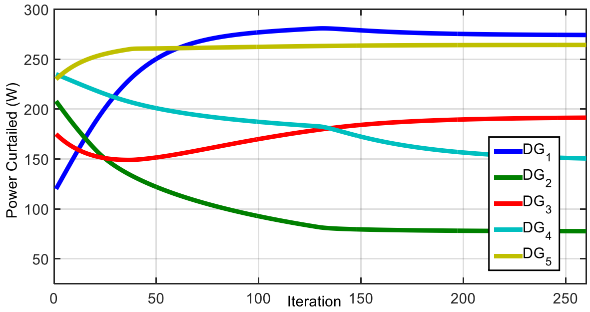

Figure 6 – Optimal active power curtailment scenario for the real-time congestion management algorithm.

CONLCUSIONS

In the context of transitioning to a more active management scheme for the distribution network, decentralized ICT-based coordination techniques provide a number of advantages. Three techniques for decentralized system operation are presented in this paper. Results are given from simulation scenarios in the distribution grid of the Meltemi demonstration site, part of the Greek distribution system, that show the effectiveness of the proposed solutions.

ACKNOWLEDGMENTS

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