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Activate Distributed Energy Resources' Services: Hierarchical Voltage Controller as an Application

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Abstract—The flexibilities from controllable distributed energy resources (DERs) offer the opportunities to mitigate some of the operation problems in the power distribution grid. The provision of system services requires the aggregation and coordination of their flexibilities, in order to obtain the flexible capacity of large scale. In this paper, a hierarchical controller is presented to activate the aggregation, and tries to obtain a global optimum of the grid operation. A distribution grid with large penetration of highly varying generation or load is under the risk that the voltage quality delivered to the end users is very poor. Hence, a coordinated voltage control function is investigated given such control hierarchy utilizing the flexibilities from the DER units to obtain an optimal voltage profile along the distribution feeder. The results are two folded: the controller enables the efficient aggregation and dispatch, and it simplifies the optimization complexity; the involvement of DER flexibilities in voltage services can significantly improve the voltage quality and reduce the grid power loss without additional regulating devices.

Index Terms—voltage control, distributed energy resources, flexibility, aggregation

I. INTRODUCTION

The environmental concerns, the trend of market deregulation, and the requirement of sustainability and security, are driving the large integration of renewables (e.g. wind power plants) and distributed energy resources (DERs), including photovoltaic (PV), electric vehicles (EVs), and the controllable house appliances in Denmark and other European countries [1] [2]. Take PV as an example: according to [3], the annual growth of the grid connected PV is about 120% in 2011 in Denmark, and the annual increase of installed PV in Germany is around 7.5 GW. The introduction of PV plants in the grid may cause problems like overloading of network equipment and voltage rise. Challenges introduced in the distribution grid, such as new load patterns, distributed generations with fluctuating features, and more requirement (e.g., regulating power to balance the wind production) from the transmission system operator (TSO), make it more complex to operate the distribution grid. However, the controllable DER units could provide the flexibilities to face the aforementioned challenges without investing much on the extra regulating equipment (e.g., online tap changer) in the medium and low voltage grids. A smart grid strategy has been made in Denmark [4], in which DERs are anticipated to play major roles in the future grid by providing system services.

Different kinds of DER units have different characteristics and constraints. To contribute to the system services, the units

are required to be coordinated under a control scheme to scale up the amount of power and energy. Several studies have been focused on obtaining system services using the flexibility from DER units [5] and controllability from regulating devices (e.g., compensators and online tap changers) [6]. Significant changes of voltage profiles are observed when new load patterns and distributed generation units are introduced in the grid, which violate the power quality promised by the distribution system operator (DSO) [7].

To solve such problems, different types of local droop control of PV inverters to optimize the voltage profiles based on the linear relation between voltage and power at normal operating point are introduced in [5]. Compared to a distributed control approach in [5], a hierarchical control system make it easier to find a global optimum while updating the grid operation states. Intelligent controllers in the hierarchy deconstruct the optimization problem, which decreases the computational complexity of individual controllers. [8] presents a centralized control scheme, in which all the information from the DERs is interpreted in the control center. Due to the existence of a single entity that is required to gather and analyse data from all DERs, find global optimal solution, and dispatch control signals to all units, the scalability is limited in this set-up.

Thus, we propose a hierarchical voltage controller, in which the information from the DER units is aggregated in each level of the hierarchy, and generic information structures are used to achieve a flexible and extendible architecture. The grid voltage quality, the DERs' capabilities to provide flexibilities, and the efficient grid operation are considered in the optimal control algorithm proposed in this paper. The work presented in this paper is a continuation of work described in [9]. It introduces how the aggregation is built and proposes an underlying algorithm to determine the roles and compose the aggregation. The presented infrastructure focuses on resiliency, reliability, flexibility and fault tolerance of the aggregation, transparently managing addition, removal, failure and reorganisation of units. Once the aggregation is composed and maintained, the control mechanism is activated to deal with the aggregation operation. This paper explains the control structure and how an application (in this paper, voltage control) is managed on the different levels of hierarchy.

The remainder of the paper is structured as follows. Section II describes the composition of the control system. Section III presents the how the voltage control is formulated in

the proposed control hierarchy. It is followed by section IV, containing some simulation results and analyses. The paper is concluded in section V.

II. HIERARCHICAL CONTROL SYSTEM

In this paper, a portfolio of DERs are considered to provide flexibilities by curtailing or stimulating their power consumption or production (active power P and reactive power Q). The controllers of DER units contain two separate modules: *Service Provision Module* that executes the services and functions, and *Hierarchy builder module* that builds up the flexible aggregation hierarchy and decides the roles [9]. Location, DER types, and other DER properties can index the classification or the aggregation of units. Thereby, Each unit is dynamically assigned to one of the local controllers (LCs), which is the first level controller in the hierarchy. Furthermore, the LCs are aggregated into the second level by the supervisory controllers (SCs). The aggregation hierarchy can be extended as required by the system scale. For example, if the location is the index and the highest level aggregation is allocated at the HV/MV substation, a four-level hierarchy can be built: the first level controller is at the point of common coupling; the second level controller is at the MV/LV substation; the third level controller is in charge of a zone in MV grid, and the highest level controller aggregate all the zones together. Fig. 1 shows the structure of a two-level controller.

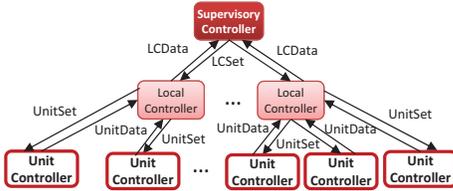


Fig. 1: Sketch map of a hierarchical controller

A. Roles in the control system and their functions

1) *Unit Controller*: UC's main responsibility is to represent a DER to a LC, provide interfaces, and enable DER state acquisition, so the DER behaviour can be alternated. UC interfaces the capabilities of different DER types into a generic format that can be aggregated afterwards. UC estimates DER's behaviour and operating plan based on the embedded unit model and the measured data. This estimation is sent to LC upon request, and it is used to plan the operation of the local aggregation. It receives the dispatch commands from the higher level controller (i.e., LC). To connect the real world with the control system, UC enables an aggregation friendly plug-in of different types of DERs, providing interfaces for control and unit state collection.

2) *Local Controller*: In the presented hierarchy, LC is a middle level controller, serving as a primary aggregator. The main functions are to exchange the data with SC and UC, and control the local aggregation based on signals received from the SC and the internal approaches. This role can

release both the computational (i.e., part of the calculation is undertaken locally) and the communicating stress (i.e., less data is exchanged) of SC.

3) *Supervisory Controller*: SC is responsible for managing the overall aggregation and obtaining the global optimum. The grid information is gathered and handled here. The aggregated data from LC with location indices are sorted according to the grid topology. The grid related calculation are executed when the messages from all LCs are available. Given the parameters (calculation results), SC calculates the optimal results, which are dispatched to LCs.

B. Information exchange structures

In Fig. 1, several information structures are used to transfer the data between the roles. The exchanged information is generic, different types of units use the same information structures to represent its request to LC and get operation set-points. Information exchanged between LC and SC is also based on the same information structure and does not depend on the type of units aggregated by LCs.

1) *UnitData*: It contains time instant, location index, unit identity, operation states (voltage magnitude U , P and Q), capacity of the flexibility (the range for up/down adjustment $[\Delta P_{-}, \Delta P_{+}]$ and $[\Delta Q_{-}, \Delta Q_{+}]$), and the service cost.

2) *UnitSet*: It contains time instant, location index, and the set-points of changes to UCs (ΔP_{set} and ΔQ_{set}).

3) *LCData*: It contains time instant, location index, LC identity, aggregated operation states (U_{av} , P_{sum} and Q_{sum}), aggregated capacity of the flexibility ($[\Delta P_{sum,-}, \Delta P_{sum,+}]$ and $[\Delta Q_{sum,-}, \Delta Q_{sum,+}]$), and the aggregated service cost.

4) *LCSet*: It contains time instant, location index, and the set-points to LCs ($\Delta P_{sum,set}$ and $\Delta Q_{sum,set}$).

III. VOLTAGE CONTROL IMPLEMENTATION

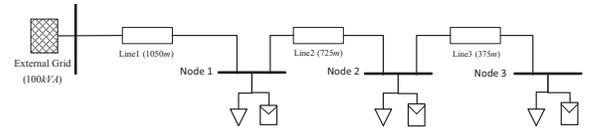


Fig. 2: One line diagram of the symmetrical 3-phase grid

A. Grid set-up

The grid model used in this paper consist of 6 DERs (shown in Fig. 2), 3 PV panels with rated power of 10 kW, and 3 controllable heaters in the buildings with rated power of 10 kW. The cable properties are also determined according to the grid data in SYSLAB, a research facility for smart, active and distributed power systems at Technical University of Denmark's Risø campus [10]. The nominal voltage is 0.4 kV (phase-phase). This set-up is modelled in MATLAB, to simulate the grid operation, using historical data (voltage profile at the external grid point, the original PV production profile, and the initial load conditions) measured on 12-05-2013 in SYSLAB. The operation states are estimated using the data provided by UCs. The future field demonstration will share a similar set-up.

B. Supervisory Controller

The SC performs the control loop every 10 minutes. The measurements are 10-minute average values. The functions in LCs and UCs are activated by the threads from the SC.

After collecting the information from all the LCs, the sensitivity calculation is performed to obtain the linear relation between the operation states, based on which a quadratic optimization problem is formulated to make the decisions for the units. In order to reflect the contributions of DER units and their capability of providing flexibilities, and to maintain the efficient operation of the grid, the optimization function also includes the service costs, and the power loss in the grid.

1) *Sensitivity coefficients calculation*: Based on the collected data from LCs (U_{av} , P_{sum} and Q_{sum} in this application), load flow calculation is performed. The relations between the power loss (P_{Loss})/ U and P/Q are calculated by linearising the system at the operation point, and inverting the Jacobian matrix [11]. The impact of small changes of the system inputs (i.e., P/Q) can be derived by having these linear relationships:

$$\begin{bmatrix} \Delta\theta \\ \Delta U \end{bmatrix} = JAC^{-1} \cdot \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial\theta}{\partial P} & \frac{\partial\theta}{\partial Q} \\ \frac{\partial U}{\partial P} & \frac{\partial U}{\partial Q} \end{bmatrix} \cdot \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (1)$$

We only take the lower half of the matrix (relation between voltage magnitude and power) as the parameters to obtain the optimization represented as $\frac{\partial U}{\partial S}$.

The power loss sensitivity respect to power, $\frac{\partial P_{Loss}}{\partial S}$ can be denoted as the equation below:

$$\frac{\partial P_{Loss}}{\partial S} = \begin{bmatrix} \frac{\partial P_{Loss}}{\partial P} \\ \frac{\partial P_{Loss}}{\partial Q} \end{bmatrix} = (JAC^{-1})^T \cdot \begin{bmatrix} \frac{\partial P_{Loss}}{\partial\theta} \\ \frac{\partial P_{Loss}}{\partial U} \end{bmatrix} \quad (2)$$

where, JAC is the Jacobian matrix obtained from the power flow, and $\begin{bmatrix} \frac{\partial P_{Loss}}{\partial\theta} \\ \frac{\partial P_{Loss}}{\partial U} \end{bmatrix}$ is the partial derivative of the power loss calculation equation (by summing up the power injection from the two ends of a line) [11].

2) *Optimization problem*: The optimization problem is formed as a quadratic multi-objective function, where the voltage deviation, total power losses, and the cost of services are considered:

$$\begin{aligned} \min_x \quad & \alpha \cdot \sum_{i=1}^N \text{cost}_i(x) + \beta \cdot \frac{\partial P_{Loss}}{\partial S} \cdot x + \gamma \cdot \sum_{i=1}^N (U_i - U_{ref})^2 \\ \text{s. t.} \quad & x_{min} \leq x \leq x_{max}, \\ & U_i = U_{org,i} + \frac{\partial U}{\partial S} \cdot x. \end{aligned} \quad (3)$$

where, x represents the variable vector including the change of power injection, $\Delta P_{sum,set}$ and $\Delta Q_{sum,set}$ at each node, U_i is the improved voltage at node i , N stands for the number

of nodes, U_{ref} is the reference voltage value, x_{min} and x_{max} denote the minimal and maximal limit of the power for regulation (i.e., $[\Delta P_{sum,-}; \Delta Q_{sum,-}]$ and $[\Delta P_{sum,+}; \Delta Q_{sum,+}]$), $U_{org,i}$ is the measured present voltage, and α , β , and γ are the weighting factors (virtual price) of different objectives.

C. Local Controller

In LCs, the injected P and Q are summed up as P_{sum} and Q_{sum} . So are the flexibilities ($[\Delta P_{sum,-}, \Delta P_{sum,+}]$ and $[\Delta Q_{sum,-}, \Delta Q_{sum,+}]$). The average voltage U_{av} is taken from all the DERs. The services from the units are sorted by the cost, and the marginal cost is calculated when reporting to SC in the aggregation. Here is an example: By aggregating the costs from the UCs, the LC obtains a cost function as shown in Fig. 3. Knowing the historical information of occupied flexibilities (dashed lines), the LC can derive the marginal costs of the aggregated unit services (large dots in the figure).

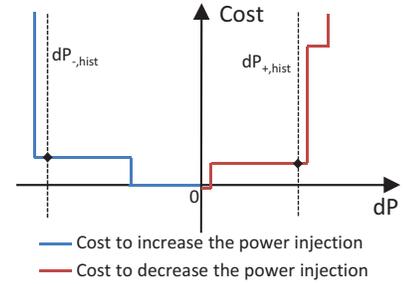


Fig. 3: An example of aggregated cost function

Similarly, the services are actuated according to the cost in the dispatch. More complex method could be deployed in the aggregation if necessary.

D. DER Controller

1) *Cost generation*: The cost of services is generated based on the current operation states of the units. Here is an example: The cost of the flexible active power is determined by the room temperature following a certain curve (see Fig. 4). The cost reflects the operation of the heaters and maintains the temperature close to the reference. Other cost functions can be designed for different purposes.

PV units can provide flexible Q (constrained by the inverter rated power and active power production), and P if the virtual price of power loss or voltage is high enough. Controllable loads can only provide the flexible active power (constrained by the indoor temperature). Generally, the cost of Q from PVs is cheapest, and the cost of P from PVs is most expensive.

2) *Prediction models*: A PV model [12] is used to predict and calculate the expected range of flexible power given the environment forecast (e.g., wind speed, outdoor temperature, solar irradiation). A simple water dam model (a stock with certain inflow and outflow) is used to represent the thermal model of a building. The stock level is the indicator of the service cost. In the present simulation, it is assumed that the stock level will remain constant when the inflow power is 3.5

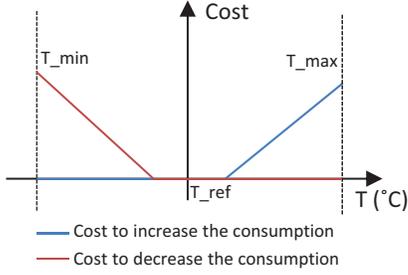


Fig. 4: The cost function regarding to room temperature

TABLE I: The values of weighting factors in different cases

Case No.	α	β	γ	Comment
1	1000	1	1	voltage dominant
2	5	1	1	
3	2	1	1	balanced condition
4	2	1000	1	loss dominant

kW. A thermostat model of the building in [13] can be further implemented to obtain the thermal dynamics .

IV. SIMULATION RESULTS AND ANALYSIS

Based on the proposed hierarchical controller and its particular features, the voltage control services are performed in MATLAB. In the optimization objective, the weighting factors are determined by the DSO. One of the objectives is dominant if the weighting factor is relatively high. Table I summarizes the weighting factor values used in different cases.

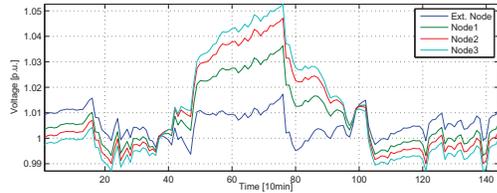


Fig. 5: The original voltage profiles at each node

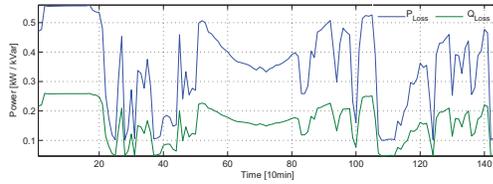


Fig. 6: The original total Power Losses

Fig. 5 and Fig. 6 shows the original voltage profiles in each node and total power losses without implementing the voltage controller. The voltage rise due to high PV production is significant. The voltage increases along the feeder when the PV production is higher than the consumption. At other time, the voltage decreases. The total power loss is least when the mismatch between the production and consumption is close to zero (around 06:30 and 18:20).

Case 1 shows the result when the voltage deviation is of grave concern. Case 4 shows the result when the power loss is of most concern. No flexibility will be occupied if the service cost is high. Fig. 7 shows the comparison of object values among the first three cases. It can be seen that the minimization of voltage deviation is prioritized and thus the value keeps constant zero in Case 1. While α is reduced, the values become balanced among three objectives.

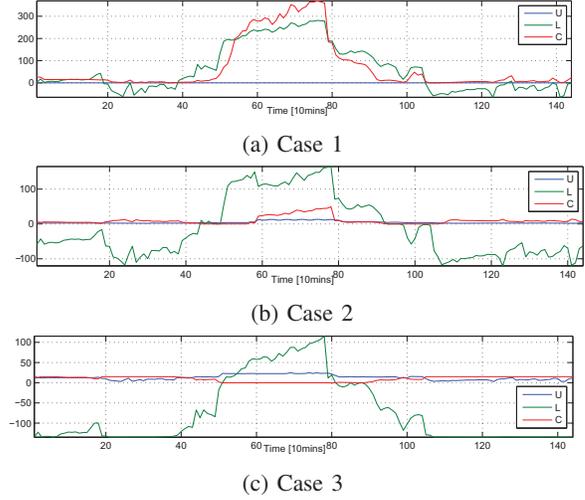


Fig. 7: The values of objectives (U: voltage, C: cost of service, L: power loss)

Fig. 8 presents the occupied flexibilities in each node in Case 1. The units in Node 3 are more active than the others, because the sensitivity coefficients of that node are larger. In the early morning and late evening the heating consumption is curtailed and is over-compensated around noon. PV production is also cut to avoid large voltage rise. Reactive power at Node 1 and 2 are absorbed and is compensated at Node 3, in order to flatten the profile along the feeder.

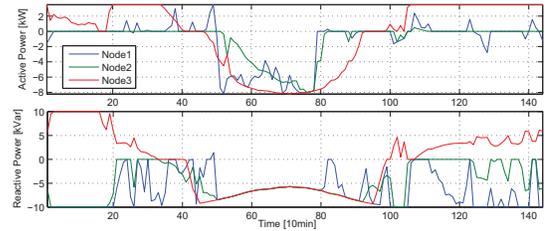


Fig. 8: The usage of the flexibilities from DERs

Fig. 9 shows the modified voltage profiles when the voltage controller is deployed. In Case 1, the voltages are varying around 1 [p.u.], the largest deviation is 0.03 [p.u.]. In Case 3, the PV inverters compensate a lot of reactive power to smooth the voltage and to reduce the power loss by limiting the current. The largest deviation is 0.04 [p.u.]. In the last case, power loss is dominant in the entire objective. To minimize as much current flow as possible, the controller not only requires reactive compensation but also mitigate the active

power mismatch. Thus, it can be observed that in Case 4, the voltage deviation is even larger than the original profile.

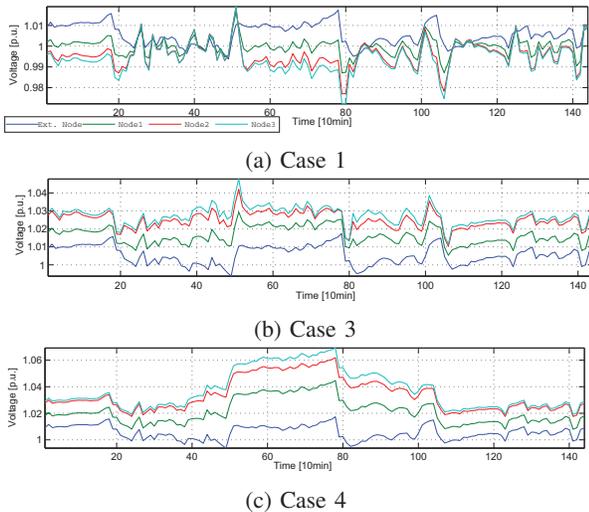


Fig. 9: The voltage profiles when deployed the controller

Fig. 10 shows the modified total power loss in the feeder when the controller is deployed. In Case 1, the curves have no difference comparing to Fig. 6. In Case 3, they are improved by around 70%, and the largest loss occurs in the afternoon where some active power are used and the cost of active power becomes high. In Case 4, the power losses are improved by around 90%.

The control results (Fig. 9 and Fig. 10) shows that the dominant objectives can significantly improve the corresponding operation states, but the eclectic solution may obtain the improvements in every aspect of the optimizing objectives (e.g. Case 3).

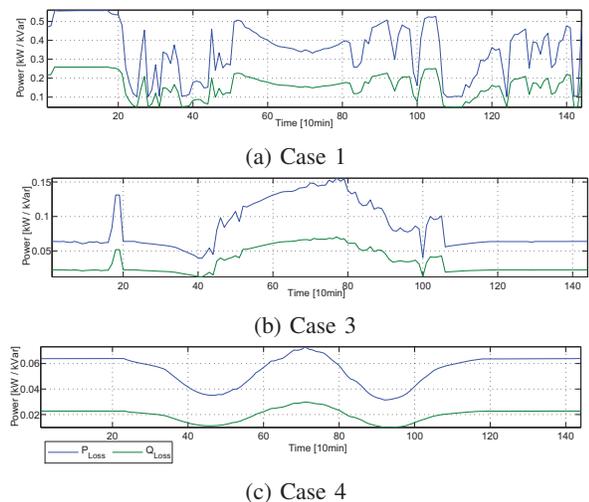


Fig. 10: The total power loss when deployed the controller

V. CONCLUSION

In this paper, a hierarchical controller is presented for managing the flexibility of DER units and providing various

system services. In the hierarchy, the aggregation is deployed in different levels. Generic information models are used to transfer the data among different roles that enables the further expansion of the control structure. The global optimum of the control decisions can be made having the overview of the system operation in SC, and the DERs' activities can be coordinated in this control system. The hierarchical structure reduces the computational stress of an individual controller (by deconstructing the optimization problem into several levels).

A voltage controller is implemented using this hierarchy, where PVs and heaters in the building provide the flexibilities to adjust the system operation. A multi-objective optimization is simulated and obtains the control results using different weighting factors. The results shows that the controller is functional and can very well aggregate the flexibilities and dispatch the orders. The performance is improved by implementing the control system. The system can be optimized at different operation points when the objectives have different virtual values, which enable the DSO to make their decisions considering specific operation problems (e.g., to improve the voltage quality or to reduce the operation cost).

All these set-up will be demonstrated in the test field, SYSLAB, by integrating the hierarchy building function in [9]. Furthermore, a multi-objective optimal set can be investigated in a real smart grid solution.

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