TRANSACTION AREAS FOR LOCAL VOLTAGE CONTROL IN DISTRIBUTION NETWORKS

Monica BISERICA
Alstom Grid – France
monica.biserica@alstom.com

Guillaume FOGGIA
Alstom Grid – France
guillaume.foggia@alstom.com

Emmanuel CHANZY
Alstom Grid – France
emmanuel.chanzy@alstom.com

Jean-Christophe PASSELERGUE
Alstom Grid – France
jean-christophe.passelergue@alstom.com

ABSTRACT

The paper presents a method to design transaction zones for commercial aggregation at the distribution level for voltage mitigation purpose. The core principle of this zoning is the nodal voltage sensitivity for active power variation. As the transaction zone delimits the elementary area for DER aggregation and separates the distinct roles of the network operator and of the aggregators, a fair non-arbitrary efficient zoning method is needed. The zoning problem is explored using a modified hierarchical clustering method, applied to a set of voltage sensitivity factors. The impact of this method is illustrated on a study case of a balanced MV distribution network.

INTRODUCTION

Due to the increasing penetration level of distributed generation (DG), network operators are facing the challenge of the integration of these resources on the distribution networks, which shall support bidirectional flows, while respecting technical or regulatory constraints such as equipment thermal ratings, voltage levels, short-circuit fault current levels, short-term voltage drops, harmonics, system stability. These problems might be handled prior to the connection of a new DG unit, as the DNO must realize technical studies to evaluate the eventual consequences of the insertion of each additional energy resource and plan for required network reinforcement. However, this passive worts-case approach might lead to rising drastically costs of network investments and renewal of system operations tools.

Under the appellation of Smart Grid, the deployment of advanced networking technologies will tend to promote a new management of the existing power systems, based notably on the principle of an active distribution network. In this perspective, installed distributed energy resources (DER) can be observed notably by the system operator and could be controlled as well, for technical or economical purposes. Expert evaluations of the trends on the development and operation of active distribution networks give first insights on their strengths and weaknesses [1]. While pending issues are identified, like maintenance of the future system, the communication infrastructure or the lack of background experience, the main benefit of the active distribution networks will come from the provision of a new operating framework, allowing every DER to participate in energy markets as well as in ancillary services for the network operators [2].

One of the pending issues of DG connection is the technical challenge to maintain an acceptable voltage level. Actually, in presence of DG, overvoltage occurrence risk may be severe when the load demand power is low in comparison with the local power production, inducing possible local overvoltage at several nodes of the distribution network. A particular case concerns the penetration of small residential photovoltaic (PV) generators connected to low voltage (LV) public networks.

Various methods have been proposed in order to maintain the grid voltage in the admissible range. These methods may be categorized as coordinated control, semi-coordinated and decentralized control strategies. Centralized or coordinated control strategy provides voltage regulation from the substation to the rest of the network, using network devices such as OLTC, voltage regulator and capacitor banks, with the relevant communication system to ensure the coordination. By contrast, the semi-coordinated or distributed control strategies involve a local voltage-related control of the DG unit, while eventually complementing it by coordination with a limited number of other network devices. Finally, the entirely distributed methods are based on local control decisions, integrated in the equipment, such as reactive power compensation method, generation curtailment, combinations of power factor -voltage control method, or auto-adaptive PV inverters [3].

As mentioned, centralized or semi-coordinated methods require mitigation by the operator, although some of the available resources may be managed rather by other actors, which could be as well power producers, aggregators and so on. Supervision and control coordination implies an estimation of the voltage magnitude at each network node using real time measurement, network data and load data. By resorting to external resources from third parties, network operator shall also manage commercial relations and information asymmetry regarding the details of the portfolios of these parties. In such conditions, performance improvement can be achieved by node aggregation, reducing the size of the problem to a number of aggregated zones.

The proposed paper focuses on this particular issue of zoning, whose objective is to simplify the voltage control problem and improve the calculation performance, without significant loss of accuracy. The principle of the subsequent voltage control mechanism and the relations between the operator and the aggregators are described in a first section. In a second part, a review of different network zoning methods evaluates the different possible approaches. The chosen clustering methodology is then presented. This methodology is illustrated through the study case of a 20 kV rural network with connected DG units.

MARKET-BASED MECHANISM

The background of our contribution is a voltage control approach, based on local dispersed variations of active power only, and called “flexibilities”. Reactive power regulation is not considered here. DERs are seen as able to provide upward or downward variations of active power injections or withdrawals, from a reference baseline. These DERs could be dispatchable generators, Demand Response resources or energy storage units. During a day-ahead or intraday process, the DSO plans the voltage profile on the network nodes; it detects the potential forecast voltage deviation, and it can achieve a resolution of the deviations, by soliciting the various local DERs through intermediaries: aggregators. The aggregators agglomerate their potential flexibilities at the level of pre-defined Transaction Areas and submit day-ahead offers per transaction area. Afterwards, the network operator selects the set of cheapest offers that can solve the identified constraints. An example of such market-based mechanism can be found within the research project Nice Grid [3].
Aggregators are intended to submit their offers at the level of the elementary transaction areas. Within such a transaction area, previously defined by the network operator, any aggregator can act as a commercial Virtual Power Plant, offering on the market the aggregated capacity of its portfolio. Therefore, it is important to provide a fair and transparent methodology for the definition of such zones, as their size and their topology will impact the efficiency of both the aggregators and the DSO. It is important to highlight that DSO does not have any information about the schedules of the various resources within a given transaction area. Without any detailed information about the nodal power injection / withdrawal, besides the initial network analysis, it is not possible afterwards for DSO to do directly power flow calculations. Approximations through voltage sensitivity factors are used for the following steps of the market-based mechanism of resolution of the voltage constraints, as operated by the DSO:

- Assessment and publication of the authorized range of active power variations per transaction area;
- Market clearing of the submitted bids;
- Checking of the resolution of the constraints.

Voltage sensitivity factors can be interpreted as the nodal voltage variations due to active and reactive node power changes. Linearized voltage sensitivity coefficients will be obtained from the differential of the voltage as a function of the active power and reactive power, derived from the Jacobian matrix, which is a sub-product of the initial power flow calculation. For a node i, this differential is expressed in the following form, V being the voltage, P the active power and Q the reactive power:

$$dV_i = \sum_{j=1}^{n} \frac{\partial V_i}{\partial P_j} . dP_i + \sum_{j=1}^{n} \frac{\partial V_i}{\partial Q_j} . dQ_i$$

The general expression for all nodes will be:

$$\begin{bmatrix} dV_1 \\ \dots \\ dV_n \end{bmatrix} = \begin{bmatrix} \frac{\partial V_1}{\partial P_1} & \dots & \frac{\partial V_1}{\partial P_n} & \frac{\partial V_1}{\partial Q_1} & \dots & \frac{\partial V_1}{\partial Q_n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{\partial V_n}{\partial P_1} & \dots & \frac{\partial V_n}{\partial P_n} & \frac{\partial V_n}{\partial Q_1} & \dots & \frac{\partial V_n}{\partial Q_n} \end{bmatrix} . \begin{bmatrix} dP_1 \\ \dots \\ dP_n \\ dQ_1 \\ \dots \\ dQ_n \end{bmatrix}$$

In the next sections, voltage sensitivity factors relative to active power differential are referred as follows:

$$S_{i,j}(k) = \frac{\partial V_i}{\partial P_j}(k)$$

This nodal expression relates to the network buses i and j, which are not necessarily adjacent. In case of zonal design, the voltage sensitivity factor would be expressed as $S_{i,G}(k)$ with G, a transaction area composed of several buses.

AGGLOMERATIVE HIERARCHICAL CLUSTERING METHOD

Zoning purpose and design consideration

Examples of design of zones on electrical networks can be found in the literature, for various purposes such as analysis performance improvement [5] [6], but are not relevant for the present issue. On the aggregators’ side, advantages of a zoning are obvious, as a large area implies a better minimization of the provision failure risks thanks to a bigger diversity factor effect. On the DSO’s side, the definition of the zones shall not induce important errors in the voltage estimations.
Relevant zones could be manually defined considering the topology, the observability and based on operator expertise. For generalization and replication, we suggest an alternative systematic approach, based on clustering technics. Actually the goal is to identify groups ensuring both accuracy and relevance with the nodes of interest, with occurrence risks of overvoltage.
As defined, our zoning design is a classical problem of cluster analysis. The purpose of this algorithm is to form clusters of electrical nodes, in such a way that any power injection/withdrawal deviation at electrical nodes within the same group should have basically a very similar impact in the network. By contrast, contribution from resources located in different clusters should have a clearly distinct effect.
Cluster analysis proposes various families of methods of classifying individual elements into consistent groups of similarity. Literature review shows nevertheless that the zoning problem is not simply a choice of a clustering

algorithm, but it requires a series of steps, with usually hidden multiple decisions at each stage that must fit with the final purpose of the user application. There is no universal right answer in a clustering problem, just a settlement between multiple possible alternatives, based on decisions done during the clustering process [7]. Basically, the points that have to be addressed are the following: the choice of the clustering elements and their attributes; the standardization of the variables; the measure of similarity or dissimilarity; the choice of the algorithm; the number of clusters (or the stopping criteria); finally, the assessment of the results in the context of the applied problem. These points are described in the following section.

Clustering method description

The purpose of this application is to group all the electrical nodes (the *clustering elements*) that have the similar impacts on some node voltages into cluster. The *attributes* are the voltage sensitivity factors, calculated through the initial power flow calculations. Constitution of the dataset can concatenate sensitivity factors for several nodes of interest; the attribute for the element *j* is then the vector:

$$X_j(k) = [S_{1,j}(k) \quad S_{2,j}(k) \cdots S_{M-1,j}(k) \quad S_{M,j}(k)]$$

Several time steps can be also combined to constitute the dataset:

$$X_j = [X_j(1) \quad X_j(2) \cdots X_j(K-1) \quad X_j(K)]$$

For simplification, only one steady state has been considered in our application.

The hierarchical agglomerative family of methods was chosen among the existing clustering algorithms. Hierarchical clustering creates *tree* or *dendrogram* from groups of objects. The formed tree is a multilevel hierarchy and the clusters at one level are merged into a new cluster at the next level. Therefore, the user can visualize the progress in agglomeration and choose the level of clustering that is most appropriate for his application.

The steps of the hierarchical algorithm are the following:

1. Find the similarity or dissimilarity between every pair of objects in the data set. In this step, the distance between objects is calculated using the distance function. In our study, as there is no particular weighting between the different sensitivity factors, the Euclidean distance was utilized to compute the distance between elements.
2. Group the objects into a binary, hierarchical cluster tree. In this step, the links between objects that are in close proximity is made using a linkage function. This linkage function uses the distance information generated in step 1 to determine the proximity of objects to each other. As objects are paired into binary clusters, the newly formed clusters are grouped into larger clusters until a hierarchical tree is formed. The Ward method was utilized to compute the linkage [7]. Ward's linkage uses the incremental sum of squares; that is, the increase in the total within-cluster sum of squares as a result of joining two clusters. The within-cluster sum of squares is defined as the sum of the squares of the distances between all objects in the cluster and the centroid of the cluster. The sum of squares measure is equivalent to the following distance measure d(r,s), which is the formula linkage uses:

$$d(r,s) = \sqrt{\frac{2n_r n_s}{n_r + n_s}} \|\overline{x_r} - \overline{x_s}\|_2 \qquad (1)$$

where:

- n_r and n_s are the number of elements in clusters r and s
- $\| \ \|_2$ is the Euclidian distance
- $\overline{x_r}$ and $\overline{x_s}$ are the centroids of clusters r and s

3. Determine where to cut the hierarchical tree into clusters. In this step, the cluster function is used to cut branches off the bottom of the hierarchical tree, and assign all the objects below each cut to a single cluster. This creates a partition of the elements. The cluster function can create these clusters by detecting natural groupings in the hierarchical tree or by cutting off the hierarchical tree at an arbitrary point.

The number of clusters has not been pre-defined. The cutting off technique was utilized and the point for the cut was the number (0.8). This parameter was tested systematically for the utilized network and the value of 0.8 provided the best results.

Finally, the assessment of the results is not done through a statistical analysis, but by comparing empirically the errors in the voltage estimation to the reference nodal case. This validation process is described later within the study case.

STUDY CASE

The algorithm was tested on a balanced distribution network. The topology and the network parameters are defined in [2]. It models a 20kV rural network of 55 nodes, 52 loads and 2 DGs. The slack bus has been set up at bus 55. Virtual buses, e.g. nodes without load, are considered as load buses.

A validation approach has been also defined. To validate the method, the initial voltage profile, showing some over-voltages, is compared with the profile obtained once the active power injection/withdrawal for each cluster has been modified based on the sensibility matrix in order to bring back the voltage profile within the mandatory limits. The purpose of this comparison is to validate our method, checking that the power deviation results effectively in a voltage deviation as quantified through the sensivity matrix. The validation of the voltage profile found with the proposed method is performed by comparing it with the profile obtained with a classical load flow where the resource flexibility is linked to a specific node within the cluster. Figure 1 shows the different calculation steps. For simplification, the method is used in static state and focuses on one given operating point only.

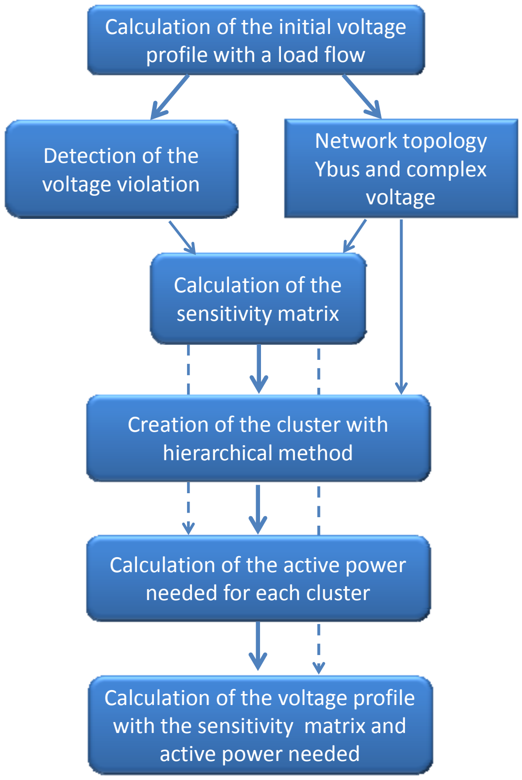

Fig. 1. Study case calculation steps

The algorithm is tested for a constrained scenario. The case corresponds to a small load level, i.e. 0.808 MW and 0.160 MVAr. The DGs produce a total power of 1.08 MW and 0.432 MVAr, while the voltage at the slack bus is 1.045 p.u. Such a situation, showing a load level lower than the distributed generation level corresponds to a situation that will occur more and more frequently in the future due to the significant penetration of distributed generation in the distribution systems. Eligible DERs are supposed to be flexible demand. Therefore, the slack bus and the generation buses were excluded from the clustering dataset.

RESULTS

The Table 1 indicates the hierarchical clusters obtained with the Ward method. The agglomerative clustering algorithm stopped at the level of 19 clusters, composed from one bus to 6 buses.

Cluster	Buses
1	6, 13
2	25, 26
3	20, 21
4	47
5	16, 19
6	17, 18
7	54
8	30, 33, 34
9	3, 14
10	2, 10, 12
11	38, 39, 49, 53
12	5, 8
13	23, 24
14	22, 27, 28
15	42, 43, 44, 45, 46, 50
16	40, 41, 48
17	29, 31, 32, 35, 36
18	4, 9, 11
19	1, 7, 15, 52

Table 1. Solution of the clustering process

Figure 2 shows the voltage profiles obtained when applying the proposed method. The dashed curve (red) corresponds to the initial voltage profile (including voltage limit violations), while the solid line (blue) shows the voltage profile obtained after modifying the net injection on the clusters identified with the proposed method. The resulting voltage profile is within the imposed limits, i.e. within the [0.95 p.u. - 1.05 p.u.] range.

As the solution of any voltage deviation shall be ensured independently of the location of the resource within the transaction area, the aggregation of the different sensitivity factors must be done on a conservative basis, as the minimum of the sensitivity factors of the different nodes:

$$S_{i,G}\_(k) = Min_{j\in G}\left(S_{i,j}(k)\right)$$

The active power founded for each cluster is associated for all loads of the concerned cluster. The used algorithm was to found the maximum active power, based on the minimum sensitivity among the nodes of each cluster, which responds to all constraints. The final voltage for the proposed method was calculated with equation 2:

$$V_f^k = V_i^k + S^k \Delta P_{cluster}^{found} \qquad (2)$$

To validate the proposed algorithm, the dotted curve corresponds to the voltage profile obtained with a load flow algorithm for the active power founded with the sensitivity matrix for each cluster. The load flow calculation represents the reference case and the relative errors obtained with equation 3 are show in the Figure 3

$$error = \frac{\text{value LF - value proposed method}}{\text{value LF}} \cdot 100 \qquad (3)$$

The maximum error obtained is close to 0.8%, which is a small value for the error voltage. Therefore, the performance of the proposed method is proved.

The voltage profile given by the load flow calculation is smaller than the voltage found in the proposed method. The active power demand found with sensitivity matrix for each cluster is calculated for the most constrained case. Therefore, in order to improve the proposed algorithm, other methods less constrained can be utilized and our method can be considered valid for all cases.

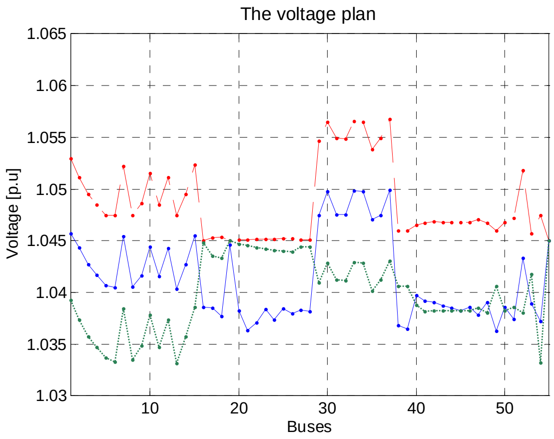

Fig. 2. Initial and final voltage profiles

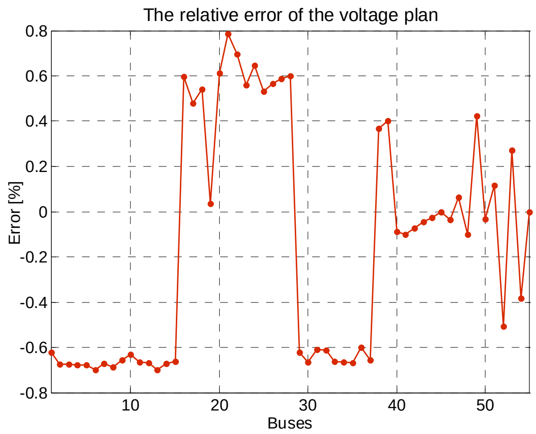

Fig. 3. Relative error of the voltage profile

CONCLUSION

The study addresses the issue of network zoning, whose objective is to simplify the problem and improve the calculation performance, without significant loss of accuracy for a market-based ancillary service devoted to distribution voltage control. The contribution of this paper is the provision of a clustering approach that is replicable, adaptable, and transparent. The presented method has been successfully tested on a study case of a rural MV feeder. This work might provide also methodology guidance for any comparable implementation of service-oriented zoning definition at the distribution level for advanced distribution management functions.

REFERENCES

[1] C. D'Adamo, J. Samuel, A. Chad, 2009, “Global survey on planning and operation of active distribution networks”, Update of CIGRE C6.11 working group activities, 20th. International Conference and Exhibition on Electricity Distribution - Part 1, (2009), 1-4.

[2] D. Pudjanto, C. Ramsay, G. Strbac, March 2007, “Virtual power plant and system integration of distributed energy resources”, IET Renewable Power Generation, Vol. 1, No. 1, pp. 10-16.

[3] T. Xu, P. C. Taylor, “Voltage Control Techniques for Electrical Distribution Networks including Distributed Generation”, International Federation of Automatic Control, 17th World Congress (2008).

[4] Grid4EU Demo 6 - dD6.1 Initiation of the demonstration, v.1.0 (2012), www.grid4eu.eu

[5] F. Capitanescu, T. Van Custem, 2005, “Unified Sensitivity Analysis of Unstable or Low Voltages Caused by Load Increases or Contingencies”, IEEE Transactions on Power Systems, Vol. 20, No. 1.

[6] G. Ezhilarasi, K. Shanti Swarup, 2011, “Network Decomposition using Evolutionary Algorithms in Power Systems”, International Journal of Machine Learning and Computing, Vol.1, No. 1.

[7] B. S. Everitt, et al. “Cluster Analysis”. John Wiley & Sons, 5th edition, 2011.

[8] M. Biserica, Y. Besanger, R. Caire, O. Chilard, P. Deschamps, Sept. 2012 ,“Neural networks to improve Distribution State Estimation – Volt Var Control performances”, IEEE Transactions on Smart Grid, Vol. 3, Issue: 3, pp. 1137- 1144.

[9] M. Eremia, 2006, “Electric Power Systems – Electric Networks”, Editura Academiei Romane, Bucharest, Romania, pp. 509- 520.