FAST ESTIMATION OF EQUIVALENT CAPABILITY FOR ACTIVE DISTRIBUTION NETWORKS

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ABSTRACT

The electricity system is subject to continuous evolution stimulated by the integration of renewable energy sources. This transformation is having deep impacts on the planning and operation of networks and new potential roles of system operators are currently investigated. In particular, having assumed a future in which the energy demand is largely satisfied by distributed generation, it can be reasonably expected that distribution networks will be soon enabled to offer balancing and regulation services to the market. In this scenario, the distribution operator may aggregate all the local dispatchable resources and, from their combination, a single capability can be obtained to represent the flexibility limits of the entire network. This paper presents few simple and intuitive methods for a fast and accurate construction of this equivalent capability.

INTRODUCTION

In the next future, the contribution of DRES (Distributed Renewable Energy Sources) on the share of electricity production will be more relevant [1]. The stochastic and not-programmable nature of many renewable resources and the decrease of the conventional units, will impact on the stability of the power system. In order to maintain an adequate balancing reserve, distributed resources can be likely allowed to participate in the ancillary services market. Besides, DRES, together with the asset of the Distribution System Operator (DSO), have the potential to contribute to the voltage management also at transmission level. However, the constraints of distribution networks, could limit the potential of DRES in services provision. In fact, variations in the power exchanged by the flexible devices (led by the market), can be in conflict with the planning and operation procedures of DSOs.

Since only resources at transmission level are often allowed to participate, market clearing algorithms are designed in order to identify the optimal solution for the energy system balancing, and the HV network constraints are constantly taken into account. It is obvious that, once higher participation from distribution programmable units will be exploited, congestion management at lower voltage levels will be required.

Different market schemes have been recently proposed to foster the participation of distribution resources to the balancing market [2]. Depending on the evolution of the scenario, the potentialities of each coordination scheme are different. However, for most of them, the interface between transmission and distribution network (Point of Common Coupling – PCC) plays a fundamental role. In particular, it is important that the Transmission System Operator (TSO) knows what is the level of flexibility that distribution resources can promptly provide, both for operational and planning purposes. On the other side, the DSO needs to know the maximum power that can be generated/absorbed by the local resources without endangering the safe operation of its network, especially when the DSO itself is in charge of the aggregation of distributed resources. Besides, the DSO can also participate directly to the voltage support of the transmission network by managing, in addition to third-party resources, its own assets. Thus, it is necessary to develop some fast and efficient methods in order to compute the equivalent *P-Q* capability as seen from the HV node. Firstly, because of the in-between MV network affects the actual power provision from resources, secondly the active power can change in real time depending on the availability of the primary source.

These issues have been already faced behind the concept of Virtual Power Plant (VPP) [3]÷[6], where multiple resources are aggregated by a market operator to obtain an equivalent conventional power-plant. In this case the contribution of the distribution network constraints is neglected. However, in order to calculate a correct capability, the limits introduced by the distribution networks (lines loading, voltage limits, etc.) as well as the operational procedures of the DSO have to be included. For example, the OLTC or the local droop control of generators can greatly affect the total capability as seen by the HV node.

In the following sections, different methods for the calculation/estimation of active distribution networks capabilities have been investigated. These procedures have been designed in order to be easily adapted and/or selected on the basis of the optimization tools currently used by network operators. In addition, each proposed method is presented by highlighting its peculiarities in order to better understand its application in particular network situations.

In the article an optimization algorithm, previously developed and already tested on real SCADA, has been used [7]. The algorithm offers the possibility of taking into account resources capabilities, local controllers and inter-temporal constraints.

ACTIVE DISTRIBUTION NETWORK AND EQUIVALENT CAPABILITY

The proposed procedure is applied to the rural reference distribution network of the Atlantide project [8]. The network has been modelled by assuming four controllable generators, a storage unit and a controllable load (Figure 1) characterized by the parameters reported in Table 1.

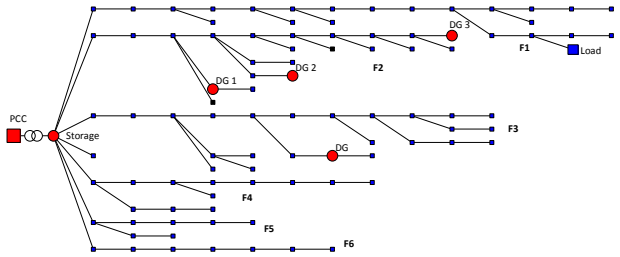

Figure 1: Test network. The red circles identify controllable generators and the storage unit, and the blu square is the flexible load.

Table 1: Flexible resources and their characteristics. C_{up} and C_{down} are the costs related to increase and decrease of the power set-points respectively, P_0 is the power exchange of the devices, while P_{min} and P_{max} are the minimum and maximum active power respectively for each unit. Triangular capabilities have a minimum power factor of 0.9 and the load has a power factor equal to 0.9.

Resource	capability	C_{up}	C_{down}	P_0	P_{min}	P_{max}
name	shape	€/MW	€/MW	MW	MW	MW
DG 1	triangular	120	100	1	0	1
DG 2	triangular	120	100	0.5	0	0.5
DG 3	triangular	120	100	0	0	1
DG 4	square	100	80	1	1	2
Load	constant PF	220	NA	-0.8	-0.8	0
Storage	circular	50	0	0	-1	1

The aggregated flexibility can be easily calculated under ideal conditions by algebraically summing all the capabilities of the available resources. It results similar to a trapezium (blue curve in Figure 2) with rounded edges, due to the circular capability of the storage. Of course, network characteristics affect the shape of the area (green curve in Figure 2): in fatc, the aggregated capability results about 1-MVAr shifted with respect to the one related to the copper plate approximation because of actual impedances.

As anticipated above, this theoretical capability cannot be entirely ensured because of the network operational limits (i.e. voltage and current constraints). In particular, the considered network is characterized by overloading issues in feeder F2 and voltage violation risks in both feeders F1 and F2. They limit the capability of the network when high share of both active and reactive power have to be exchanged (red curve in Figure 2).

This last curve delimits the possible active and reactive power values that can be exchanged by the distribution network at the PCC. Its area correspond to the set of activations and/or modulations of the connected flexible resources that do not determine network congestions.

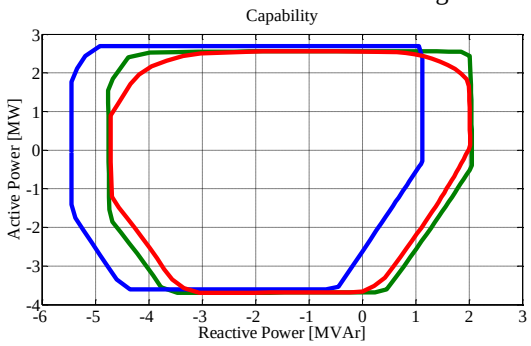

Figure 2: Aggregated capability of the considered distribution network in correspondence of the PCC. Copper-plate (blue) *vs.* unconstrained (green) *vs.* constrained network (red).

CALCULATION OF THE EQUIVALENT CAPABILITY

The easiest way to obtain the aggregated capability for an active distribution network is to poll a conventional Optimal Power Flow (OPF) for a grid of power values on the *P-Q* plane, corresponding to the desired power exchange in correspondence of the PCC. The set of values for which the OPF converges and returns feasible solutions corresponds to the equivalent capability of the network. This method has been applied to the three cases considered within the previous section: the resulting capabilities (completed with the internal cost function) are reported in Figure 3, Figure 4 and Figure 5.

From these results it can be easily deduced that, according to Table 1, the blue area corresponds to the contribution of storage and DG 4 (which are the resources with lowest cost), the green area refers to the activation of DG 1÷3, while the red area corresponds to the modulation of the load (highest flexibility cost).

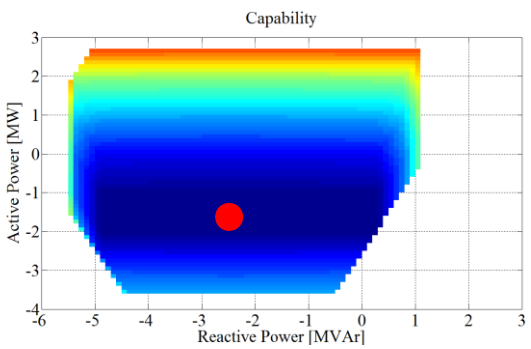

Figure 3: Aggregated capability, computed point by point, having considered the distribution grid as a *copper plate*. The red dot corresponds to the current working point.

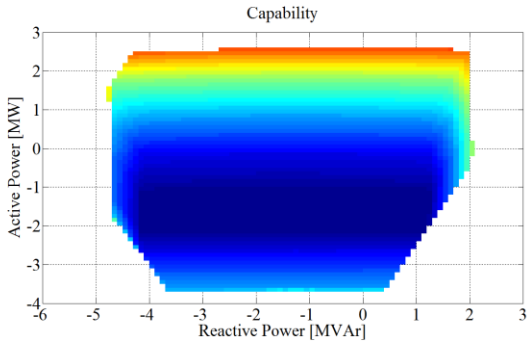

Figure 4: Aggregated capability, computed point by point, having included the *grid impedances* (voltage and current constraints of the network are not considered).

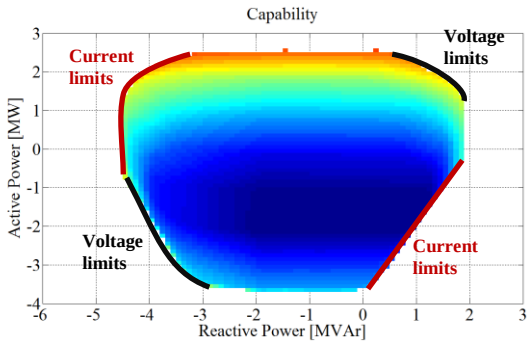

Figure 5: Aggregated capability, computed point by point, considering the *network constraints*.

In addition to the internal cost function, this method returns many additional information on the equivalent capability. In fact, for each investigated point of the *P-Q* plane, the activated resources as well as the network constraints criticalities can be extracted. This can be easily noticed in Figure 5, where the effects of over/under-voltage and overloading limits can be seen: the voltage constraints affect the 1st and 3rd quadrants while the current constraints limit the capability in the 2nd and 4th quadrants. Besides, by approaching the capability boundaries, more resources have to be used to compensate the ones that would cause network congestions.

In spite of the completeness of this capability-extraction method, the inspection of the *P-Q* plane with acceptable resolutions is time consuming. This aspect is extremely important, especially for real time markets (such as the balancing one) in which the prompt estimation of the ancillary services provision is fundamental.

FAST ESTIMATION OF EQUIVALENT CAPABILITY

Since the working point of distribution networks is subject to continuous variations, the reconstruction of the aggregated capability has to be frequently reprocessed. To overcome the time-consuming method discussed in the previous section, a faster procedure is developed.

The proposed method is based on the use of a conventional OPF tool. The basic principle of calculation can be summarized with the following steps:

a) a *Fictitious Unit* (FU) is added to the network model in correspondence of the PCC;
b) a positive cost is assigned to the fictitious unit when its power exchange is not null;
c) zero cost is assigned to distribution flexible resources;
d) an arbitrary power exchange (P_{PCC}, Q_{PCC}) at the PCC is imposed (it has to be outside of the 'ideal' capability area);
e) the OPF is performed.

The general principle behind this method is that the fictitious unit will exchange the minimum amount of active and reactive power (P_{FU} and Q_{FU} respectively), fulfilling the constraints. Therefore, the OPF returns a situation in which the distribution resources will try to exchange the maximum power to minimize the fictitious unit contribution (which has a cost) and to maintain the network in its safe operation area. Acting on the FU costs, OPF objective function, constraints and initial power, it is possible to obtain many information on the equivalent capability. In particular, three methods have been investigated:

- Fixed power factor (radial reconstruction)
- Linear cost: $|P_{FU}|+k|Q_{FU}|$ cost (reconstruction by fixed tangents)
- Quadratic cost: $P_{FU}^2+Q_{FU}^2$ cost (reconstruction by points and slopes)

Radial reconstruction (fixed power factor method)

In this case the FU is modelled in order to exchange power with a fixed power factor ($\tan(\varphi_{FU})$) and with a cost proportional to $|P_{FU}|$. Thanks to this, the OPF solution lies on an arbitrarily selected straight line, for which the slope and the position on the *P-Q* plane depend on the imposed power exchange (P_{PCC},Q_{PCC}) and on $\tan(\varphi_{FU})$. The capability curve is screened by polling a series of OPFs for which different PCC power exchanges and FU power factors have been imposed.

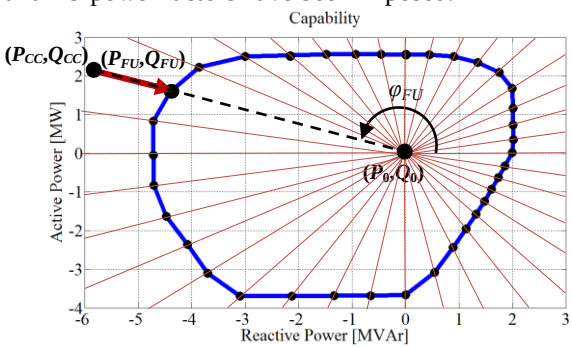

Figure 6: Aggregated capability, computed with the fixed power factor method.

For this exemplificative investigation, the values of P_{PCC}, Q_{PCC} and $\tan(\varphi_{FU})$ have been selected in order to form an

equally spaced sunburst of straight lines centred in the *P-Q* plane origin. According to the working principle described above, each OPF converges on a point that, in this case, corresponds to the intersection between the distribution network capability curve and the selected straight line. Figure 6 reports the interpolated results of this process, extracted with a resolution of 10° for a total of 36 independent OPFs.

Of course, the procedure can be repeated for any desired central point (P_0,Q_0) and angular resolution.

Reconstruction by fixed tangents (linear cost method)

For this particular method, the fictitious unit is modelled without any particular limitations, except for its cost which is assumed to be a linear function of FU exchanged active and reactive power ($|P_{FU}|+k|Q_{FU}|$ with $k>0$).

From the analysis of this cost function, it can be noticed that a given cost value describes a rhombus perimeter on the *P-Q* plane. This means that the OPF identifies the intersection point between the distribution network equivalent capability and the rhombus corresponding to the resulting P_{FU} and Q_{FU} cost (Figure 7). In addition, having assumed that the OPF returns the absolute minimum of the objective function, it can be easily demonstrated that the capability curve:

- is not invading the rhombus internal area;
- is tangent to the intersected rhombus side.

In order to simplify the geometrical interpretation, it can be noticed that, if the imposed power exchange point (P_{PCC},Q_{PCC}) is far away from the investigated capability curve, the rhombus can be reasonably seen as a single straight line (corresponding to one of its sides). The slope of this line depends on the cost factor *k* and it can be demonstrated that (for each quadrant of the *P-Q* plane separately) it is the only parameter influencing the OPF solution. According to this, a single OPF returns:

- a *P-Q* point lying on the distribution network capability;
- a straight line (passing through the previous point) which delimitates the plane where the capability is located.

As for the other methods, the OPF is polled for different values of *k* and the returned results (point and line slopes) are collected. With respect to the procedure described in the previous section, this method allows a faster estimation of the aggregated capability curve: in fact, the resulting set of points and slopes determines a polygon that exactly circumscribes the equivalent capability. Figure 7 demonstrates that, even with 12 OPFs only, the approximated capability is fairly approaching the actual one.

For higher resolutions, it can be noticed that OPF solutions tend to concentrate in correspondence of the capability corners, since these are the areas in which the curve slopes are subject to variations (Figure 8).

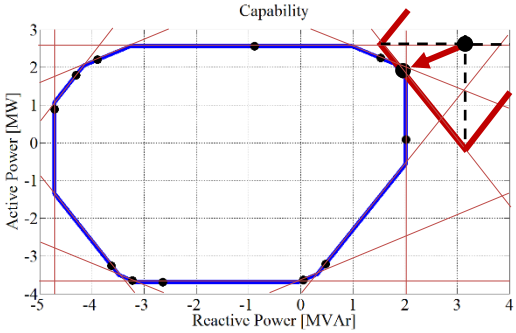

Figure 7: Aggregated capability, computed with the linear cost method by 12 test points.

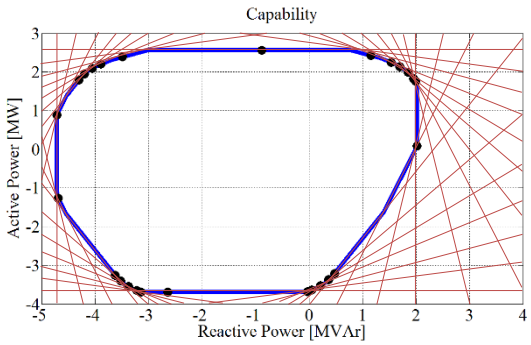

Figure 8: Aggregated capability, computed with the linear cost method by 36 test points.

Reconstruction by points and slopes (quadratic cost method)

Also for this method the fictitious unit has no power exchange limitations but, in this case, it is modelled with a quadratic cost function ($P_{FU}^2+Q_{FU}^2$). In spite of the similarities with the fixed tangent method, the objective function describes a circle (instead of a rhombus) and its geometrical properties can be exploited as well:

- the OPF result is the geometrically closest point of the distribution network capability to (P_{PCC},Q_{PCC});
- the OPF returns also the slope of the capability curve in correspondence of the resulting point.

However, these peculiar characteristics do not provide significant added values with respect to the linear cost method. In fact, neither the solution domain (fixed power factor method) nor the slope of the capability point (linear cost method) can be fixed *a priori*. However, this method can be used to further refine the other estimation processes:

- The fixed power factor method does not return the slopes of the capability curve and the quadratic cost procedure can be used to determine them.
- The linear cost method returns a circumscribed polygon of the equivalent capability and it may hide curve depressions/concavities that cannot be revealed with the same procedure. The quadratic cost method can be used in order to further explore the capability near the polygon sides.

DISCUSSION ON THE PROPOSED METHOD

The proposed three procedures allow a fast and efficient calculation of the equivalent capability curve of a distribution network. There are many advantages in having different approaches to obtain it. Firstly, they allow a cross check of the results and the selection of the most efficient method (which may depend on on the characteristics of the network and flexible resources). Secondly, system operators, as well as aggregators, can adopt the method that better fit the optimization algorithms already available for other purposes. This can greatly facilitate the integration of the functionalities within the operators' SCADA reducing also the licensing and development costs.

On the other side it is immediate to notice that the main limitation of the proposed methods consists in the lack of information related to the capability internal cost function, which is provided instead by the inspection method (Figure 5). However, it is also true that some functionalities require only the capability boundary:

- The three procedures define a profile that is close to the capability curve. This information can be used to optimally select the granularity and the domain of the internal inspection method.
- The capability curve correspond to the maximum possible contribution of the distribution grid in case of contingency at transmission level (situations in which the costs of distribution resources are not often needed).

Nonetheless, the proposed methods can be adapted in order to extract an approximation of the internal cost function. This can be obtained by reprocessing the estimation methods and activating a limited set of resources which is then gradually increased (the first process is executed for the cheapest flexible device, the next one includes also the second cheapest units, etc.). Thanks to this procedure, a series of concentric capability areas can be extracted (with the desired cost resolution). Figure 9 reports the obtained results which are accurately representing the real ones (reported in Figure 5).

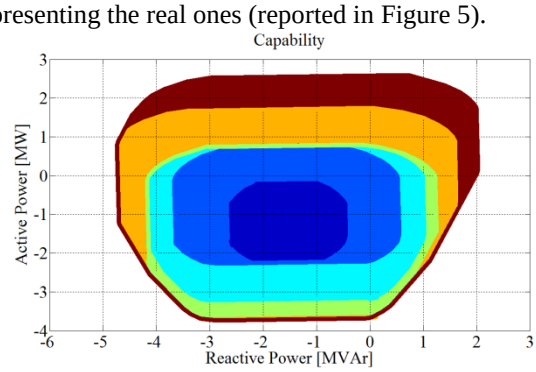

Figure 9: Aggregated capability for increasing number of resources according to the marginal cost, computed with the proportional cost method.

However, this method tends to overestimate the cost function: in fact there are cases in which the partial activation of expensive resources may significantly increase the exploitation of units with lower marginal costs. On the other hand, these situations can be considered very unusual.

Finally, by modifying the costs of the fictitious unit (used for the OPF processing) it is possible to obtain more information about the internal cost of the capability. These methods will be showed in future works.

CONCLUSIONS

In the paper, three methods for a fast computation of the maximum capability of a distribution network and connected resources are proposed. They can be easily adapted to different optimization algorithms, facilitating the implementation in existing SCADA. A fast computation of the capability of the distribution network is a fundamental step to support the coordination between TSO and DSO, facilitating the participation of distributed resources to ancillary services, where the promptness of the resources selection and activation is fundamental. The method can be further extended in order to obtain information concerning the capability internal cost function. Some procedures are shown in the paper and a further discussion will be held in future work.

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