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An Optimization-based Method in Determining the Capability Curve of a Microgrid

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SUMMARY

The capability curve of generators is essential in power system operation as it determines a generator's capability in delivering real and reactive powers. Reactive power dispatch is an integral part of power system operation to ensure system load balance and further manage voltage stability. Although these capability curves are provided by generator's manufacturers and readily available for power system studies, the same is not true for microgrids which comprise various distributed energy resources. The main purpose of this paper is to find the capability curve of a microgrid as a single unit (i.e., a virtual power plant) in a distribution grid. Obtaining the capability curve of the microgrid provides the microgrid owner with a better understanding on how much ancillary services the microgrid can offer to the utility grid, mainly via reactive power production. To determine the microgrid capability curve, an optimization-based method that identifies the maximum and minimum reactive power capability in various real power operation points is proposed. The results of numerical analyses in this paper show how the reactive power behaves under changing of real power production in a microgrid and how these two outputs are correlated.

KEYWORDS

Ancillary services, capability curve, distributed energy resource, microgrid, reactive power.

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1. INTRODUCTION

A microgrid is a small scale power grid, operated at low voltage level, which is implemented by integrating various distributed energy resources (DERs) with the goal of improving local reliability, resilience, and power quality [1]-[3]. In addition to all merits of microgrids, microgrids have also been considered as viable ancillary service providers to utility grids and by increasing their penetration in the network, this role is now ever more attractive [4]-[6]. Considering that all common microgrid DERs can produce reactive power (diesel generators and microturbine through their synchronous generator and solar PV, wind, and batteries through their power electronics interface), microgrids can potentially provide reactive power support to the utility grid in terms of both injecting or withdrawing reactive power.

The reactive power management and voltage stability are strongly related to each other to keep voltage in its proper operational limits. Reactive power requirements usually change over time as loads change and accordingly inductors are used to manage high voltage on transmission systems, while capacitors are used to control low voltage on both transmission and distribution systems. In [7], an optimal reactive power dispatch is proposed to improve voltage stability margin and increase reactive power reserve. Droop control is introduced to adjust reactive power in order to keep voltage stability in microgrids [8,9].

In order to provide the ancillary services to the utility grid, the amount of exchanged real and reactive power between microgrid and the utility grid should be managed. Therefore, obtaining the microgrid power exchange capability, both real and reactive power, is important. The capability curve of DERs could be defined as a boundary within which the generator operates safely. Accordingly, reaching to microgrid capability curve is the first and most important step for microgrid owners in order to contribute to ancillary service needs of the grid. To this end, the capability curve of all DERs in microgrid should be combined to achieve an integrate capability curve for the microgrid.

In synchronous generators, the P-Q capability curve is ruled by some constrains that are explained and calculated in [10]. Leveraging solar PV as a reactive power source and determining its limits and capacity is described in [11]. The possibility of using solar PV as a source of ancillary services to support reactive power compensation, as well as modeling an approach to develop capability curve of solar PV using an advanced control method is proposed in [12]. Real and reactive power in solar PVs could be controlled by various algorithms, applicable to fixed real power mode and maximum power point tracking (MPPT) control mode, that provide fast reactive power with voltage stability during switching between these two modes as discussed in [13]. Energy storage systems could also be used to improve the power quality, including frequency and voltage level and support the system with needed backup power [14]. The battery energy storage system would help in mitigating power fluctuations of PV units and wind turbines under various weather conditions [15]. During the daytime, the battery gets charged from PV system, and during the nighttime the battery discharges to the critical loads or feeds the grid for reactive power and harmonic compensations. A reactive power controller is designed in [16] to control the amount of reactive power delivered to the grid. This controller operates based on power factor measurement.

The objective of this paper is to determine the real-reactive power capability curve of a microgrid with various DERs. To achieve such a curve, the reactive power profile at different load points is determined using a proposed optimization-based method, and consequently the capability curve is drawn. By obtaining capability curve of the microgrid, the microgrid with

different DERs is seen as a single unit in the network, or a virtual power plant, with the ability to offer reactive power. The rest of the paper is organized as follows. In Section 2, the limits of reactive power for each individual DER is explained briefly. In Section 3, the capability curve of a microgrid is calculated using the proposed optimization-based method. Section 4 concludes the paper.

2. CAPABILITY CURVE OF INDIVIDUAL DERS

The capability curve of a microgrid is determined based on the individual capability curve of each of its DERs. The discussion on the capability curve of synchronous generator, solar PV, and battery energy storage is provided below.

Synchronous generator: The capability curve of a synchronous generator is considered as a semicircle with radius S as apparent power, as shown in Fig. 1. The relation between real power (P) and reactive power (Q) is shown in (1) and the limits of apparent (S), real, and reactive powers are illustrated in (2)-(4), respectively.

$$S^2 = P^2 + Q^2 \quad (1)$$

$$0 \leq S \leq S^{max} \quad (2)$$

$$0 \leq P \leq P^{max} \quad (3)$$

$$Q^{min} \leq Q \leq Q^{max} \quad (4)$$

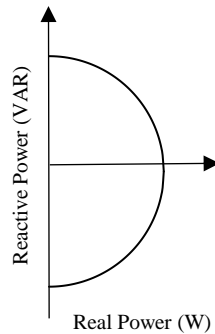


Figure 1: Synchronous Generator and Solar PV capability curve.

Solar PV: The PV unit contains three elements: PV panels, inverters, and transformers [17]. The PV generator is controlled to operate at MPPT and the PV array is modeled as a current source connected in parallel with a capacitor, while the inverter is modeled as a voltage source. The PV unit's output power depends on weather conditions and solar radiation during the day. Maximum delivered real power by PV unit occurs at maximum solar radiation and minimum temperature [18]. The DC voltage of solar PV inverters may limit the reactive power capability of the inverters. The reactive power capability of clustered inverters in PV units is analyzed in [19]. The relationships between apparent, real, and reactive powers are as those in (1)-(4) for a solar PV unit, and the capability curve is shown in Fig. 1, the same as for a synchronous generator.

Battery energy storage: The battery energy storage is used to seamlessly supply the loads during peak hours and to capture power fluctuations of variable DERs. The battery energy storage system has two operating modes of charging and discharging, in which its power is positive at discharging mode and negative at charging mode. The battery energy storage

system's capability curve is a circle with radius S , and with both leading and lagging power factors associated with its operating modes, as shown in Fig. 2. The relation between real power (P) and reactive power (Q) of battery energy storage system is shown in (5) and the limits of apparent power (S), real power (P), and reactive power (Q) are illustrated in (6)-(9), respectively.

$$S^2 = P^2 + Q^2 \quad (5)$$

$$S^{min} \leq S \leq S^{max} \quad (6)$$

$$P^{min} \leq P \leq P^{max} \quad (7)$$

$$Q^{min} \leq Q \leq Q^{max} \quad (8)$$

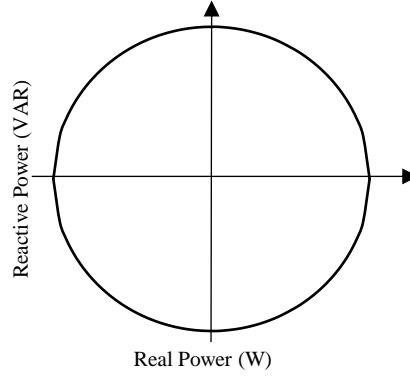


Figure 2: Battery energy storage capability curve.

3. MODEL FORMULATION

To find the microgrid capability curve, an optimization model is proposed as follows:

$$\min/\max Q \quad (9)$$

s. t.

$$P_s + P_b + P_g = P_d \quad (10)$$

$$\text{and (1) - (8)} \quad (11)$$

The objective of this model is to find the minimum and the maximum reactive power that can be produced by the microgrid (9) based on the net real power it produces. This objective is subject to a load balance constraint (10) in which the summation of power output of solar PV (P_s), battery (P_b) and the synchronous generator (P_g) equals a hypothetical net load (P_d). The objective is further subject to constraints associated with individual DERs' capability curves as in (11).

Variables P_s and P_g are positive, while P_b can be either positive or negative based on the battery's charging and discharging state. P_d is initially assumed to be equal to the maximum charging power of the battery (a negative value) and then in each several iterations P_d is increased by a selected step. In each iteration for the selected P_d value, minimum and maximum amount of reactive power that can be produced (two points) are calculated and then P_d is increased by the selected step. This process continues until P_d reaches the generation capacity of the microgrid. In that point the reactive power generation will reach zero as all DERs will generate maximum real power and therefore their respective reactive power generations will be zero, i.e., intersection of their capability curves with the horizontal real power axis.

Given the small size of this optimization problem, a very small step can be considered and the problem can be solved from several iterations to find a very accurate capability curve. The proposed model is generic and can consider any number of DERs as long as individual capability curves are available.

4. NUMERICAL ANALYSES

A microgrid consisting of a synchronous generator, a solar PV, and an energy storage is considered. In order to cover various conditions, three cases with various power capacities for microgrid DERs are considered as follows:

- Case 1:** All three DERs have the same capacity.
 - Case 2:** Two DERs (PV and energy storage) have the same capacity while the synchronous generator is larger.
 - Case 3:** The DERs have different capacities.
- The capacities of microgrid components in aforementioned cases are tabulated in Table 1.

Table 1 Microgrid DERs Capacities

Case Number	Synchronous generator (MVA)	Solar Photovoltaic (MVA)	Energy Storage (MVA)
Case 1	10	10	10
Case 2	20	10	10
Case 3	15	5	10

The proposed model is applied to these cases and the obtained results are plotted in Figs. 3-5. As the figures show, capability curve of microgrid in all three cases are different from capability curve of each component of the microgrid, i.e. semicircle for synchronous generator and solar PV, and full circle for energy storage. Moreover, the figures clearly prove that the capability curve of the microgrid depends on the capacities of its DERs.

Capability curve of microgrid in all three cases are non-symmetrical, however, Case 1 (Fig. 3) has the closest curve to capability curve of each DER since the capacity of all components are the same. Capability curve of microgrid in Case 2 (Fig. 4) has a breakpoint, stemming from the different capacity of the synchronous generator. Fig. 5 depicts the most non-symmetrical figure, belonging to Case 3, with two breakpoints in the curve which stems from the difference in capacities. Thus, the results demonstrate that the shape of microgrid capability curve is affected by the size of units in the microgrid for each case.

It is interesting to note that the shape of the microgrid capability curve is much different from individual DERs; first the shape is not a circle or half circle as is common in DERs; second it has a negative part as well which is resulted from battery charging. However similar to individual DERs' capability curves, once microgrid's capability curve is obtained, a closed form mathematical model can be fitted into the curve to be used for ancillary service studies.

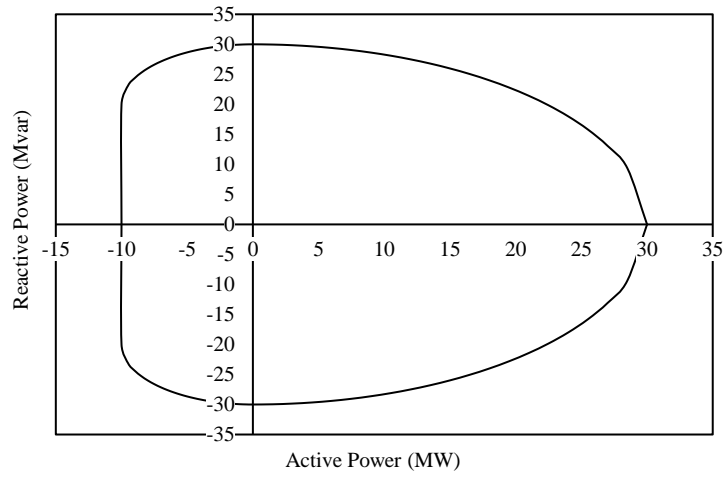


Figure 3: Capability curve of microgrid for Case 1.

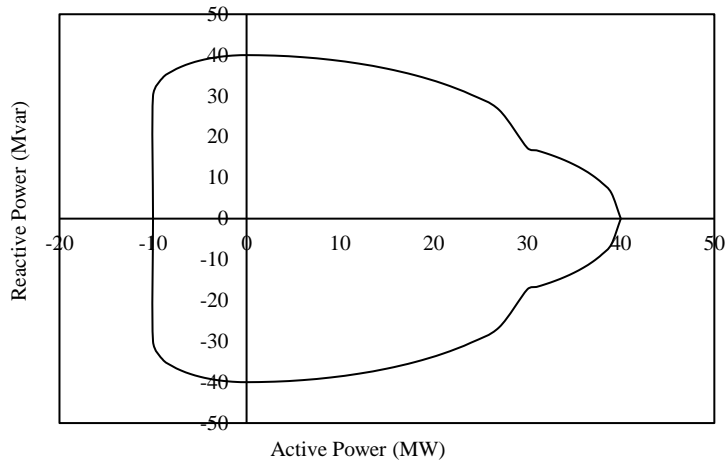


Figure 4: Capability curve of microgrid for Case 2.

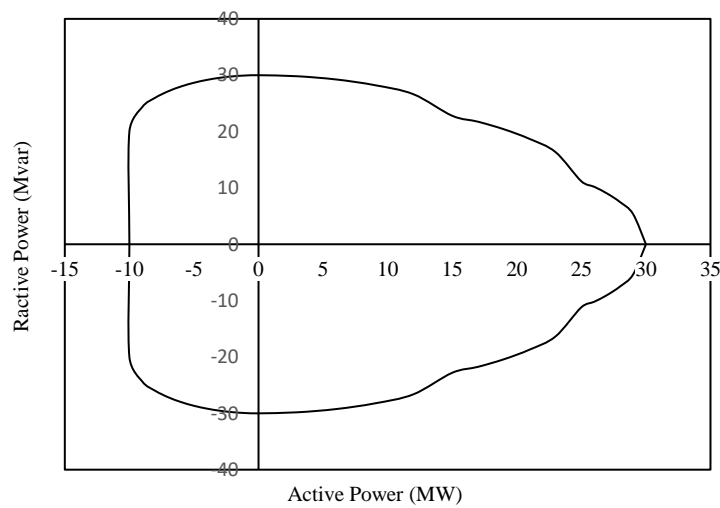


Figure 5: Capability curve of microgrid for Case 3.

5. CONCLUSIONS

Microgrids can be utilized as ancillary service providers in the distribution grid, besides all their other benefits. Accordingly, capability curve of microgrid plays a key role in participating in ancillary service market. This paper developed an optimization-based model to find the capability curve of microgrid as a single unit. The numerical analyses were carried out in various cases and the obtained results showed that the capability curve of microgrid depends on the capacity of its DERs. The shape of capability curve would be significantly changed when the DERs have different capacities.

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