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Modeling inverters with volt-var functions in grid-connected mode and droop control method in islanded mode

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ABSTRACT

New control strategies for distributed generation have emerged in recent years. Since 2009, EPRI and others have been defining standard functions for inverters operating in grid-connected mode. In islanded mode, droop control method is one of the strategies commonly used for distributed generation in microgrids. This paper develops steady-state models for inverters operating with advanced functions such as "intelligent volt-var" or with droop control for simulations with backward-forward sweep power flow-based methods. The models consider changes in system frequency and reference node voltage, fulfilling the zero external power condition, as the case may require. A linear approximation of the system is used to avoid convergence issues in the iterative adjustment of reactive power. The numerical results in the grid-connected mode were consistent with OpenDSS. In the islanded mode, the inverter model faithfully represents the droop control, and the proposed method for power flow based on backward-forward sweep set zero power from the outside, adjusting both system frequency and the reference voltage efficiently. The models proposed will help researchers and companies to update power flow tools, including advanced operating modes of inverters.

1. Introduction

The power inverters in the modern distribution systems are one of the most important elements, being a power interface of a large part of small generators connected to the distribution systems. Due to power electronics, today these devices have advanced control functions that allow accurate control of the active/reactive power and other electrical parameters, which opens up the possibility to have other extra functions in electric power systems [1].

When the system operates in a grid-connected mode, the distributed generation (DG) can provide ancillary services, such as voltage control or reactive power support. On the other hand, when the system operates in an islanded mode, DG can operate through Droop control, controlling both the frequency and voltages of the system.

Currently, regarding grid-connected mode, new control strategies for DG are emerging. Since 2009, EPRI and others [2] are defining functions for inverters: the Intelligent Volt- Var (IVV) and Intelligent Volt-Var with Hysteresis (IVVH) are among the various proposed functions. These functions control the reactive power injected depending on the voltage at Point of Common Coupling (PCC), becoming the DG an important element for electric power quality.

Because these functions are piecewise linear, their modeling by traditional nodes PQ and PV present difficulties in classical solution methods for power flows. For example, in Backward-Forward Sweep (BFS) method [3] there could be convergence issues as will be illustrated in Section 4. Those issues were already reported in Ref. [4]. In reference [5] the modeling of these functions was implemented in OpenDSS [6], which uses a method based on current compensation. However, the same modeling cannot be implemented analogously in BFS method.

Regarding the islanded mode, the droop control is one of the most commonly used in DG [7]. The paper [8] develops a method to solve the power flow through Newton's method in balanced systems operating with droop control. Ref. [9], also solves load flow in an islanded system using Newton's method, characterized by not using the slack bus. The authors of [10] modeling droop based DG inverters in the islanded mode for phasor simulation method. In paper [11] the multi-terminal voltage source converter HVDC systems with droop control are modeled for power flow solving by Newton's method. Ref. [12] has formulated power flow for an islanded system with generators operating via droop control, the

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slack bus is an only angular reference, and it is solved through Newton-trust region method. In Ref. [13] have formulated power flow for islanded balanced system and optimize the droop gains with a metaheuristic. It would be convenient to develop a method to solve the power flow in the distribution system with DG operating through Droop control, ensuring fulfill conditions of isolation, such as frequency and reference voltage changes. The authors of Ref. [14] proposed a method based on BFS with these characteristics, although it could be modified to improve convergence issues, modifying the adjustment mode of the reference voltage, frequency, and reactive power.

Literature review shows that PQ and PV nodes are usually used to model the inverter behavior in power flow methods. The authors in Ref. [15] present an adaptive method based on compensation to solve power flow, and PQ and PV nodes model DG. In Ref. [16] stability analyses are performed using a nodal matrix-based method to solve power flow and inverters were modeled as PQ and PV nodes without considering Volt-Var functions. In paper [17] the DG model used in the BFS method has also been PQ and PV nodes. The effects on voltage profile and power losses were tested in Ref. [18] by varying the allocation and capacity of DG, they used BFS method, and in the same way, the inverter was represented as PQ or PV node. On the other hand, there are already publications about control models in distribution systems. In Ref. [19] presented a power flow algorithm, where all control actions of LTC transformers, switched capacitors, and PV nodes have been modeled through current source injections. The letter [20] proposed a model for bi-directional voltage regulators avoiding convergence problems in BFS method.

In literature, none of those above studies have modeled the volt-var functions for DG in BFS method. Thus, the development of a reliable model of volt-var functions into this method is necessary. The BFS is currently the most used method in radial or weekly meshed systems. Thus, the implementation proposed will help researchers and companies from changing power flow tools to use the new control functions offered by modern inverters or other devices with volt-var functions.

One contribution of this paper is to model the volt-var functions in BFS method. For the IVV function, a novel model is proposed to avoid convergence issues using a linear approximation of the system; this model can easily be extended to consider other control strategies, including the classic PQ and PV nodes. For the IVVH function, a method to model the inverter in steady-state is proposed, the method uses the IVV modeling to obtain the operative limit points. Another contribution is a method to solve the power flow in islanded systems with DG operating through droop control, considering both system frequency change and voltage magnitude change on reference node (fixed angle only). The method also uses a linear approximation of the system to avoid convergence issues caused by inadequate updating of reactive power values in inverters.

Sections 2 and 3 present IVV and IVVH functions; Section 4 details the convergence issues in the power flow due to the direct modeling of the IVV function; in Section 5 a model that avoids the convergence issue is proposed for grid-connected mode; Section 6 explain the generalization of modeling for other control strategies. The last proposed model, in Section 7, deals with power flow solution in islanded systems with DG operating via droop control method. All tests and discussions are in Section 8. Finally, in Section 9 the conclusions are exposed.

2. The IVV function

The IVV function determines the response of reactive power as a function of the voltage, being able to collaborate in voltage regulation or to provide reactive power support to the system. The reactive power that injects/absorbs the inverter has a linear dependence with the voltage at PCC, defined by a piecewise linear function, Fig. 1.

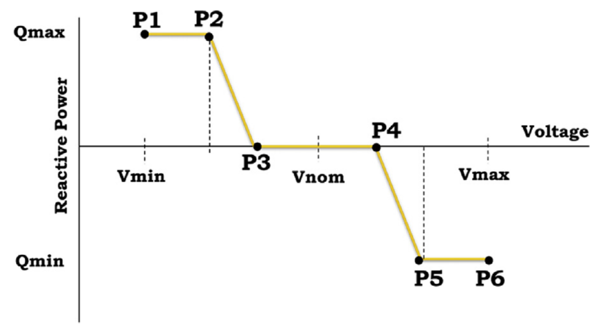

Fig. 1. Intelligent Volt-Var function.

The inverter absorbs the maximum reactive power capacity from the grid when the voltage is higher than the point P5 and injects the maximum reactive power capacity if the voltage is less than P2. When the voltage drops from v_{min} or exceeds v_{max} the inverter is disconnected from grid. The reactive power injection between P2 and P3 is calculated linearly, and likewise between P4 and P5. It includes a dead zone between P3 and P4, not injecting reactive power between these values [21].

The mathematical formulation to update the reactive power injected by the inverter is given by Eq. (1).

$$f_{IVV}(v)\begin{cases} 0 & \text{if} \quad v < v_{P1} \\ Q_{P2} & \text{if} \quad v_{P1} \le v \le v_{P2} \\ Q_{P2} + \dfrac{Q_{P3} - Q_{P2}}{v_{P3} - v_{P2}}(v - v_{P2}) & \text{if} \quad v_{P2} < v < v_{P3} \\ 0 & \text{if} \quad v_{P3} \le v \le v_{P4} \\ Q_{P5} + \dfrac{Q_{P5} - Q_{P4}}{v_{P5} - v_{P4}}(v - v_{P5}) & \text{if} \quad v_{P4} < v < v_{P5} \\ Q_{P5} & \text{if} \quad v_{P5} \le v \le v_{P6} \\ 0 & \text{if} \quad v_{P6} < v \end{cases} \tag{1}$$

where Q_{Pi} is the reactive power and v_{Pi} is the voltage of each point Pi belonging to configuration of function $f_{IVV(v)}$. The $f_{IVV(v)}$ gives the reactive power depending on voltage v.

3. The IVVH function

The IVVH function has two curves similar to the IVV function defining a region of hysteresis, as shown in Fig. 2. When the voltage at PCC is increasing, the operating points are those that are given by curve P1–P2–P3–P4. Otherwise, the operating points are defined by curve P4–P5–P6–P1. If the voltage magnitude reverses its sign, the reactive power remains constant until it reaches a perimeter point of the hysteresis zone and only then begins to change the reactive power as a function of P2–P3 or P5–P6, depending on the case. There are also operating limit voltages when the voltage drops from P1 or exceeds P4 the inverter disconnects from the grid [21].

4. Convergence issues in IVV function model

When the IVV function is modeled similarly to [5] or as compensation method of PV nodes [22], would normally have the following steps: