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Theme 1: Integrating New Flexibility Tools and Principles for Planning

Advances in OpenDSS smart inverter modelling for quasi-static time-series simulations

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Abstract: The fleet of smart distributed energy resource (DER) inverters is expected to grow rapidly as a result of growing DER penetration levels and requirements in interconnection standards/rules such as IEEE Std 1547-2018. Smart inverters have the potential to help to maintain and/or enhance grid safety, reliability and customer affordability. Advanced modelling and analytical capabilities are required from distribution planning tools to understand the full potential of smart inverters. This study presents enhanced smart inverter modelling and simulation features included in a recent release of the open-source distribution system modelling and simulation software suite OpenDSS. The enhanced features include detailed modelling of the inverter capability curve along with significant improvements to the simulation speed and convergence. The enhanced features make it more practical to perform long quasi-static time-series load flow simulations with thousands of time steps on large-scale utility feeder models with up to thousands of autonomously controlled smart inverters. Some of the enhanced speed, convergence and other features are demonstrated on a large-scale real U.S. utility feeder model with >1100 solar photovoltaic systems.

1 Introduction

Interconnection standards and rules, including the recent IEEE Std. 1547-2018 [1], which is widely adopted in the U.S. and internationally, require the so-called smart features from distributed energy resource (DER) inverters. Driven by these requirements, the fleet of smart DER inverters is expected to grow rapidly potentially helping to maintain and/or enhance grid safety, reliability and customer affordability. However, many challenges remain to be addressed for this potential to be fully realised. Distribution planning approaches, data, models and analytical features that have been commonly used are now proving to be insufficient to efficiently and reliably interconnect, integrate and utilise DER in the electric grid. In particular, enhanced features to model and simulate future distribution systems with high penetrations of smart DER inverters are required from distribution system modelling and simulations tools such as OpenDSS. OpenDSS is an open-source distribution system modelling and simulation software suite widely used by utilities, researchers and other stakeholders worldwide [2].

This paper discusses enhanced modelling and simulation features of smart inverters of solar photovoltaics (PVs) and energy storage (ES) included in a recent OpenDSS release. This paper also discusses the complexity of smart inverter modelling and the challenges associated with ensuring rapid and robust convergence with a large number of autonomously controlled smart inverters.

The remainder of this paper has the following structure: Section 2 introduces the enhanced OpenDSS modelling and simulation features for smart inverters of PV systems and ES. Section 3 demonstrates these enhanced modelling and simulation features on a large-scale real U.S. distribution system circuit. Finally, Section 4 concludes the paper and discusses future work.

2 Enhanced OpenDSS smart inverter model

In OpenDSS, smart PV and ES inverter models consist of two components. The model of the physical inverter component with its associated ratings (kVA, reactive power limit, among others parameters) is incorporated into the models of ‘PVSystem’ and ‘Storage’ elements. The two elements belong to a set of elements, which exchange power with the grid and hence, are referred to as power conversion elements. The control logic for smart inverter functionalities, such as the Volt-Var (VV), Volt-Watt (VW) and dynamic reactive current (DRC) functions are modelled within a separate ‘InvControl’ element, which belongs to a set of control elements (CEs). Fig. 1 shows the relationship between these elements.

A major update to the OpenDSS PV system and ES system inverter modelling was released at the end of 2019. The update added several enhanced smart inverter modelling and simulation features, such as the capability to control the inverter based on remote voltage monitoring points (as opposed to the inverter terminal) and the addition of a built-in inverter to the ES model. The two most important improvements are (i) detailed modelling of the inverter capability curve and (ii) significant improvements in the convergence and speed of simulations involving smart inverter functionalities. As follows, these two key improvement areas are discussed.

2.1 Inverter capability curve

Modelling of the inverter capability curve was significantly refined to allow, among other aspects, the representation of diverse complex real-world inverter capability curves, such as defined in IEEE Std 1547-2018 [1]. The refined modelling features allow representing settings and limits such as apparent power, cut-in/cut-out power and maximum reactive power. The flexibility of the modelling is shown in Fig. 2. The inverter capability curve defines the feasible inverter operating regions. Fig. 2 shows three different regions:

(i) *Normal operating region:* Region in which the inverter is most likely to operate throughout the day. The inverter can exchange both active and reactive power with the grid.
(ii) *Operating region with watts only:* Region in which the inverter does not exchange reactive power with the grid.

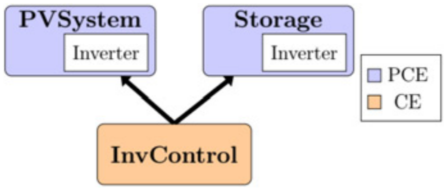

Fig. 1 *Relationship between OpenDSS PVSystem, Storage and InvControl elements*

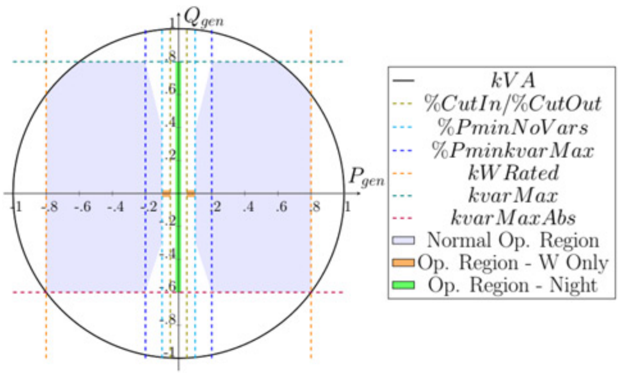

Fig. 2 *Inverter capability curve and settings*

(iii) *Night operating region:* Region in which there is only reactive power exchange with the grid (if enabled).

The settings and limits shown in Fig. 2 are OpenDSS parameters, described below:

- kVA [kVA] indicates the inverter nameplate capability.
- kWRated [kW] indicates the maximum active power that the DER can exchange with the grid.
- kVarMax [kVar] indicates the maximum reactive power that the inverter can provide.
- kVarMaxAbs [kVar] indicates the maximum reactive power that the inverter can absorb.
- Cutin [kW] is the minimum DC power necessary to turn the inverter ON when it is OFF.
- Cutout [kW] is the minimum DC power necessary to keep the inverter ON.
- %PminNoVars [kW] is the minimum active power under which there is no reactive power exchanged with the grid.
- %PminkVarMax [kW] is the minimum active power that allows the inverter to exchange reactive power.

The aforementioned parameters allow the user to generate a myriad of inverter capabilities by disabling one or more of the parameters (a parameter is disabled by assigning it a zero value). Fig. 3 shows the first quadrant of the inverter capability curve for two sets of parameters. Fig. 3 on the left is generated by disabling parameters *%PminNoVars* and *%PminkvarLimit*. Fig. 3 on the right shows a capability curve defined by a constant power factor that is generated by disabling parameters *%CutOut* and *%PminNoVars*, and by assigning %PminkvarMax equal to the desired power factor.

Another important feature added was the possibility to assign each inverter active power, reactive power or power factor priority. The priority defines how the inverter is returned to the normal operating region when the inverter powers requested (by either a smart inverter function such as VV or directly by the user) at a given power flow iteration are outside the inverter capability curve. Fig. 4 illustrates few examples of how the different priorities return the inverter operating point into the normal operating region, see [3] for details.

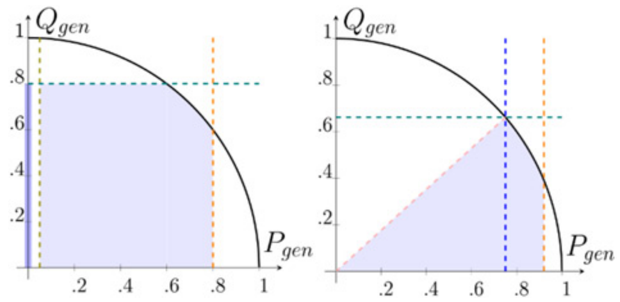

Fig. 3 *First quadrant of the inverter capability curve with %PminNoVars and %PminkvarMax disabled (left) and %PminNoVars and %CutIn/CutOut disabled and %PminkvarMax = 0.75 (right)*

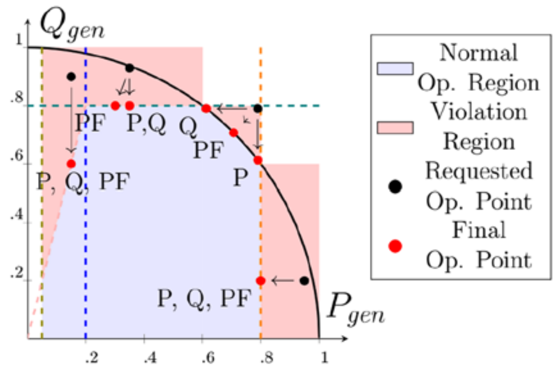

Fig. 4 *Inverter operation, e.g., conditions on the inverter capability curve*

2.2 Speed and converge enhancements

OpenDSS manages the operation of CEs as a part of the 'control loop'. To simplify, this process works as follows. First, all controllers sample the variables they regulate (e.g. voltage for VV function and reactive power for power controlled switched capacitor bank) and, based on their control logic, define (or request) new values for the control variable (e.g. reactive power for VV function and capacitor state for switched capacitor bank). Then, the control actions are executed, and a new power flow is solved. The process is repeated until all CEs have converged and no more control actions are needed. For the case of smart inverters, this is when (i) the controlled variable assumes a value close enough (by a pre-defined tolerance) to the value requested by the smart function and (ii) the variation in the regulated variable between two subsequent control loop iterations is within a pre-defined tolerance. Note that a single solution time instant may require many iterations of the control loop and hence, many power flows. For more details on this process, see [4].

In traditional distribution systems, with just a few controlled elements, this process converges quickly and robustly. However, it is not trivial to achieve rapid and robust convergence in modern distribution systems with up to hundreds if not thousands of smart DER inverters. This becomes particularly important in quasi-static time-series (QSTS) simulations with thousands of time steps.

The main reason for non-convergence is the impact that a given controller can have on the other controllers. For instance, suppose that the smart inverters of two adjacent customers operate under the VV function and detect a low voltage. Typically, both inverters will inject reactive power in the grid to support the local voltage. However, if the resulting voltage rises too high, in the next control iteration the VV function of both inverters may request the inverters to absorb reactive power to reduce the voltage. Then, in the next control loop, the process repeats again and in the worst case, may never converge. This happens because these functions are designed to operate locally, i.e., solely on the local measurements available. This behaviour in the control loop is somewhat like the hunting effect [5], which may happen with discrete controllers of load tap changers and voltage regulators.

In OpenDSS, the strategy adopted to overcome this behaviour is to slowly move the controlled variable to the target requested by the smart functionality. This is performed by applying constant and less than unity scaling factors to the entire fleet of controllers. The scaling factor applied depends on the nature of the function. For reactive power functions (such as VV and DRC) and active power functions (such as VW), *deltaQ_factor* and *deltaP_factor* factors are used, respectively. This strategy has been proven to sufficient to achieve convergence in low to medium DER penetration levels. In general, low factors tend to provide more robust convergence, but at the expense of solution speed. In earlier OpenDSS versions, these scaling factors were manually defined by the user and finding good factors for complex simulation scenarios could require considerable effort and user expertise. Poorly selected scaling factors could result in non-convergence.

A single and constant set of factors to the entire fleet of smart inverters is not optimal given that different inverters can be subject to considerably different node voltage sensitivities. For instance, for a DER connected to the beginning of the feeder (stiff region) a variation in the reactive power exchanged with the grid leads to lower voltage change compared to the same reactive power variation in a region farther from the feeder's head.

The recent update in OpenDSS tackles this issue by automatically updating the scaling factors during each control iteration and for each DER inverter. This is accomplished by adjusting the scaling factor based on the voltage changes between successive control iterations. This change considerably improves the simulation speed and convergence robustness.

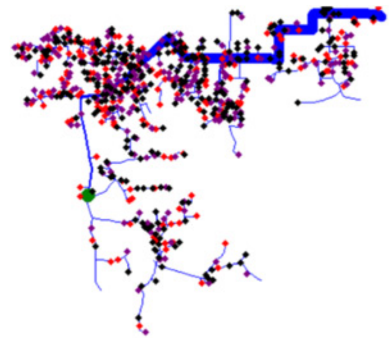

Fig. 5 *Case study feeder highlighting PV systems with VV, VW and CPF functions activated with red, purple and black dots, respectively. The green dot indicates the location of the utility-scale PV system*

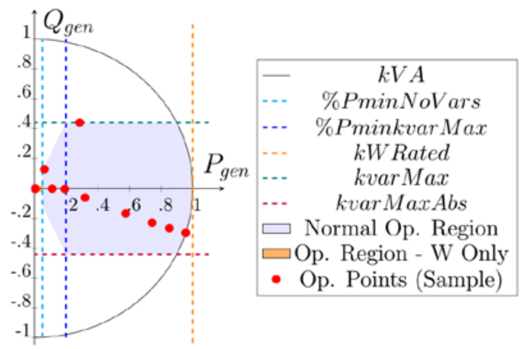

Fig. 6 *Inverter capability curve for the utility-scale PV system with selected points of operation*

3 Case study analysis

This section demonstrates the enhanced OpenDSS smart inverter modelling and simulation features on a distribution system model of a real U.S. 12-kV distribution feeder modelled in OpenDSS. The feeder has a peak load of ~3.8 MW and serves 1140 residential and commercial customers. The large-scale model has 4690 devices and 5710 nodes. A daily QSTS simulation was performed at 5-second time granularity (17,280 time steps) using a real high-granularity PV irradiance data set. To create a highly complex case study, each of 1140 customers in the model was given a PV system. The PV systems were set with a kW rating equal to the customer peak load and the DC-to-AC ratio of 1.2. For each PV system, one of the following smart inverter functions was randomly activated:

- IEEE Std. 1547-2018 VV with category B default settings with var priority,
- IEEE Std. 1547-2018 VW with default settings or
- constant inductive power factor (CPF) of 0.98 with reactive power priority.

Additionally, a 4-MW utility-scale PV system with a DC-to-AC ratio of 1.1 was added and IEEE Std. 1547-2018 VV with Category B default settings was activated for it. Fig. 5 shows the topology of the case study feeder and the locations of the 1141 PV systems.

3.1 Inverter capability curve

To illustrate the inverter capability curve modelling, Fig. 6 shows the PQ plane of the utility-scale PV system and a few operation points measured throughout the simulation. As expected, some operational points lie at the border of the capability curve. These points correspond to time instances when the inverter power output was limited by the capability curve.

3.2 Convergence and speed improvements

To illustrate the convergence and simulation speed improvements achieved by the enhanced OpenDSS features, the same circuit was simulated with two OpenDSS versions: an earlier version from before the enhancements and Version 8.6.7.1 from after adding the enhanced smart inverter features.

The simulation time of the earlier and the enhanced OpenDSS versions were 10.34 and 7.16 min, respectively. The enhanced version reduced the simulation time by 3.18 min or 30.74%. To put the 7.16-min simulation time into perspective, the performed QSTS simulation involved solving 17,280 time steps (each involving multiple load flows and control iterations to reach convergence) with 1140 autonomously controlled smart inverters with discrete smart inverter functions, and the feeder conventional voltage regulation equipment. The simulation with the earlier OpenDSS version was performed with *deltaP_factor* and *deltaQ_factor* parameters that were manually optimised to perform relatively well. Using other parameters could have resulted in considerably longer simulation time or the lack of convergence.

4 Conclusion

Effective and efficient integration of high penetrations of DER requires new distribution system modelling and simulation capabilities, including enhanced capabilities to assess the impact and value of smart DER inverters. This paper discusses enhanced smart DER inverter modelling and simulation features developed in the open-source distribution modelling and simulation software OpenDSS. The enhanced features significantly improve the simulation convergence and speed, and provide many other new features, such as detailed inverter capability modelling features, as defined in IEEE Std. 1547-2018.

The improved simulation convergence and speed achieved by the enhanced OpenDSS modelling and simulation features were demonstrated on a complex large-scale case study feeder model. Compared to an earlier OpenDSS version, the enhanced OpenDSS version improved the simulation speed by 30.74%. The enhanced OpenDSS version also significantly improves the simulation convergence by automatically finding good convergence parameters for each individual smart DER inverter. This not only yields optimal balance between convergence robustness and speed, but also frees the user from the burden of finding good convergence parameters, as was necessary for earlier OpenDSS versions. The case study is further used to demonstrate the enhanced inverter capability modelling features.

5 References

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