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Accuracy and Validation of Measured and Modeled Data for Distributed PV Interconnection and Control

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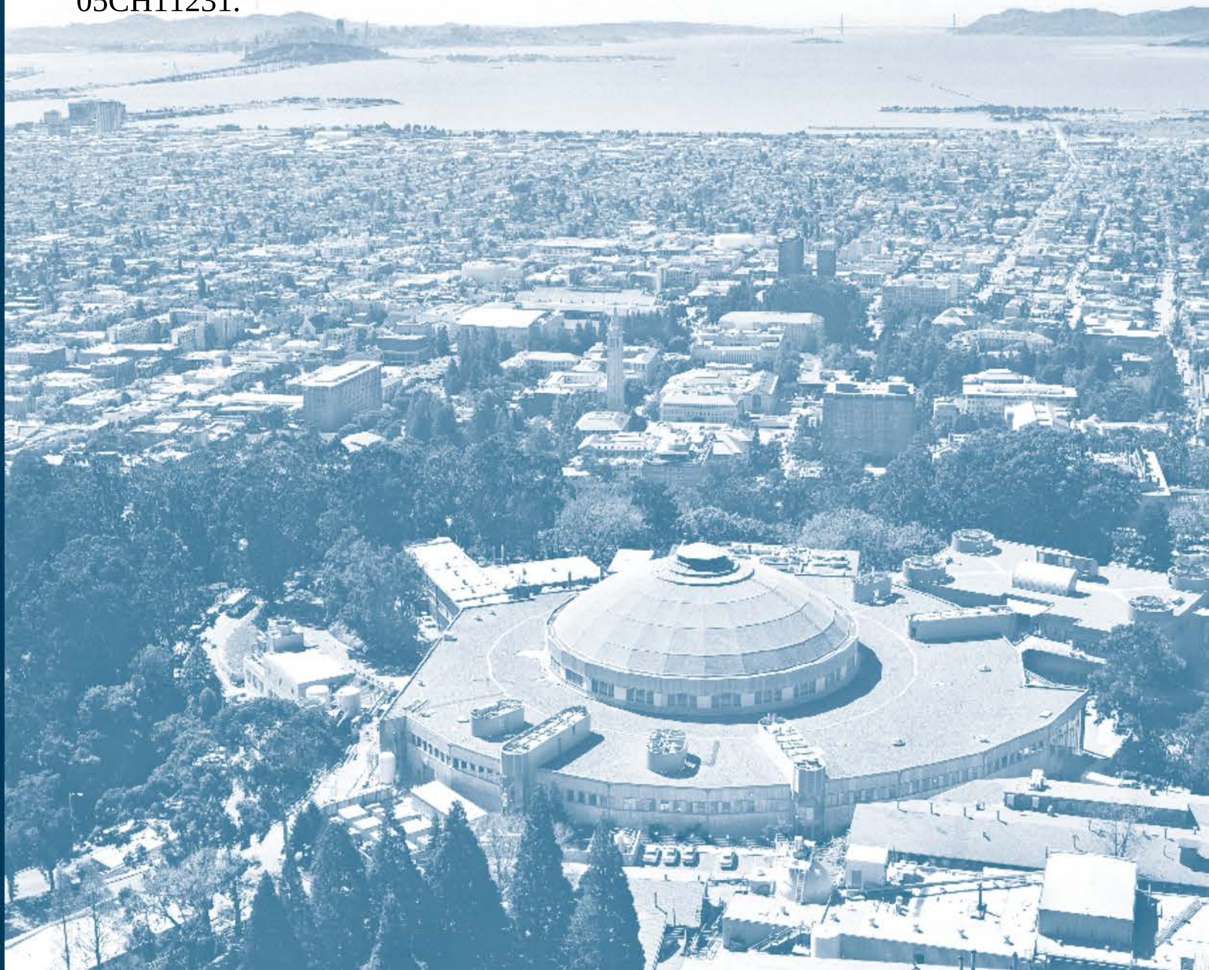

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***Abstract*—The distribution grid is changing to become an active resource with complex modeling needs. The new active distribution grid will, within the next ten years, contain a complex mix of load, generation, storage and automated resources all operating with different objectives on different time scales from each other and requiring detailed analysis. Electrical analysis tools that are used to perform capacity and stability studies have been used for transmission system planning for many years. In these tools, the distribution grid was considered a load and its details and physical components were not modeled. The increase in measured data sources can be utilized for better modeling, but also control of distributed energy resources (DER). The utilization of these sources and advanced modeling tools will require data management, and knowledgeable users. Each of these measurement and modeling devices have accuracy constraints, which will ultimately define their future ability to be planned and controlled. This paper discusses the importance of measured data accuracy for inverter control, interconnection and planning tools and proposes ranges of control accuracy needed to satisfy all concerns based on the present grid infrastructure.**

***Index Terms*— Distribution, Measurement Standards Photovoltaic, Validation, Simulation Tools.**

I. Introduction

California and the U.S. have an ambitious vision for the utilization of distributed energy resources in the distribution grid, which involves high penetration of photovoltaic (PV) and other active resources. The future grid will have more complex analysis needs and new control architectures, coordinating load, storage and generation based resources. To interconnect these resources, we utilize models and simulation at distribution planning and operations levels. The accuracy of these models, and availability of measurement data to validate the models will be a key component in defining overall deployment and future control strategies. In contrast to this, the representation of the control systems performance will require alternate modeling paradigms. There is a growing number of measurement resources becoming available including distribution phasor measurement units, a technology pioneered for transmission visibility and stability now being applied to complex distribution issues. For these data sources to be useful, they must be accurate, and interpreted correctly. Errors in models are prevalent in the distribution system, and data accuracy is a key challenge that leads to a lack of confidence in analysis and operations, and reluctance to move forward with advanced grid analyses in the simulation environment. We will discuss and provide an analytic example of the impact of lack of model validation on interconnection of renewables to the distribution grid and the impact of this accuracy on control strategy.

Barriers to modernization of the distribution system include availability and capabilities of existing planning tools, data availability, model validation and accuracy, particularly inaccurate representation of impedances and loads. This paper reviews and discusses the limitations of distribution planning tools, in the context of inverter modeling and control First we identify three key barriers to the integration of renewables. Second, we discuss each barrier in detail with emphasis on the impact of model inaccuracy and uncertainty on control outcomes. Lastly, we discuss the future of distributed resources and how these tools must evolve.

II. Existing Interconnect Process

When highly distributed generators such as residential and small commercial PV apply for interconnection to the utility network, there are limited analytic tools available to evaluate their potential impacts. Since their deployment has not been strategically controlled, these renewables can be significantly clustered: In Hawaii and California there are a significant number of distribution feeders where distributed PV amounts to well over 15% of peak feeder capacity, including some feeders in Hawaii where PV capacity represents 120% of minimum daytime load. This can have technical and economic consequences for both the consumer and the utility [1][2]. PV could, under the correct operational control scenarios, provide numerous benefits to the grid, including operational reserve and voltage support, but to ensure grid reliability we need to be able to analyze the behavior of the large number of inverters that will be present on the future

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grid as well as their interaction with other devices. At the moment, the restrictions imposed by IEEE 1547 [3] prevent PV resources from providing the protection and control benefits they could offer to the grid, such as participating in voltage control or intentional islanding. To date, the steady-state and time series performance of small residential inverters can be roughly predicted with simple unity power factor models. Introducing complex control parameters to inverters poses a new challenge, because for interconnection studies, we must account for the legacy control schemes already in place as well as the new schemes to ensure coordination and reliability. Consequently, the future distribution grid has complex analysis needs, which may not be met with the existing processes and tools. Even if distribution circuit models are capable in theory to support the requisite analyses, they have inherent accuracy problems due to lack of validation in the absence of measured data. Data availability and accuracy is a key barrier to the growth of the future distribution grid, as is ensuring complex control strategy can be represented and adapted at the planning level.

Thus, from a planning analysis standpoint, there are three related barriers to the integration of renewables to the distribution grid:

- The lack of tools to adequately represent high penetration levels and advanced control strategies for distributed resources;
- The lack of accuracy and trustworthiness of models , often due to limited availability of data for their validation; and
- The limited accuracy of measured data sources in and of themselves, for control and validation purposes.

We will address each of these issues and recommend the potential improvements that need to be made to enable the future grid.

III. TOOLS DEVELOPMENT

Distribution planning tools were developed in response to the need for efficient analysis and digitization of data, but most were developed based on the assumption of one-way power flow, without high penetration of renewables and short time scale control characteristics. Short time scales in this context mean minutes or hours versus a six-month planning horizon. The standard approach in the distribution grid planning software development is a combination of accommodating or approximating representations of key components, such as inverters and detailed loads. Overall, today's distribution grid planning tools are in a rudimentary stage. Although some advanced analysis tools have been developed, their capabilities, data requirements and applications (i.e., identifying when it is necessary to use an advanced tool) are not well understood.

A. Inverter Modeling

As PV and distributed resources are allowed to play a deliberate role in grid stability and interaction, the modeling complexities will increase. The way distributed PV is currently modeled, as a load reduction or negative load that does not cause reverse power flow, means that modeling cannot account for its effects on protection and control. In the event of a fault, distributed PV as a negative load cannot be modeled as islanding or tripping during load-shedding and switching operations. Therefore, because models cannot simulate what PV can actually do, it is not possible to plan for fully utilizing its protection and control capabilities.

Inverter topologies and control characteristics vary significantly for each vendor. The importance of that topology increases as the complexity of the analysis increases; that is, in a simple steady-state model advanced features might not need to be included, but in a dynamic situation control and protection must be simulated and a vendor-specific model is often needed. In transient analysis in a component-level model, detailed feedback loops and sub-cycle performance characteristics must be included. As complexity grows, so does the risk of error in model validation. However, rather than having an inverter model in each software package, for the future distribution grid analysis, the ability to use similar models or hook a single model in a generic package (such as Simulink) into different commercial analysis packages would be advantageous [6][7].

Models for inverter dynamic and transient stability are generally proprietary. Although some generic modeling is available, the components' time constants and control loops are unpublished, so detailed modeling will always have inherent estimations and errors. The single-model-source concept, in which the user of simulation software would not need to coordinate among multiple model types (steady state, short circuit, dynamic, transient) to analyze advanced grid conditions, would address the limitations imposed by the current proprietary models. The complexity and volume of potential inverter models makes the high penetration of renewable distribution grid a daunting prospect [4].

B. Dynamic and Time-Series Analysis Data Constraints

Advanced control schemes may be executed on varying time steps, some of which could be rather short. Therefore, instead of the circuit model representing a snapshot of the system operating in steady-state, time series and dynamic modeling is expected to become essential. Time-series or quasi-steady-state analysis as outlined earlier (in Section 4), is time-stepped steady-state analysis, meaning that each time step requires a full power flow for however many nodes and control points the distribution model has. Thus, for one-second steps for 24 hours, a total of 86,400 power-flow simulations would be required. Dynamic and active sources will require additional models.

Therefore, for each inverter or equivalent PV system, there are three or four dynamic model pieces on top of the basic steady state model. To perform modeling for a small western U.S. utility that presently has more than 7,000 on-line inverters, at least three times as many dynamic models as inverters would be required (21,000). This is outside the model processing capability of many transmission models; most transmission analysis packages can only use approximately 4,000 models. In addition to analyzing distributed energy resources (DER), models (dynamic, transient, and steady state) are also required for transformers, and protection and voltage regulation devices. In dynamic analysis control, models are required to invoke such features as under-frequency load shedding, which exponentially increases the processing requirements. However, there are a number of ways to address this problem other than increasing computing power; these include model aggregation and node reduction, as described in the next subsection [8][9].

As the distribution grid modernizes and DER become an integral part of the control schema, aggregating models and device control features may reduce accuracy; therefore, inverter and load characterization will be essential. Characterization means representing performance using representative differential equations, control loops, or measured data. Planners and operators will need rapid analysis and processing time for dynamic and increased switching operations. This is another example of the need for quick planning analysis that rapidly translates into operational actions. The accuracy of the analysis will depend on convergence of the simulation, which, without improving the data processing capacity that is found in commonly available distribution software, will limit planning capabilities.

IV. Accuracy of Models and Benefits of Validation

We have now addressed the abilities and need for various features within distribution analysis and modeling tools, and discussed what features may be present in the future distribution grid that drives the need for more accurate analysis. Following this we concentrate on accuracy of model outputs. Accuracy means how closely a tool's predictions (for example, instantaneous voltages and currents during a fault or generator trip) represent the measured, real-world grid behavior. While tools may be developed with many advanced features, these will not be useful if the models are not accurate. The quality of the data input to the models directly impacts the usefulness of the output. Putting the measurement and modeling portions of analysis together into a validation and calibration process will enhance the value of grid analysis tools exponentially.

Some degree of error in engineering analysis of the distribution system is generally accepted. Across various tools, the standard for accuracy is within 0.5% for voltage and current output at individual nodes [7][9]. In practice, the impact of errors of this magnitude is small, but greater errors can begin to have significant economic and technical implications.

While in previous generations of studies, knowledge of the ratio of peak load to PV capacity was considered the most important factor, recent work [10] supports the intuitive notion that daytime minimum load is the relevant measure for comparison, and time series analysis must be represented. For example, consider the interconnection of a 2MW resource, expected to inject approximately 1.5MW peak during optimal conditions. The feeder load capacity peak is 4MW, but during weekend loading the feeder has only 1MW daytime load. Therefore during weekend hours there is a high probability of reverse power flow to occur, which could require changes to protective relaying and operation of the load tap changer. If minimum and time-series load is not accounted for, there could be detrimental impact to the system.

A more complex example of impact would be during planning for upgrades and interconnection. A distribution system impact study could indicate, for example, a power quality or flicker issue caused by an interconnecting generator. During simulation, a number of factors could contribute to producing this result, from conductor type to source impedance, or control strategy for existing equipment. Suppose that some of the model data is incorrect, however: say, the impedance indicated a weaker distribution line. It is possible that a power quality issue would be flagged in basic modeling of step change performance of the generator. The utility could then require the interconnecting generator to install expensive or even prohibitive mitigation techniques, which, had the model been correct, would not have been found necessary. By raising spurious flags, the interconnection process based on inaccurate models could limit renewables integration, an important target in many areas for utilities. Conversely, inaccurate models could fail to predict an actual power quality issue, which would then economically and technically impact customers and the utility – or, even more important, compromise safety. For example, without accurate knowledge of topology, field workers could inadvertently switch into an unknown topology and cause arc flash or overloading. Many of these issues could be solved by validating the distribution models, but until recently data was not available for this function.

V. Measurement Data Sources for Control and Validation

Possible data sources required or desired in the future distribution grid scenario include at the basic level household level smart metering, and Supervisory Control and Data Acquisition (SCADA) at the substation and selected components. Advanced grid level sources include transmission and distribution phasor measurement units (PMUs), inverter measurement and communications, and line sensors. Non grid based data include weather data and geographical information systems. Note that each of these measurement devices operates and measures on a different time scale. Mismatch in time steps or lack of time synchronization among devices adds to inherent measurement errors and thereby increases the complexity of the PV integration solution.

The quality of measurement data from existing and future sources for utilities, system planners and operators must improve relative to present standards, and model validation is an essential and desirable application of enhanced measured data. Data quality should be defined by the latency, accuracy, ease of use, and most important availability. Distribution planners and operators must have accurate and timely information to make the correct choices in both the near and long term. Data quality will translate directly into power systems model accuracy, and quality of the analysis results from the distribution grid analysis tools.

A. *Device and Model Accuracy*

The data sources available can have multiple objectives. Data can be used to control resources such as inverters in a grid, be utilized for visualization and control at a central point, or be utilized in the planning environment to plan for the future [11][12]. There are varying accuracy concerns and data needs for all of these scenarios. In a grid control scenario, the impact of the error in control would significantly depend upon the penetration of renewables deployed. In a standard distribution measurement system there are multiple voltage and current measurement error ranges to be considered. We initially consider accuracy of the instrument transformer for voltage and current that physically connects to the system, and secondly the measurement device itself. The combined accuracy of these can be calculated using a Gaussian distribution [15].

Performance classes for instruments and metering include the ANSI C12.1 [13] standard that covers demand meters and instrument transformers and C12.20 [14] that covers metering. We use these standards to calculate the maximum range of error that would be seen at output. An instrument transformer can have a relative error range of 0.2% to 0.5% (0.2 to 0.5 Class devices). Including both the current and voltage measurement the total error is calculated using Equation (1). The error for the whole system including measurement device is then calculated using Equation (2). The error range for these two metrics is shown in Figure 1. The maximum error visualized at the output of the measurement device is approximately 1.0% [15]. A further metric to consider is the error of the modeling tool for distribution planning (3).

$$\varepsilon IT = \sqrt{\varepsilon VT^2 + \varepsilon CT^2} \quad (1)$$

$$\varepsilon TS = \sqrt{\varepsilon M^2 + \varepsilon IT^2} \quad (2)$$

$$\varepsilon MV = \sqrt{\varepsilon TS^2 + \varepsilon S^2} \quad (3)$$

Where:

εIT = Error of instrument transformer

εVT =Error of voltage transformer

εCT = Error of current transformer

εTS = Error of measurement system

εM = Error meter

εMV = Expected error of model validation

εS =Error of simulation tool

Assuming a maximum error for modeling of 0.5%, the outer band for model validation potential from measured data is therefore 1.1% (Figure 1). This example assumed the common ranges of measurement devices available commercially at present. A final impact of the error that must be considered is the impact of the simulation tool error on control actuation.

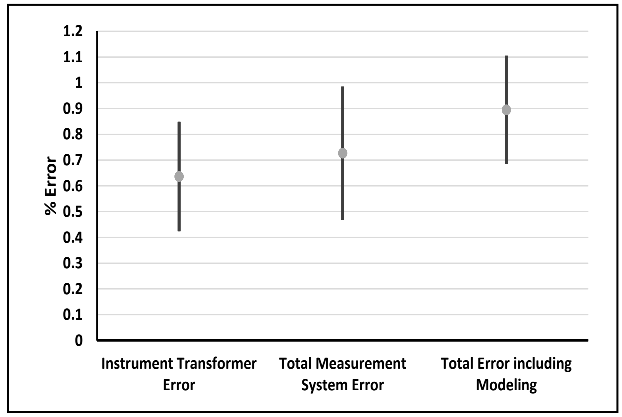

Figure 1. Error range for instrument transformers, total measurement system and modeling

B. *Inverter Control Strategies*

When one considers the suite of strategies being proposed to manage PV inverters and other distributed resources, it is possible to broadly categorize these efforts into two control frameworks: decentralized and centralized. Centralized approaches are extremely attractive as they oftentimes characterize the absolute best way to utilize distribution system assets to address a particular objective. Developing some specific examples in the context of optimal power flow, the authors of [18] considered voltage regulation and loss minimization in distribution circuits using second order cone relaxations of balanced feeder models.

The work in [19] and [20] considered voltage regulation in distribution networks in the context of power flow through framing the decision process as a semi-definite program. The results of [19] provide conditions under which the semidefinite relaxation of the nonconvex power flow problem is tight in balanced distribution circuits. In [20], semi-definite relaxations are applied to unbalanced distribution systems, but no optimality conditions are provided. As is characteristic of these examples, centrally-based control methods typically depend on two critical elements: 1) availability of suitable and accurate models, and 2) large communications requirements.

In any model-based control paradigm, decisions are made in the context of knowledge of the system, and inaccurate or incomplete knowledge can lead to poor decisions. In addition, information used in the decision-making process must be collected from sensors and subsequent control decisions must be relayed to agents. If one or more components involved in the information/control signal exchange has high latency, then the accuracy and performance of the strategy will undoubtedly be affected. Even in the case where modeling information is perfect, large communication delays would translate into decisions being based on “old” information.

In view of these difficulties, it is attractive to consider alternative, decentralized control strategies for distributed resources. Such strategies typically sacrifice optimality guarantees in favor of less reliance on required communications and *a priori* knowledge. The authors of [16] considered a suite of distributed control strategies for reactive power compensation using four-quadrant inverters. The authors concluded that using local information alone is sufficient for voltage regulation, but the incorporation of real and reactive power flows improves control system performance. Using a fully decentralized approach, the work of [17] studied the effect of the shape of different inverter volt-VAR control curves for voltage regulation in high PV penetration scenarios. These techniques have low barriers to implementation, but typically do not achieve high levels of performance. Since these methods do not depend on system models or large communications networks, they are somewhat immunized from inaccuracies in system models and communications delays. They are still susceptible, however, to measurement errors associated with locally obtained information, although it is expected that this level of uncertainty would be much less than aggregate error of centralized approaches as discussed in the previous section.

Regardless of the control paradigm (i.e. whether a centralized or decentralized framework is used), uncertainties and inaccuracies will be ever-present and should be incorporated into the planning/modeling process.

VI. CONCLUSIONS

We have reviewed some of the emerging data needs for integrating both simple and complex high penetrations of renewable resources to the distribution grid. The time scales and accuracy of data in both realms will define the limits of integration and control of resources at the customer level for optimal economic and technical operation.

The data needs for real-time operational control objectives are significantly different from the data needs for initial assessment in the planning context, but there must be appropriate bandwidth and allowance for error to account for the entire chain of instrument transformers, measurement devices, modeling tools and control actuators. An iterative validation process is likely needed, where a diverse set of measured data and component models (specifically, inverter models) is integrated to effectively baseline the system and furthermore exercise generic control algorithms appropriately allocated for cluster control. Once the control algorithms have been deployed, measured data would be fed back into the distribution modeling process, to set a new baseline for future studies and inverter model enablement. It is essential that such an integrated approach is taken to utilize the full capabilities of the grid and its advanced components.

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