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Meeting New Distribution Power System Challenges

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Abstract— **Distribution utilities are facing challenges arising from rapid technology developments coupled with strong drivers to minimize operating and capital expenditures. Embedded generation including solar rooftop PVs and other demand management means do not only change the demand profile of the system but also other electrical characteristics of the distribution network. Advanced power system analysis tools are required to address the needs for more accurate modelling. The ability to integrate with other enterprise software systems offers opportunities to achieve efficiency gains in day-to-day operations as well as investment planning. Three projects undertaken by the authors are selected to illustrate how the new challenges are resolved using advanced analysis tools. The projects include the modelling of PV and battery inverter systems on distribution system, calculation and optimization of distribution losses, and fast assessment of domestic PV connection based on GIS and asset management data.**

Index Terms-- **Distribution system modelling, geographic information systems (GIS), embedded generation, distribution loss factor.**

I. Introduction

Technology and economic factors are driving significant changes in transmission and distribution networks, with the most significant changes and challenges emerging in the distribution sector. Societal concerns about carbon emission and climate change are driving intense interest in renewables, particularly wind and solar [1]. Dramatic advancements in photovoltaic (PV) systems and battery storage systems (BSS) technologies are causing reduced or negative load growth in developed economies [2]. Network investment decisions are made in an environment of great uncertainty, which is challenging when the life of investments is typically around 40 years.

Distribution engineers used to be able to rely on continued and predictable growth and well understood patterns of consumption. The increasing uptake of renewable generation, energy storage and changing consumer behaviour has created many new challenges for the industry.

II. New Challenges

This section describes some of the key challenges faced by the distribution companies recently.

A. Accurate and advanced power system analysis

With exceptional growth in the installation of solar PV systems, and embedded generation within the distribution network, the hierarchical model of power systems is no longer valid. The changes in load compositions and generation technologies have resulted in a number of challenges with respect to power flow, protection system coordination, dynamic system performance as well as the introduction of power quality issues such as voltage flicker and harmonic distortion [3]. All of these challenges lead to a requirement for detailed and advanced power system analysis of accurate system characteristics. This will require an increased and spatially aware understanding of the full distribution system and of the patterns dictating consumption and embedded generation at the customer connection locations.

Accurate power system analysis from a reliable and traceable data source allows utility engineers to better plan, manage and optimise system operation. This information also improves the effectiveness of network planning in prioritisation of network investment projects.

B. The death spiral

The death spiral – where increasing network charges drive disconnections, which leads to fewer customers paying even higher network charges – is becoming a possibility, assuming no changes to current network charging structures [4]. There is also increased pressure for utilities to materially reduce costs and increase asset utilisation. Efficient recovery of network losses and the optimisation of network losses are examples of where distribution companies could seek to reduce costs and deliver more efficient signalling and pricing outcomes. This requires detailed modelling of the network, tools to calculate loss factors, optimisation of open points and the ability to automate these processes.

C. Information technology and data management

The development of information technologies and low cost data storage create both opportunities and risks to the distribution utilities. The obvious risk is the growing amount of data and the number of special purpose or bespoke software applications that are deployed. For example, there are typically several commercial and in-house software applications within an engineering department to carry out its day-to-day operations. Many of these tools are specific to the task at hand, requiring several data models, which creates challenging support functions. Each time there is an upgrade over the enterprise operating system, compatibility issues are likely to arise. Security issues are also critical, with enterprise-wide solutions preferred over individual passwords per application.

Most utilities have an asset management database storing key attributes of each piece of equipment. Some of this information is extracted and used in analysis tools, often in the form of simplified models. The data manipulations and "rules

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of thumb" are then embodied in application specific data files with poor linkages to their source databases. Upgrades to plant, which are captured in the asset databases, are often not rippled through to local or application-specific data systems. There is therefore an increasing demand for "single source of truth" for power system models and it is becoming attractive to integrate engineering tools with other enterprise software so that data linkages are preserved and the best available data is used. Automatic generation of the network model based on the asset databases and the GIS topology is an example of how data integrity can be managed [5].

III. INTEGRATION OF SOLAR PV & BATTERY SYSTEMS

This section discusses the integration of photovoltaic (PV) solar generation on an industrial and domestic level, with respect to the implications to the wider distribution system users and responsibilities of the owner/operators.

A. PV installations in distribution systems

Growth of solar PV uptake onto the distribution network was once attributed to generous government subsidies and high utility feed-in tariffs. However, increases in technical efficiency and material manufacturing as well as the decreased installation costs attributed to competitive market conditions, has seen the domestic and industrial uptake of integrated grid connected and standalone PV systems grow substantially on their own accord.

In July 2012, the uptake of the solar PV system in the metropolitan area of Brisbane, Australia, doubled from an installed capacity of 415MW in July 2012 to more than 800MW in June 2014 [6] [7]. This was despite slashing of the feed in tariff rates from around AU$0.44 /kWh to equivalent wholesale energy prices (5-8c/kWh) [6]. This continuing trend illustrates the need for distribution owners/operators to consider the larger impact to managing increased penetration of PV systems now and in the future.

Traditionally, the distribution systems were designed to deliver energy in one direction in a generator-transmission-distribution-customer style system arrangement with decreasing system voltage, statically tapped distribution transformers and voltage regulation points. As distributed generation changes this pattern, there are indications of voltage regulation issues attributed to the reverse flow of power as well as ongoing power quality issues corresponding to large generation fluctuations. These issues have impacts on system voltage regulation, system fault level, system capacity limits, voltage flicker and system harmonics, and dynamic response and fault ride through capability.

The traditional hierarchical power system structure has been used by distribution planners and protection engineers in considering the investment and network operation schemes. Metering and protection devices have been designed with this fundamental assumption, but the infrastructure has been rated according to the forecasted loads. In areas of high local generation, this may require more sophisticated protection systems as well as revised voltage control strategies, possibly with active rather than passive voltage regulators.

Previous studies suggest that the unregulated application of solar PV installation impacts the voltage profile of the distribution network [8] [9], in some cases causing voltage to rise outside of the standard range. The implication of this voltage excursion has the potential to cause protection devices to trip for over-voltage events or to damage connected appliances.

Most PV inverters have acceptable grid frequency and voltage tolerance bands. The setting of these tolerance bands is not well coordinated as a whole, and impacts the systems' ability to respond effectively to significant transient events. For example, during a system fault it is likely that the voltage or frequency could move outside of the inverters defined operational range, causing the inverter to trip and isolate from the network. At an individual level the implication is not of concern. However, if a system has a significant amount of generation supplied by many inverter fed sources, all of which trip under the same conditions, there is significant concern of large voltage swings and cascading protection events.

The degree to which utilities embrace the increased application of embedded PV generation is dependent largely on their resources and infrastructure. Utilities with highly integrated systems and databases have fewer issues in managing systems with larger amounts of embedded PV.

Proactive utilities are addressing issues of increased renewable penetration by building detailed LV system models and integrating automated workflow process to conduct system analysis to outline system requirements and direct capital investment of network reinforcement projects [10].

B. Domestic roof-top PV loadflow assessment

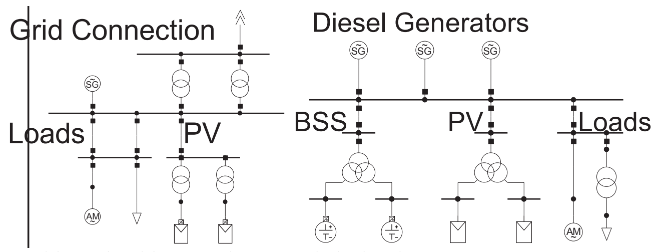
Attractive feed in tariffs have resulted in a rapid uptake of residential PV solar in Germany [11]. One issue facing authorities is the approval of applications to install a new PV array. Previously engineering advice was required as part of the approval process. One distribution company has adapted two key steps to automate this process; they are based on the integration between the GIS with LV network model and analytical tool.

When an application for a new PV installation is received, the specifications are filled in on a template and the array is located graphically at the applicant's address. The GIS operator, who does not need to have an engineering background, then initiates an evaluation script. This script adds the new PV system to the LV network model and then utilises the integrated power system analysis application to run seven verification studies on the feeder.

Results are returned to the GIS operator in the form of a traffic light sequence: Green means the new PV system can be approved; yellow means engineering advice is required; and red indicates a significant problem requiring the feeder to be upgraded. These indicators will allow the majority of the application to be dealt with expeditiously without recourse to engineering resources.

C. Large-scale solar PV integration

For larger scale PV systems matched to BSS, the integration process requires more detailed analysis. Two examples of larger scale PV system are shown in Figure 1, representative of two projects undertaken by the authors in a remote mining site with a weak grid connection (a) and isolated from the system (b).



a. with weak grid connection b. isolated system

Figure 1. Large-scale solar farm integration at a remote mining site with a weak, single circuit grid connection

There are technical issues to be addressed for a system shown in Figure 1a, particularly to cater for the conditions where the single circuit grid connection is unavailable. Some of these issues include:

- Reduction of fault level and system inertia

  During grid outages, the solar PV and backup diesels supply the load. The load and the size of PV dictate the number of diesels in service; there is a potential risk of significant short circuit level reduction. Additionally, there is a risk of a reduction of system inertia, potentially creating frequency regulation issues.

- Dynamic performance

  During isolated operation, events such as loss of a diesel generator, a network fault or the starting of a large motor load can have a significant impact on both frequency and voltage.

- Other performance issues as defined in [3]

Recent technology advancements allow static converters to operate in grid-forming mode. In other words, the static converters are setup to operate as 'virtual machine' and regulate the system's frequency and voltage. This increases the complexity of the power system and the modelling activities associated with it, as detailed (full three phase or unbalanced) models for these new technologies need to be developed in assessing the performance of the distribution system [12]. Figure 2 presents an example of the response of an isolated diesel-PV-BSS hybrid system (as illustrated in Figure 1b) to a large disturbance (loss of a diesel generator).

This time-domain study demonstrates the importance of detailed models of power system elements such as PV inverters, the BSS and its 'virtual generator', and the overall master controller that supervises spinning reserve, voltage, and frequency regulation. As the system loses one of the diesel generators, the other two generators would increase their output power level to supply the power demand and regulate the system frequency. The BSS contributes to the frequency and voltage regulation as it operates in the grid-forming mode by balancing the active and reactive power demand to the system. It can be observed that the system's frequency and voltage can be maintained within the site's acceptable operating range.

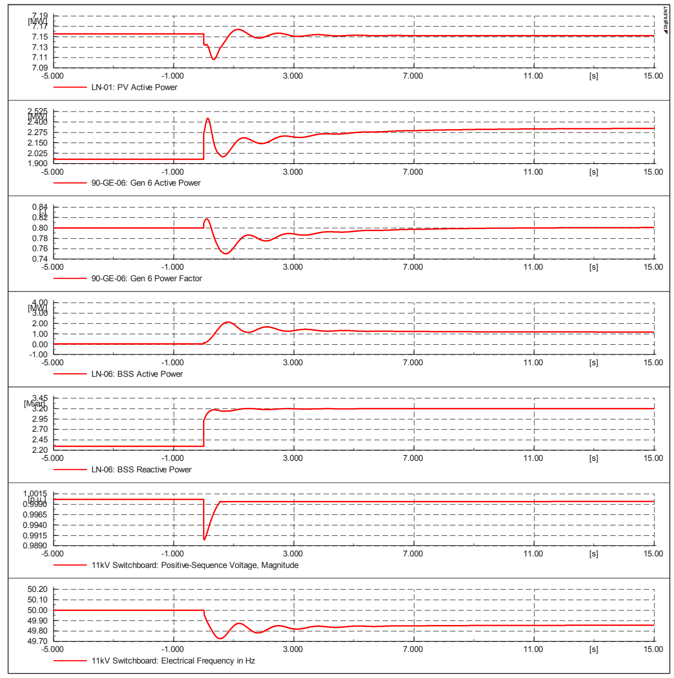


Figure 2. Response of an isolated diesel-PV-BSS hybrid power system to the loss of a diesel generator rated at 2.4MVA and operating pre-fault at 2.0MW

IV. CALCULATION OF DISTRIBUTION LOSS

Another challenge faced by the distribution companies in operating the electricity assets is in determining the losses in distributing the energy to the customers and the associated costs. In the conventional distribution system, the losses are calculated in terms of the required unit of energy to be supplied through a supply point in order to meet a unit of energy demand for a customer at the distribution level. Marginal loss factor (MLF) is defined as

$$MLF = 1 + (\Delta_{loss} / \Delta_{load\_increment}) \quad (1)$$

As an example, for the customers in connection point B in Figure 3 to increase its load by 1kW, the supplied energy through the connection point A needs to increase by 1.014kW as the losses in the distribution feeder are considered. In other words, the network losses for this additional load are increased by 14W.

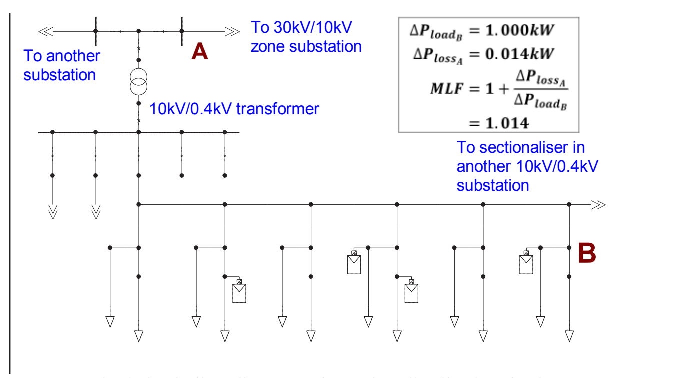


Figure 3. Typical single line diagram of a 0.4kV distribution feeder

In addition, to calculate the distribution loss factor (DLF), the distributors need to calculate the weighted average loss factor over a period of time timeframe (e.g. every 30 minutes) for every connection points in the distribution systems.

The addition of distributed generators (DG) such as PV systems in the distribution network increase the complexity in calculating the DLF at the connection point A, especially as the operation of these distributed generators is highly dependent on the time of day and weather conditions. As the distributed generators displace the customers' energy demand, the network losses are reduced.

Loadflow sensitivities can be extracted from the loadflow Jacobian. This will allow the calculation of MLFs at the connection point with respect to a specified bus bar. Further integration and automation using object-oriented scripting languages such as Python make the calculation and estimation of losses more tractable and auditable.

The capability of advanced distribution tools to optimally reduce system losses by selecting open points within a studied network can be used to support operational activities or in offline studies as part of planning investigations. Figure 4 shows a system with two feeders being optimised with multiple potential open points. In order to demonstrate the tie open point optimisation, the feeder losses have been assessed for tie open point at A, B, and C.

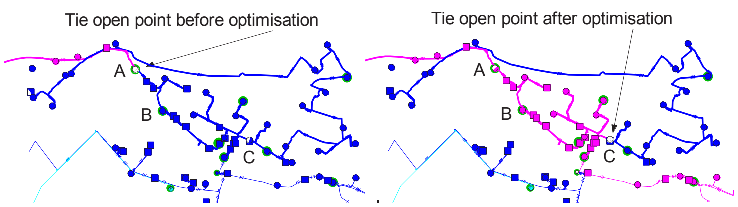


Figure 4. Single line diagram of the network before and after optimisation

This optimisation feature would allow the tools to search for the optimum switching states of the switching elements within the feeders and to share the distributed loads across the networks being optimised to reduce the overall system losses. Table 1 summarises the total feeder losses for each of the three open point options. Option C represents the minimum overall loss and should therefore be selected. Tools are now available to provide this advice automatically.

Table 1. Total losses in the two feeders for three different open point options

Feeder	Feeder losses (kW)		
	Tie open point location		
	A	B	C
61 (Blue)	412.86	376.89	78.54
73 (Red)	5.01	9.05	113.79
Total	417.87	385.94	192.33

V. System Integration

This section describes how integrating power system analysis tools with other information systems employed by distribution utilities can yield significant advantages.

System integration with power system analysis tools is not a new concept, however utilities are collecting and managing ever increasing quantities of data which allows for increasingly sophisticated analysis for network development, control and optimisation [13].

The amount of information required in a distribution network model is often so vast that it is a challenge to gather and manage this information and ensure it is kept up to date and accurate. In the past, this has forced the utility to process large amounts of data, but also compromise on model accuracy. For example, the LV network is seldom modelled as a whole. However more accurate models of the network, in particular the LV network, have become an increasing requirement predominately due to the rapid expansion of household generation in the past 10 years.

A. GIS and asset management system integration

Most modern distribution utilities possess commercial or in-house developed GIS software. This software is used by numerous departments but its basic function is to locate assets in the utilities region of responsibility and to provide information relating to those assets to users. GIS is useful for dispatching maintenance crews and planning new works. The power system analysis model requires the same connectivity information that is generally recorded in a GIS system, hence integration between power system analysis packages and GIS systems is logical. The integration also provides tangible benefits to the power systems engineer for these reasons:

- Network updates can be applied once in the GIS and replicated across to other systems via the integration
- The power system model can also incorporate GIS coordinates to allow geographical representations of analysis outputs – e.g. load and generation densities. An understanding of the geography, in particular the urban density is also useful for power system planning functions. These require assessment of viable options, which are often constrained by environmental factors in the vicinity of the network constraint.

In addition to GIS systems, utilities usually also maintain a separate asset management database. This database contains detailed information on assets such as equipment nameplates, construction and maintenance schedules, and equipment test results. The detailed information contained in the GIS and asset management database systems is able to produce the majority of the connectivity and nameplate information required to develop a power system model.

B. Forecasting, metering, and customer information system integration

A key requirement of a power system model is the ability to accurately model the past, present and future load to examine the performance of infrastructure over time. Information systems usually exist within a distribution utility to support this requirement via integration to augment a power system analysis model. Examples of these systems include:

- Forecasting systems – required to determine the future loading on the distribution system
- Metering systems – useful to determine the past loading on the system
- Customer information systems – useful to determine the customer impact for certain power system contingency events (i.e. load at risk and customer outage calculations)

C. Data integration workflow

The data integration information flow is illustrated in Figure 5.

Figure 5. Information flow throughout the data integration stage

The general flow of information is from source systems through some data transformation logic into a data staging area. Once in the data staging area, the data can then be loaded into the power system simulation software. Within the software additional data processing can occur to validate, format and publish the data as required for a particular study.

Once the integration is complete, from a user perspective, model updates are handled in the background via database processes.

D. Completing the integration cycle

Whilst traditional integration has been in line with the information flow in Figure 5, as demonstrated in the example in section III. B., opportunities exist to close the integration cycle and use the power system analysis software as an additional data source for other applications, as illustrated in Figure 6. Numerous opportunities are possible including protection setting calculation, load and generation connection applications and asset condition monitoring.

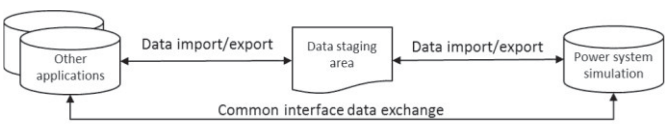


Figure 6. Closed data integration cycle

E. Integration challenges

Whilst it is clear that there are numerous advantages to system integration, there are some challenges that need to be considered. The source data must still be collected and maintained, as engineering decisions are very reliant on correct inputs. In terms of human resources, system integration requires different skillset as information technology skills are not traditionally the domain of the power system engineer. Complex software often requires complex integration, which makes changing software platforms difficult and expensive. It is important that systems are encapsulated with clear interface boundaries. Some common information standards such as the CIM standardise data formats and improve system interchangeability.

VI. Conclusions

This paper presents the challenges faced by the distribution utilities in addressing the recent issues such as the increasing implementation of embedded generators in the distribution systems, and the corresponding changes in the customers' energy consumption patterns.

There is a need to accurately model and analyse power systems as the complexity of the system increases proportionally to the increasing number of embedded generation installations. In addition, there are challenges in terms of the information system and data management. Three projects have been selected to demonstrate how the modern and advanced power system analysis tools can benefit the distribution utilities in meeting these challenges.

Section I discusses the importance of detailed modelling of PV and BSS inverters for static and time-domain studies. Automated loadflow assessments would expedite the processes of providing the approval for the majority of the new rooftop PV applications. Detailed models of PV and BSS inverters allow distribution utilities to investigate the systems behaviour for various contingency events.

Section IV discussed the calculation of distribution losses that allows the utilities to optimally minimise the losses in distribution systems by considering every available switching arrangement / scenario in the system.

Lastly, section 0 describes the advantages of integrating the power system analysis tool with the enterprise information system. This allows the utilities to maintain accurate modelling of the constantly changing states of the network.

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