Managing DER in Distribution Networks Using State Estimation & Dynamic Operating Envelopes

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2021 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia) | 978-1-6654-3339-6/21/$31.00 ©2021 IEEE | DOI: 10.1109/ISGTASIA49270.2021.9715663

***Abstract*— This paper explores an implementation of state estimation and dynamic operating envelopes (DOEs), applied to manage distributed energy resources (DER) within distribution networks. A technology platform has been established within the Ergon Energy Network and Energex digital domain to implement a novel Distribution System State Estimation (DSSE) engine. The network visibility achieved using DSSE supplies subsequent capacity constrained optimisation processes which facilitate the determination of dynamic operating envelopes. The envelopes, calculated in near real-time, reflect the export and import opportunities for DOE-enabled DER while maintaining the network within operational and technical limits. Results from analysis on networks in south-east Queensland reveal the opportunity to export exists for previously constrained DER. The work also highlights the potential for networks to manage the anticipated growth in electric vehicles and batteries using DOE without needing to augment physical assets.**

***Index Terms*—Distributed energy resources, distribution networks, state estimation, dynamic operating envelope, solar power generation.**

I. Introduction

Limitations in distribution network operational visibility coupled with an inability to intelligently and dynamically manage export from rooftop photovoltaic (PV) systems means networks must consider a worst-case scenario when determining a static export limit. As PV penetration increases within distribution networks it is inevitable that more systems will be required to connect to the grid with export limits to mitigate capacity constraints during reverse flow periods with high solar export and low load, unless a paradigm shift in the current approach can be brought about.

Advances in computing, communications and the increased availability of network monitoring has enabled state estimation techniques, widely applied in transmission networks, to enter the realm of distribution networks. These techniques provide economically achievable visibility generating a complete and consistent picture of the electrical state of the network with limited input data. The approach proves particularly valuable when applied downstream of zone substations which have limited monitoring and increasing penetrations of Distributed Energy Resources (DER) connected.

This paper explores the application of a locally developed, novel and robust distribution system state estimation (DSSE) engine on feeders within the distribution network in south-east Queensland. Also covered is Capacity Constrained Optimisation (CCO), a post-estimation application, which allows calculation of an envelope in which DER can independently operate such that their combined behavior does not push the network beyond a defined set of constraints.

As is discussed in the remainder of this paper, the DSSE utilised in the presented implementation expands on the capabilities of traditional power system steady-state estimation. Traditional power system steady-state estimation, as it is adopted on a transmission system level, was introduced by Prof. Schweppe et al. in 1970 through a three-part publication [1]-[3]. The approach presented by Schweppe et al. remains the reference technique, despite some implementations using modifications that increase computational performance. The main challenge in applying this technique to distribution networks is the requirement for sufficient measurement data to allow the formulation of at least a determined problem, in addition, the need for more detailed modelling of unbalanced conditions. The aim would usually be to create an over-determined problem by using additional measurement data, so that bad data detection and identification methods could be applied to the estimation results. But in general, the approach is functional for at least fully-determined problems.

The amount and spread of measurement data required to achieve at least full determinacy is usually not available in distribution systems, which makes the approach infeasible in its traditional form. The DSSE used in the implementation presented here overcomes these limitations in two ways, which can be combined if so desired. It is based on an approach that is tolerant to partial under-determinacy and allows for the identification of aspects of a networks operational state that are unobservable based on the available measurement data [4]. On top of this functionality, available statistical data can be incorporated to formulate mathematical expectations that the system state is likely to satisfy.

The combination of these two modifications to the original approach have not only made power system steady-state estimation applicable to distribution systems, the functionality can be leveraged to implement higher-level applications based on it, as is demonstrated in this paper.

We organize the paper as follows: An overview of the novel DSSE engine and capacity constrained optimisation approach adopted in this work is given in Section II. The concept of dynamic operating envelopes as applied to DER on the distribution network is given in Section III. The technology framework established to deploy the capability within Queensland's distribution network is presented in Section IV. Analyses and results are demonstrated in Section V with conclusions in Section VI.

II. Distribution System State Estimation & Capacity Constrained Optimisation

A. Distribution System State Estimation

As mentioned in the introduction, the DSSE implementation used by Ergon and Energex is based on the approach published in [4]. It was purpose-developed for use in distribution systems including low-voltage networks and is based on a four-wire representation of the network to capture all network topological (e.g. number of phases, connectivity), electrical (e.g. impedances, ratings) and operational imbalances. The DSSE accepts a wide range of measurement data which may be complemented by statistical data for use in establishing mathematical expectations as to interdependencies within the most likely system state.

To generally achieve full determinacy, leading to full visibility of the system state, the DSSE requires the following types of data:

- knowledge of the physical network (e.g. network topology, conductors, equipment specifications and ratings, transformer tap positions),
- measured data from the network (e.g. voltage, real and reactive power outputs from network monitors, SCADA and/or smart meter data); and
- statistical data about typical network utilisation (e.g. aggregated billing data, customer counts).

The approach was proven to be technically feasible as demonstrated through the Solar Enablement Initiative, a university-industry collaboration project which tested the DSSE on three Australian distribution networks [5].

As with the traditional state estimation, and power flow analysis techniques, the results of the DSSE are complete in the sense that they allow the computation of any steady-state parameter for the network under the estimated system state. Mathematically the result is a set of complex-valued voltages for each electrical node of the modelled network plus a mathematical approximation of unobservable state components. This allows, in combination with the network model, the corresponding value of any operational steady-state parameter to be determined and a decision if these parameters are fully determined or not, as demonstrated in [4].

This significantly reduces the requirements in terms of measurement quantity and distribution of measurements across the modelled network, while offering the ability to ingest almost any type of measurement data, but also complementing statistical data bringing the measurement density requirements to a level that most Distribution Network Service Providers (DNSP) can satisfy today with their existing data.

B. Capacity Constrained Optimisation

One of the primary aims when implementing the DSSE was to build the functional basis to operationalise Capacity Constrained Optimisation (CCO). Like with state estimation, similar techniques are, and have long been used, on transmission systems, but were not directly applicable to distribution systems in their original form.

CCO can be interpreted as a category of techniques that aim to find an alternative utilisation of the network by loads and generators that is optimal under some criterion while not leading to any violations of a set of operational and technical limits on the interconnecting network. Common examples are electricity markets.

The implementation used by Ergon and Energex follows a similar approach, where a constraint analysis uses a set of operational and technical constraints to identify the feasibility region within the control space spanned by the control variables available to the optimisation algorithm. In order to do this, a network model and network analysis techniques need to be employed to model the interdependencies between operational parameters, their associated limits and the influence of a set of controllable parameters on them. The most common technique used at a transmission system level is the DC power flow technique, which is then often complemented with outcomes of dynamic stability assessments. In most cases the outcome of this assessment is a set of linear inequalities defined on the control variables, which, when taken together, describe the control subspace that contains all feasible control variable set-point combinations and can be used as a constraint system to an optimisation problem.

The approach used by Ergon and Energex is, in its outcome, similar, but conceptually and mathematically different. The main differences are the types of operational and technical limits that can be processed, the use of a multi-phase AC network model that enables capturing voltage magnitude variations, and the geometric interpretation of limits and constraints in general. In combination this leads to the generation of constraint systems that eliminate the need for iterative re-evaluation by a power flow analysis process for all but the most extreme optimisation outcomes.

The concept and a preliminary discussion of the geometrical shape of original operational and technical limits relevant in distribution systems, as well as the resulting shape and features of the corresponding feasibility sub-space, can be found here [6][7].

III. Dynamic Operating Envelopes

A. Interpretation and Application

The DSSE and CCO implementation used by Ergon and Energex, and briefly described in the previous sections, is being used to calculate Dynamic Operating Envelopes (DOEs).

A DOE is increasingly being viewed as a fitting approach to manage DER within distribution networks. In their joint 2018 Open Energy Network Consultation Response the Australian Energy Market Operator (AEMO) and Energy Networks Australia (ENA) introduce a DER operating envelope as a dynamic value range (positive or negative) provided at the NMI

(National Metering Identifier) level that defines DER generation or load limits [8]. Blackhall broadens the NMI or customer-level definition to describe DOE as a principled allocation of the available hosting capacity to individual or aggregate DER or connection points within a segment of an electricity distribution network in each time interval [9].

A DOE, as interpreted for this work, is the combined allocation of operational intervals to participating customers in which the customer can choose to operate freely, without the need or requirement to further coordinate with other network users or the DNSP. Mathematically this corresponds to a control space spanned by the operational parameters the DOE-enabled customers can individually control – usually the active power balance at the connection point. Allocating intervals to all these controlled parameters to be used independently spans a hyper-cube within the control space containing all possible combinations of possible control actions performed by the customers within these intervals. To ensure no network constraints would be violated under any of these possible combinations, the hyper-cube spanned by the DOE allocations needs to lie fully within the feasible sub-space, as described by the constraint system.

Hence, DOE allocation becomes a multi-dimensional sizing problem with both shape and size having to be considered. The shaping problem corresponds to the issue of how to allocate available network capacity to customers *relative* to each other, while the actual size of the hyper-cube corresponds to how much *absolute* capacity is being allocated. With the feasibility sub-space having a non-trivial shape, there is an obvious conflict between these two objectives of finding a *relative* allocation that satisfies some criterion of perceived fairness and the *absolute* capacity that can be allocated which relates to the criterion of efficiency.

Beyond these conflicting objectives DOE generally includes an upper and a lower limit, corresponding to possible additional exports into the network and possible additional imports from the network and, thus, include managing generation, energy storage and loads alike.

The impetus to transition the connection and operation of DER to respond dynamically to network conditions, away from conservative fixed export limits, releases available network capacity while ensuring that during critical periods on constrained sections of the network, the impact of DER can be cost-effectively and equitably managed.

B. Network Constraints

The formulation of a DOE requires a defined set of network constraints, the operational and technical limits of which cannot be violated. The implementation at Ergon and Energex follows a staged approach, which currently excludes DSSE application to low-voltage (LV) networks. Instead, LV networks are implicitly included in the medium-voltage (MV) level through a specialised constraint. The constraint is defined on individual distribution transformers and extrapolates the voltage at their secondary side to the end of a simulated LV circuit using each transformer's active and reactive power flow. The simulated circuit is parameterised to experience a defined voltage drop, derived from planning guidelines, when the corresponding transformer is loaded with active power to 100% of its rated capacity. With additional voltage band constraints defined for the end of these simulated circuits, the expectable voltage drop or rise within the LV networks, the pre-eminent challenge of DNSPs with regards the impact of DER, is implicitly considered.

In addition to these voltage band constraints on transformer secondary terminals and the end of the simulated LV circuits, defined constraints include:

- transformer phase and neutral currents according to their rating;
- maximum transformer active power flow forward (load) and backwards (back-feeding) with separate values;
- MV feeder ampacity limits; and
- voltage bands on MV nodes.

Constraints may be defined for each timestep enabling the inclusion of seasonal or temperature-dependent dynamic equipment ratings, if desired.

C. Staged Implementation

Ergon and Energex are implementing DOE in a four-stage approach with each subsequent stage increasingly optimizing the use of available network capacity and network data. The four stages are:

- Stage 1: Informed by field monitor data directly using a rules-based DOE;
- Stage 2: Informed by MV DSSE data with a rules-based DOE. The advantage of Stage 2 is a greater proportion of network for which DOE can be offered as it is not reliant on local network monitoring;
- Stage 3: Informed by MV DSSE with subsequent DOE assessment. Improvements include the ability to consider DER impacts on both their local LV network and their upstream MV network; and
- Stage 4: Informed by MV and LV DSSE with subsequent DOE assessment. Improvements include complete LV visibility; however, this comes at a computational costs and Stage 3 may be sufficient in many situations.

IV. Technology Platform

To enable DSSE, CCO and DOE on their network Ergon and Energex developed a technology platform spanning field, corporate, operational and customer domains, Figure 1.

The analytics engine at the core of this work is implemented as a cloud-hosted service to provide flexibility for computational resources to be scaled in alignment with the business deployment strategy.

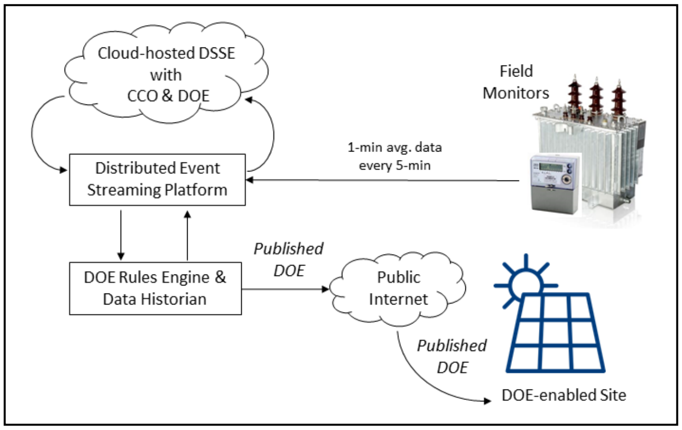

Figure 1. Technology platform architecture.

Secure, scalable dataflows between field monitoring devices, on-premise corporate and operational systems and the cloud-hosted service were achieved through the development of Application Programming Interfaces (APIs) and the introduction of a distributed event streaming platform. This architecture enables DSSE to be executed both on historical datasets and in near real-time with an updated DOE generated every five minutes.

V. RESULTS

The implementation of DSSE, CCO and DOE has been explored on 10 feeders in south-east Queensland, five of which are part of a network trial of DOE applied to enabled PV systems. Despite being trialed with PV systems only at this stage, DOEs are being calculated for additional import and export for customers grouped by the distribution transformer they are supplied from. For the sake of readability results presented here are the sum of all allocations across all distribution transformers connected to a given feeder.

Analysis of Feeder A highlighted the significance of network data quality on the envelope for both import and export. Distribution transformer tap steps are typically 2.5%. As described earlier, end of circuit voltage is determined using a simulated LV circuit based on the voltage assessed by DSSE at the distribution transformer secondary terminals. Where LV voltage data is not available the transformer tap position cannot be verified and the analysis must assume the provided network model data is accurate. Where tap position data is inaccurate this creates the prospect that the generated DOE is driven by perceived rather than actual binding network voltage constraints. Figure 2 presents the DOE profile for the week from 20 September 2020 to 27 September 2020 with incorrect tap position data while Figure 3. reflects the increased export potential with the verified and corrected tap position.

Examining the results with corrected tap position data, the DOE generated for this feeder reflected that at certain times Nil additional export could be accommodated due to an end of LV circuit voltage binding constraint. However, for the week presented in this paper, additional export could be accommodated 96.2% of the time (Figure 3). In contrast, a static approach would have to enforce Nil export on any further solar connections even though those constrained periods are the vast minority in this example.

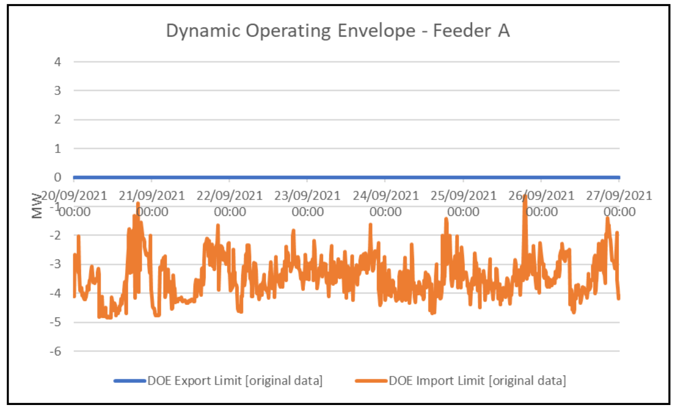

Figure 2. DOE Feeder A, incorrect tap position data.

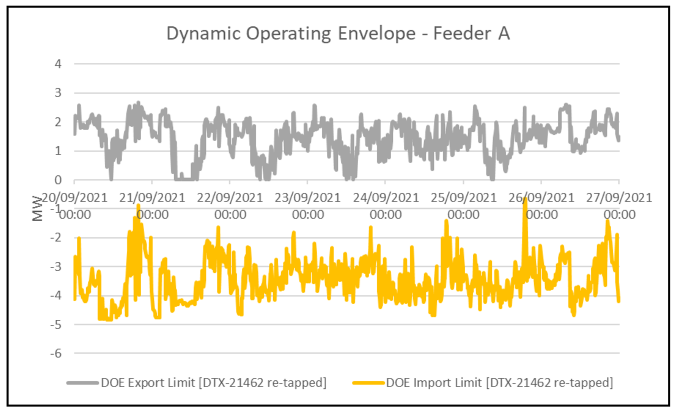

Figure 3. DOE Feeder A, corrected tap position data.

In the future DNSPs will increasingly rely on analytics to inform network operation, DER management being one example, hence it is imperative that DNSPs work to improve network model data quality. DSSE can help in this regard as any LV voltage measurement can help to pinpoint tap position allowing the data can be corrected in the asset record.

The DOE implementation established at Ergon and Energex will be equally applicable for the networks to manage imports supplying large chargeable loads such as battery energy storage systems (BESS) or electric vehicles (EVs). A DOE includes both an export and import range, unless conditions on the network preclude one or the other. In some instances DOE may be used to encourage behavior that pushes the network back within limits in the case of a breach caused by unmanaged DER or other loads.

In addition to the export side of the envelope Figure 3 also shows the import side for the previously discussed Feeder A. Figure 4 shows export and import for a largely residential feeder, Feeder B, over one week. During the day on both feeders there is ample opportunity for import where batteries could absorb excess renewable generation. The envelope reduces in line with the evening peak and then widens during the night. Most networks will have enough capacity to charge batteries if well managed which will be critical for the cost-effective adoption of EVs.

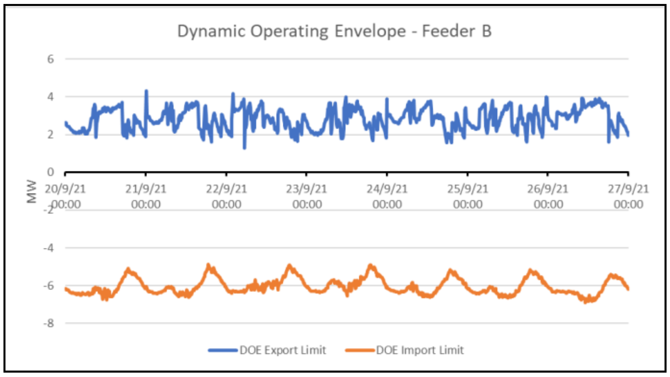

Figure 4. DOE Feeder B.

A surprising finding was the possibility for reduced DOE exports in the evening. Although solar PV systems would not be operating it is anticipated that batteries may be called upon to discharge to the grid to support it during the evening peak. Analysis revealed binding end of LV circuit voltage constraints on Feeder B causing a reduced export envelope during the evening peak. This outcome was due to the action of the on-load tap changer (OLTC) at the zone substation elevating voltages at the start of the feeder due to line drop compensation responding to the evening peak load. Traditional line drop compensation methods which dictate the behavior of OLTCs could be improved by using actual end of feeder measurements which could be derived from DSSE. For better readability Figure 5 shows a one-day excerpt from Figure 4.

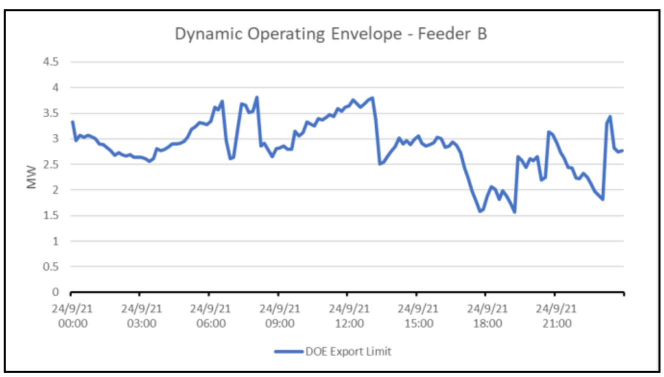

Figure 5. Reduced DOE export allocation in the evening driven by actions of the zone substation tap changer on Feeder B.

This result underscores the potential for conflict between network and market objectives. The situation could arise in which the market wishes to respond to a peak event by discharging batteries to the grid but the local network conditions prohibit such an action. Therefore, the development of operational short-term forecasts will be essential to inform the market and customers of the forecast DOE so that they can plan the use of their DER accordingly.

VI. CONCLUSION

In this paper we have demonstrated the use of state estimation, tailored for use on distribution networks, as a functional basis to operationalize Capacity Constrained Optimisation (CCO). Further, we have demonstrated the generation of Dynamic Operating Envelopes (DOEs), an approach to allocate network capacity to customers to use freely ensuring their combined actions do not violate network operational or technical limits. We presented an overview of the digital technology platform established to operationalize this capability in Ergon and Energex examining results across two of ten feeders analyzed. Results highlight that export could be accommodated from previously constrained DER and that DOE presents the opportunity to intelligently manage chargeable loads in the future.

There is immense scope for Ergon and Energex to employ these analytical capabilities to improve and automate other parts of their businesses including power quality, asset management, connections and scenario analyses, to be pursed as future work.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of T. Lewsey, A. Guinman, P. Kilby and A. Gebers and the broader support of Energex, Ergon Energy Network and GridQube in undertaking this work.

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