ENHANCING DISTRIBUTION NETWORK VISIBILITY USING CONTINGENCY ANALYSIS TOOLS

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Abstract

The East Kent area in the South East of England is the good example of how the uptake of distributed generation is changing the way electricity networks operate. This paper identifies the technical and operational challenges facing transmission and distribution networks in the East Kent area. It introduces the Kent Active System Management (KASM) project, which develops an online contingency analysis solution designed to assist UK Power Networks (UKPN) in maximising asset utilisation while maintaining the network security

1 Introduction

The electricity network operating area of East Kent, located in the South East of England, provides a good example of the operational and planning challenges that arise when large amounts of intermittent wind and solar generation are connected to a distribution network with limited local demand. In 2016, the historical records of distributed generators (DGs) connected to the distribution network displays that UK Power Networks (UKPN), the regional distribution network operator (DNO), has energised more than 800MW of wind and solar generation – see Figure 1. However, as Figure 2 illustrates, UKPN has been able to provide only few new connection offers that have been accepted in the area since 2014 and new offers are only able to be scheduled for 2020.

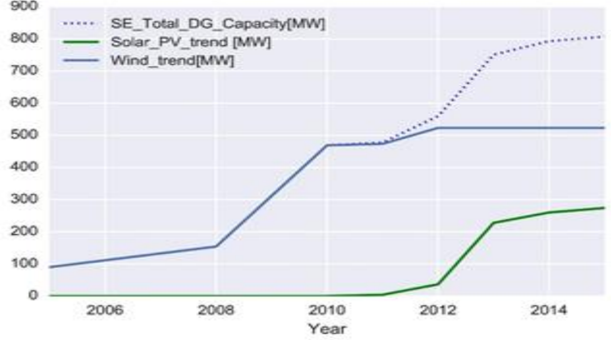

Figure 1: Intermittent generation installation trend in the South East of England Region

The main reason for new connections being difficult to accommodate in the South East of England is the system congestion that part of the network experiences under N-1 operating constraints. In this operating area, distribution and transmission networks are highly meshed and interconnected. A large portion of the 132kV distribution networks operates in parallel with the 400kV transmission network. As a result, power flows on either network can lead to post-fault overloads on the other. In addition, the transmission network in the area has two high voltage direct current (HVDC) interconnections with continental Europe, over which market forces almost exclusively determine the flows. Future HVDC connections are planned in the area for 2018 and 2019. The variability of power flows of intermittent and interconnector flows introduces various operational constraints in the area such as voltage control, system fault levels, thermal constraints and high reverse power flows. The last few years have seen a number of grid supply points (GSPs) come under pressure, due to high levels of reverse power flow as a result of increased distributed generation connected to the system.

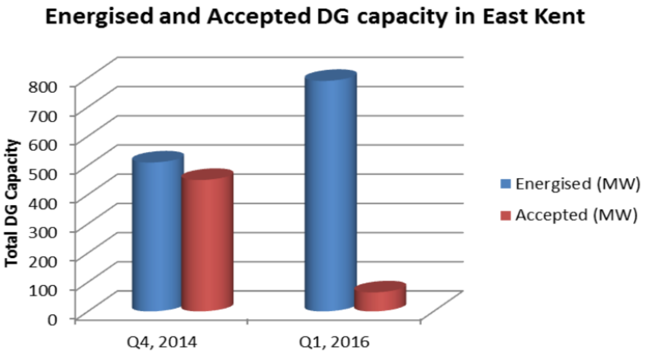

Figure 2: Bar graphs showing volumes of energised and accepted DGs in East Kent

This paper describes an innovative technical solution that is being deployed by UK Power Networks as part of the Kent Active System Management (KASM) project. The KASM project is funded through the Low Carbon Networks Fund (LCNF), which is administered by Ofgem, the industry regulator. By improving visibility and monitoring of a large set of contingencies, the solution intends to improve the operation and planning strategies of the 132kV and 33kV network consequently enhancing system reliability. The paper outlines the challenges currently facing the network, the architecture of the solution and the system integration of a Contingency Analysis (CA) software and forecasting modules in a distribution network control room. The technical solution described supports the DNO in its transition to distribution system operator (DSO). The paper highlights the challenges in developing a state estimator in this context.

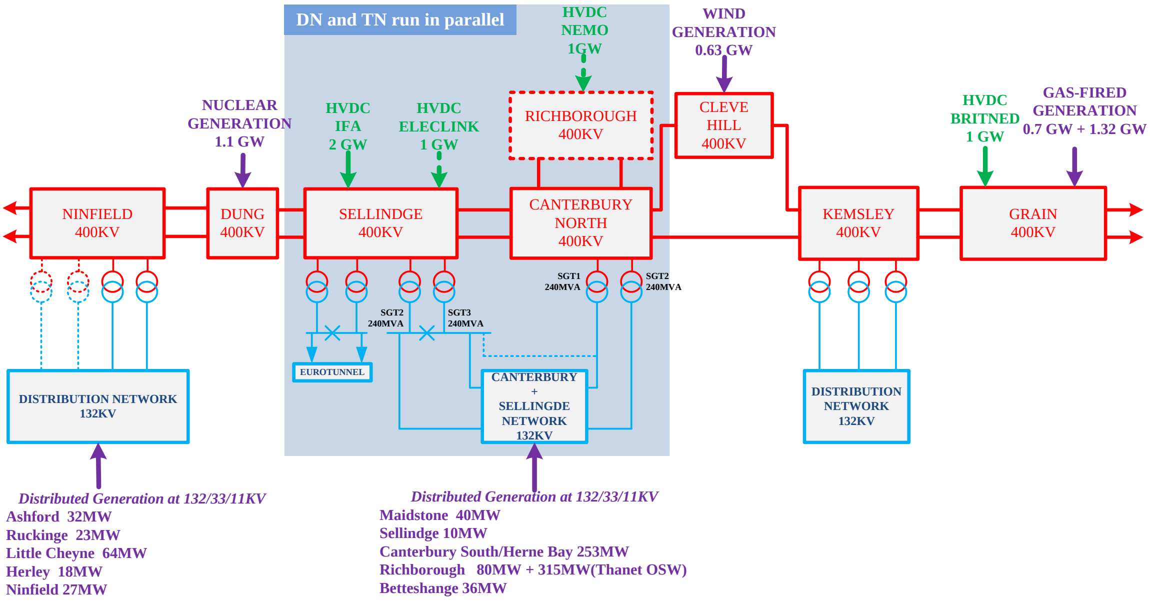

Figure 3: Distribution and transmission network interdependency in the East Kent operating area.

2 The East Kent area case study

This section describes the network challenges faced in East Kent. The UKPN 132kV distribution network is supplied from the National Grid transmission system through 400/132kV super grid transformers (SGTs) at Grid Supply Point (GSP) substations. The SGTs are normally connected to the UKPN system by National Grid owned 132kV circuit breakers at the GSP substations. The SGTs are autotransformers that have a solidly earthed neutral and on-load tap-changers to control the 132kV voltage. The East Kent operating area hosts the Sellindge and Canterbury SGT Group that is highlighted in Figure 3 . The network covers a significant geographic area incorporating Canterbury, Richborough, Betteshanger, Sellindge, Ashford and Ruckinge.

2.1 The context

Although the local demand is low in the East Kent region, a high level of power injection is hosted on the transmission networks while distribution networks experience a significant uptake of intermittent generation. At transmission level, there are a few significant generation sites including the Dungeness Power Station (1.1GW) and London Array wind farm (630MW). In addition, there are two high voltage direct current (HVDC) interconnections with continental Europe. The first is a 2GW interconnection with France that connects to the 400kV network at Sellindge – Interconnexion France - Angleterre (IFA). The second is a 1GW interconnection with the Netherlands that connects to the 400kV network slightly north of Canterbury North at Grain (BritNed). A third, 2GW interconnector (Nemo) with Belgium and a new 400kV substation and grid supply point (GSP) at Richborough is planned for 2018/2019. The interconnector power injections are driven by the market, which can render power flows very volatile; their power injections can shift from import to export within minutes. The volatility is exacerbated by the large amount of intermittent generation connected at transmission and distribution levels. At distribution level, the aggregated level of installed distributed generation on the Sellindge and Canterbury North Group stands at 690MW. This includes 554MW of wind and solar intermittent generation and 136MW of diesel, gas, biogas, landfill gas and combined heat and power (CHP).

The new “active” nature of the distribution network in the area brings significant operational and planning challenges. Since the minimum net load is reducing due to embedded generation, network assets become overloaded under “Minimum Load/Maximum generation” scenarios that result in reverse power flows. Under outage conditions, it becomes very challenging to maintain equipment within thermal and voltage constraints. Likewise, with the large amount of intermittent generation connected at transmission and distribution levels, power flows are extremely volatile in the area. Considering the limited visibility of real-time power flow throughout the distribution network under N-1 conditions, the safe operation of the network has to remain a key focus when operating the network closer to its limits.

Besides power flow volatility, the area faces voltage management issues such as high voltage when demand is low and post-fault dynamic voltage stability. A further, significant innovation project (Power Potential), led by the transmission system operator (TSO) National Grid Company (NGC) and UKPN, is currently underway to develop new commercial solutions in order to address these dynamic voltage stability issues. Similar to the KASM project, Power Potential is an Ofgem innovation-funded project.

In 2014, UKPN assessed the impacts on the distribution network of new agreed solar generation connection under various N-1 operating scenarios. Contingency analysis studies were run for various operating conditions, which included the presence of the new European interconnector Nemo, planned for 2019. The model used included the full transmission network model and the East Kent distribution network model. Studies were run for the worst-case operating scenarios occurring during the summer period where solar generation is the highest whereas local demand is at its lower point. Two extreme operating conditions described as below were simulated for as many as 34 known contingency scenarios:

- Interconnectors maximum net import with maximum generation that includes wind and solar maximum generation and minimum demand; and
- Interconnectors maximum net export maximum generation that includes wind and solar maximum generation and minimum demand.

Contingency analysis studies were run using the 2014 base-case model. The study revealed that during interconnectors' maximum net export, without generation constraints, several 132kV circuits within the Canterbury and Sellindge Group were overloaded following the SGT1 loss at the Canterbury North 400kV substation. This is due to the large amount of wind power from Thanet windfarm being re-routed into the distribution network. Under this scenario, the SGT2 at Canterbury North and the Sellindge SGT were heavily loaded with reverse power. Further contingency analysis studies were run using the 2016 base-case model, with additional solar generation. Several 132kV lines were overloaded in normal operating and under N-1 scenarios (loss of SGT at Canterbury North) when interconnectors' import were maximum. Lines connected at Richborough terminals were overloaded for each of the 34 contingency scenario.

2.2 Operational constraints on grid and primary transformers

The Canterbury North and Sellindge Group includes six 400/132kV Grid Supply Points (GSPs). All of the six SGTs at both sites have a rating of 240MVA. The firm N-1 capacity for Canterbury North, which has two SGTs, is 276.5MW in the winter and 244.2MW in the summer. The Sellindge substation operates as a split double bus, with a pair of SGTs with a firm N-1 capacity of 276.5MW in the winter and 244.2MW in the summer dedicated to the Eurotunnel high speed rail demand. The remaining two SGTs, with the same firm capacity, supply local demand. The last few years have seen those SGTs come under pressure with thermal constraints and high levels of reverse power flow as a result of increased distributed generation connected to the system. Due to the GSPs worst-case-N-1 capacity limit, distributed generation had been constrained in order to secure network operations. Thus, decisions were made based on results from studies using worst-case scenarios. The following sections discuss the operating challenges other than thermal limits that restrain distributed generation in exporting their excess power when local demand is low.

2.2.1 Transformers direct power limits

Usually, grid and primary transformers are installed in pairs to ensure resilience, in compliance with the Engineering Recommendation P2/6 [1], so power supply to the load is maintained in the event of a single unit outage. In order to prevent any limitations arising at post-fault condition and to avert potential post-fault cascading effects, pre-fault flow levels and loading conditions at each transformer are carefully managed. Planners use seasonal composite circuit rating schedules to determine the authorised post-fault short-term overloading. Table 1 shows that following a fault, SGTs can be overloaded by 23% of full rating for up to 6 hours if the transformer's pre-fault loading was at 84% of its full capacity. During normal operations and as a preventive measure, direct and reverse power flow at GSPs are constrained to 66 %.

		% Nominal	Amps		MVA
			400kV	132kV	
Pre-fault Continuous		100%	345	1050	240
Post-Fault Continuous		100%	345	1050	240
Short-Term Overloading	6hr	84% 202MVA	425	1280	395
	20m		450	1360	310
	10m		455	1370	315
	5m		455	1370	315
	3m		455	1370	315

Table 1: Seasonal composite circuit rating schedules for 240MVA super grid transformers in the study area

2.2.2 Transformers reverse power limits

In theory, the reverse power flow capability of high voltage (HV) and primary transformers is limited by the nameplate rating of transformers and the post-fault short-term overloading considerations. However, additional limiting factors such as on-load tap-changers (OLTC) mechanism and directional overcurrent (DOC) protection settings can prevent power transformers from carrying their full reverse power capability.

- **The On-Load Tap Changer constraint**

The OLTC mechanism often found in primary transformers (33/11kV) can constrain transformer's reverse power flow [2]. The OLTC is used for voltage regulation and/or phase shifting. It varies the transformer ratio during energised condition using the "make before break contact" concept. The transformer's ratio is changed by varying the numbers of turns either on the primary or the secondary winding of the transformer. A transition impedance is used as a bridging adjacent tap for the purpose of transferring load from one tap to the other without disruption or noticeable change in the load current. There are two types of OLTC: the reactor type and the high-speed resistor type [3] . The high-speed resistor tap-changers are categorised as either double- resistors or single-resistor arrangements. The resistor and reactor are used as impedance to limit the circulating current generated at bridging positions. While reactor and double-resistors tap-changer type do not alter the inherent symmetrical attribute of transformers, the single-resistor type used in the pennant cycle transition method reduces the transformer reverse power flow capability[4]. In [2], non-linear optimisation models are used to compute the reverse power flow capability for one type of single-resistor tap changer which is installed on the HV side of a primary transformer. The optimised reverse power flows were computed for various bridging resistors, HV side windings configurations, transformers sizes and vector groups. The study shows that reverse power capacity can be reduced as little as 20% of the transformer nameplate rating. Also, the results demonstrate that Dy11 transformers have greater reverse power flow capability than Yy0 transformers. Depending on the resistance value and the size of the transformer, the optimised reverse power flow capability for Dy11 transformers can reach 90% of the transformer nameplate rating while the reverse power for Yy0 transformers only extends as far as 66 % of the transformer nameplate rating.

- **The directional overcurrent (DOC) relays constraint**

In mesh or ring networks with multiple infeed points, directional overcurrent (DOC) relays are placed in locations where the direction of fault currents is likely to change. They also play an important role as back-up protection, sensing high impedance fault currents (currents that are lower than the nominal current). The pick-up settings of DOC relays can impose very challenging reverse power flow constraints. These relays are designed to operate for the minimum expected fault level at their location point. Since DOC relays typically use Standard Inverse (SI) IDMT characteristics, the relay current setting is selected to sense for at least half of the minimum expected fault level which can be very low in some grid locations [5]. The reverse power restriction for accommodating distributed generation on 33kV to 132kV distribution networks was investigated as part of the UKPN's Flexible Plug and Play project. The project took place in the area of Cambridgeshire in England. UKPN trialled a solution that combines load blinding scheme with a DOC relay. A Directional Voltage Dependent Overcurrent (DVDO) scheme was added to the solution to prevent the maloperation of the scheme in presence of high resistance fault. Thus, under true fault condition, the voltage depression is sensed and used as a discriminating factor that disables the load blinding element which allows the DOC to operate as expected [6].

2.3 Technical and innovative solutions investigation

The large amount of distributed generation connecting to the East Kent network has eroded the capacity margin that existed in the region. The congestion management issue on this complex and interconnected network has become increasingly challenging due to high volatility of power flows on this part of the network. To overcome congestion problem during N-1 operating conditions, UKPN investigated several technical solutions. The cost associated with most of the asset-based solutions were prohibitive or the solutions ineffective. For instance, the reinforcement of the Canterbury North site with the installation of a third SGT was found to exceed £20m mainly due to time constraints. The transfer of the excess power to the nearest SGT site was investigated and the associated cost was estimated at £45m. Other technical solutions such as adding additional N-1 intertrip circuits were investigated and rejected due to their prohibitive costs. Active impedance devices and quad-boosters were studied and found to be an ineffective solution. In addition to the congestion management issue, control engineers and planners have expressed concerns in managing the network in short-term and near real-time due to lack of system visibility. The range of operating scenarios has increased as well as the uncertainties related to intermittent generation, the power injection from interconnectors and the local demand. Short-term planning studies have become challenging and time consuming when performed in the usual manual way. The impacts on system operation have affected the regional DNO, the TSO and the renewable generators of which the output is occasionally constrained as a preventive action. This has led UKPN to develop the innovative Kent Active System Management project (KASM).

3 The Kent Active System Management project

3.1 Introduction

The Kent Active System Management (KASM) is a Low Carbon Networks Fund (LCNF) tier 2 project, which runs from January 2015 – December 2017. The LCNF is administered by the UK regulator, Ofgem. The project aims to carry out a range of technical innovation trials to demonstrate more advanced operations and planning techniques for the 132kV and 33kV network in East Kent. The project integrates:

- A new Inter-Control Centre Communication Protocol (ICCP) between NGC and UKPN [7].
- A new online contingency analysis system (CAS) engine running alongside the Distribution Management System (DMS)
- New standalone forecasting engine providing load and generation forecasts (up to 5 days ahead) to the CAS

The scope of the KASM model starts from the 400kV high voltage finishing at the SCADA measurements on 11kV feeders. The entire network topology includes approximately 6551 buses, 243 transformers, 2674 switches, 41 generators and 606 load points.

With the new ICCP link between TSO's and DNO's control rooms, the project has further enabled DNO-TSO coordination.

3.2 Enabling DNO-TSO coordination

UKPN is currently having to curtail generation for congestion management purposes, and TSO and distribution network planners are challenged with the net demand prediction as the number of network infeeds coming from distributed generation increases. On the other hand, the uptake of distributed generators in the East Kent region provides the DNO with an increasing active and reactive power portfolio that can in principle provide services to maintain the overall system security. Thus, the need for TSO and DNO coordination in the East Kent area is becoming increasingly important. With the implementation of the ICCP link between UKPN and NGC, one of the key requirements for the TSO-DNO coordination has been established. The ICCP link offers a range of great benefits starting with the exchange of real-time and operational data between TSO and DNO. The ICCP link increases the network's visibility on both sides and therefore improves the real-time system monitoring. Consequently, this facilitates an efficient and coordinated management of congestions, overloads and grid voltage. The link should in the long run create new opportunities for black start services and balancing mechanism as long as regulatory frameworks and policies are shaped to facilitate flexibility for new services.

3.3 The Contingency Analysis System (CAS)

For decades, security assessment applications have been integrated in transmission network Energy Management Systems (EMSs), which are more complex than the Distribution Management Systems (DMS) used in distribution network control rooms. Traditional distribution networks only required switching control decisions and potential problems were usually resolved at planning stage. Unidirectional power flows were well understood and predictable. Only a few contingencies needed to be analysed and a security assessment could be prepared manually. As distribution networks become active, they require a lot more attention and careful management particularly with the presence of intermittent generation that increases operating scenarios and the uncertainties. The previous section described the unpredictable nature of power flows in the East Kent area, and how constrained GSPs were identified based on worst-case operating conditions that assumed maximum generation and minimum demand. The CAS aims to facilitate management of the distribution network based on actual operating conditions. The analysis of constraints and operating limit violations on the East Kent's distribution and transmission networks assets will be assessed using near to real-time data, short-term forecasting data and historical operating conditions. A schematic of the CAS architecture and its data flow structure is exhibited Figure 4. The Real-Time Mode, the Look-Ahead Mode, and the Study Mode are the three main modules available within the CAS. A description of the modules can be found in [8]. The CAS can be used as a study tool for online and offline analysis of contingencies. It prepares operators to better react to outages using pre-planned recovery scenarios. The tool makes use of a deterministic approach based on "N-1" rule where events involve loss of only one component. The tools will runs a list of 300 N-1 tests cases which have been selected by UKPN's outage planners based on their experience of the network.

The Real-Time Mode, used for operational purposes, runs base-case and N-1 contingency analysis at 15 min time intervals using transmission and distribution real-time data. The tool executes the following tasks:

1. Develop power flow base cases corresponding to a specific snap-shot that includes:
    - Real-time loading conditions
    - Real-time generation conditions
    - Real-time network topology with all circuits in service
2. Select the contingency list
3. Select study parameters (voltage, voltage drop and thermal violations) and identify their ranges of operating conditions
4. Identify the limiting contingencies that violate the performance criteria
5. Identify the set of operating conditions where a limiting contingency violates the performance evaluation criteria.
6. Condense the security boundary into a set of tables that are easily understood and used by the network operators.

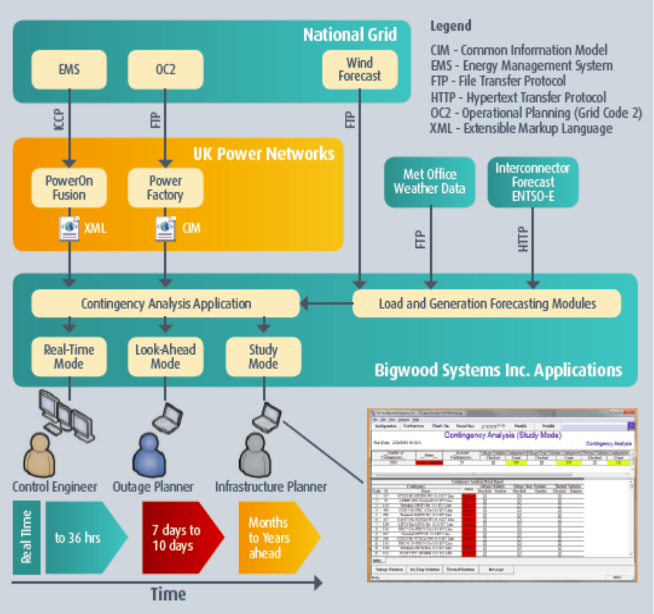

Figure 4: Contingency analysis system architecture

During the online security assessment, the CAS analyses the load margin to voltage collapse for each case in the contingency list and identifies insecure scenarios. The solution defines remedial action schemes that mitigate risks associated with potential contingencies. Control actions on OLTC tap-changer position and OLTC phase-shifter, generator real power output and system reconfiguration are proposed. The remedial control actions have being implemented in the CAS to reflect each transformers' reverse power constraints.

3.4 Real-Time power flow solvers

Traditional Newton-Raphson (NR) power flow algorithms show limitations in solving ill-conditioned or badly-initialised cases. Thus, the implementation of robust power flow techniques are needed to overcome the instability of standard numerical methods when solving power flow for large systems and/or when the power flow solution is distant from the initial guess. The CAS performs a homotopy-based power flow algorithm when NR fails to converge [9]. The algorithm uses continuous power flow technique to trace the system steady-state behaviours starting from the base-case to the post-contingency. Homotopy methods embed a continuous parameter λ to the power flow equations such that the new system of equation at $\lambda = 0$ is easy to solve and at $\lambda = 1$, the system of equation is identical to the difficult problem to be solved. The saddle-node bifurcation point calculation serves to compute sensitivity for insecure contingencies, which represent an unstable network operating condition. It is also used to determine whether NR method diverges due to insecure contingency or the divergence is caused by a numerical problem. If the system reaches saddle-node bifurcation point before the parameter λ reaches 1, the corresponding contingency is an insecure contingency. Otherwise, the divergence of the contingency is caused by numerical problem and the corresponding contingency is not insecure. In the occurrence of numerical problem, homotopy-based methods are well suited for solving power flows where global convergence regions are difficult to find by traditional methods such as NR.

3.5 The CAS's State Estimation

The state estimator is the heart of the CAS as it provides input data to the real-time power flow solver. While the CAS collects real-time raw data from the DMS, raw data requires processing before the data can be fed into the CAS's power flow solvers. Issues encountered with real-time data for global transmission and distribution networks state estimation included:

- Noisy, corrupted or missing data
- Current measurements instead of MW
- Power flows direction
- Unknown voltage profile

Some MW measurements taken at the Medium Voltage (MV) distribution network were unsigned or in some cases, polarity of measurement was not consistent across the network, which represented a major challenge for the SE development. Additionally, when only ampere measurements were available, the direction of power flow would not be indicated. With the presence of distributed generation on the network, it was essential to get a clear indication on whether power is being consumed or supplied. Power flow direction issues were resolved by investigating historical sign conventions [8] .

The traditional implementation of SE in transmission networks assumes a high level of measurement redundancy, however, there are limited number of measurements in MV distribution networks and numerous pseudo- measurements are to be generated to achieve the required system observability [10]. In CAS, pseudo-measurements on loads and generators were produced by using available voltage, current and MW on adjacent feeders.

4 Conclusion

This paper has introduced the South East of England region case study, discussing operational and technical challenges faced by the electricity networks in the area. The KASM project presents an innovative solution that combines transmission and distribution networks models, real-time data and forecasting data to enhance networks visibility, facilitating system operation while improving network reliability. Modelling distribution networks in real-time can be a challenging task and involves the use of multiple power flow solving techniques. As DNOs increase the levels of SCADA, the accuracy of the solved power flow cases will improve. Although the KASM project is not incorporating detailed protection schemes within its modelling capability, this will be an important consideration for future real-time modelling tools. As power flows become more volatile with the presence of intermittent generation and interconnectors, the dynamic behaviour of network assets such as OLTCs must be accurately modelled to better secure efficient operation of the networks.

Over the next 6-8 months the KASM project will trial the newly developed CAS to determine the full extent of the benefits it can provide to DNOs.

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