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Sensors and Measurement Strategy

WESTERN POWER DISTRIBUTION

Serving the Midlands, South West and Wales

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Contents

1. Background

1.1 The Changing Nature of Distribution

The last decade or so has seen a very significant change in the nature of connections to the distribution network. Historically, generation was dominated by large, mostly fossil-fuel powered thermal power stations connected to the transmission system at 275/400kV. Power was transferred from the transmission system to consumers via distribution system Grid Supply Points (GSPs) at 132kV and down, ultimately, to 415V (LV).

As a result of efforts to decarbonise power generation, many of these large, fossil fuel power stations are closing as they come to the end of their lives and are being replaced by multiple smaller, typically renewable, power generators which, due to their smaller capacities, are being connected to the distribution networks rather than the transmission network. These installations are referred to as "embedded" generation. In an increasing number of cases, these installations are being combined with battery storage. As well as these commercial-scale installations, domestic customers are also installing solar panels and battery storage systems.

With renewable generation being intermittent, and not necessarily producing power coincident with levels of demand on the network, the nature of power flows across the network as a whole is now far more complicated. While periods of excess generation can be compensated for with the use of energy storage (typically batteries), there are significant periods of time when areas of the network experience what is referred to as reverse power flow – when power is transferred from areas that normally consume power back through the network and from the low voltage side of transformers to the high voltage side. To provide some context across WPD's 4 license areas: a total of 21GW of embedded generation has been added to a network designed for 14GW of demand.

While the nature of generation connected to the network is changing, so too is the nature of demand. Again driven by efforts to reduce reliance on fossil fuels, Low Carbon Technologies (LCTs) such as electric vehicles and heat pumps are being installed in rapidly increasing numbers both by domestic and commercial consumers. This shift away from using fossil-fuel energy for transport and heat towards electrical energy is resulting in increasing peak levels of demand on the distribution network.

The historically predictable nature of demand and generation levels, and their associated power flows, allowed distribution networks to be designed as passive in nature – power flowed from generators connected to the transmission system, and from GSPs to consumers connected to the distribution system. As long as maximum demand levels could be determined, a distribution system could be designed to accommodate it.

Building a network to cope passively with new potential peaks and possible reverse power flows would be very costly and inefficient. However, many of the new LCTs being installed offer their own opportunities to mitigate their impact – for example battery storage systems and electric vehicles can be used to "soak up" excess generation in order to reduce levels of reverse power flow, while incentives in the form of price signals can encourage customers to modify their consumption patterns in order to reduce peak levels of demand. Such adoption of "smart" technologies to actively manage load will have significant benefit to costs, reliability, and security of supply.

Furthermore, the intermittency and diversity of renewable sources of generation can be exploited when assessing the capacity of the network to accept new connections – provided sources of generation can be controlled as necessary, additional capacity can be released in order to maximise the amount of generation connected while minimising the costs of the associated infrastructure.

This move towards active management of distribution networks has created a new role to be filled within the electricity supply industry. In addition to the existing role of Distribution Network Operator (DNO), a new Distribution System Operator (DSO) function will need to be performed.

It is WPD's view that existing DNOs are well placed to perform the DSO function, and has already undertaken a great deal of work to adopt new, "smart" technologies such as Active Network Management (ANM) which allows generators to connect under "alternative" connection agreements – the connection is permitted without costly network reinforcement in return for being curtailed during periods when network loads are too high. To date, WPD has made 2GW of alternative connection offers.

Additionally, WPD is exploiting Demand Side Response (DSR) services (sometimes referred to as "flexibility") where conventionally connected customers can be contracted with in order to change their consumption on instruction. WPD is currently seeking 334MW of total capacity of DSR (flexibility) contracts.

Critical to the successful operation of these new systems is good quality, reliable, and timely data relating to the state of the network, representing a need to carry out a significant amount of work to upgrade WPD's data acquisition capabilities which, as shall be described in later sections of this document, are becoming increasingly out of date and risk providing misleading information.

1.2 OFGEM - The Regulator's View

OFGEM currently view the DSO role as "a set of functions and services that need to happen to run a smart electricity distribution network"[1]. The view is that these functions and services need not necessarily be provided by a single organisation, but could be provided by multiple organisations, each with clear, separate responsibilities.

As part of its DSO reforms, OFGEM aim to achieve four strategic outcomes:

1. **Clear boundaries and effective conflict mitigation between monopolies and markets.**
2. **Effective competition for balancing and ancillary services, and other markets.**
3. **Neutral tendering of network management and reinforcement requirements, with a level playing field between traditional and alternative solutions.**
4. **Strongly embedded whole electricity system outcomes.**

Point 3 in particular has potentially significant impacts on DNOs. Timescales for network management services will range from weeks or even months ahead (to aid with outage planning etc) to real-time (ensuring load, voltage, security limits are adhered to), and assessment of reinforcement requirements will require detailed historical data coupled with forecasting tools. Again, good quality network data will be required.

This point is made by OFGEM, as it identifies a key enabler for DSO functions as "the need for technology, data and engineering competencies and capabilities to fully unlock the benefits of the developing energy system", and more specifically "network monitoring and visibility enablers". It also recognises the risks of inaction on key enablers.

[1] OFGEM Position Paper on Distribution System Operation, August 2019

2. Introduction

The purposes of sensing and monitoring on the Distribution Network encompass a very broad range of issues and parameters that can be summarised into three, primary aims:

1

Load Related

Determining the overall capability of the network to meet the power and energy demands on it. This could be in the short term, ensuring that assets are not overloaded as a result of real-time operation of the network; or longer term, ensuring that reinforcement is carried out ahead of anticipated changes in connected demand and generation.

2

Performance Related

Ensuring key performance targets such as Customer Interruptions (CI) and Customer Minutes Lost (CML) are met.

3

Health Related

Avoiding asset failure due to degradation and or defects and ensuring assets are replaced or refurbished in an efficient manner.

Performance and health related monitoring within WPD is already well established. Significant investment in protection, automation and remote control of the network over the last 20 years or so has enabled WPD to rapidly isolate faulted parts of the network while restoring as much of the adjacent, intact network as possible, minimising periods of supply loss to customers. At the same time, improvements in WPD's inspection and maintenance procedures and equipment have allowed for a better understanding of the health of assets, with techniques such as partial discharge monitoring detecting the early warning signs of failure and allowing assets to be replaced or repaired in good time.

With little or no change foreseen that would affect existing requirements to manage network performance and health, WPD will continue to build on past experience and exploit new technologies as they emerge.

The requirements for load related sensing and monitoring, however, are seeing significant change. Historically, distribution networks have been designed as passive networks with power flowing from Grid Supply Points at the Transmission/Distribution boundary, to customers connected at lower voltages. Very broadly speaking, provided the maximum levels of demand were understood, networks could be designed and operated accordingly with little to no management of the power flows in operational timescales.

With the significant rise of distribution-connected (embedded) generation at 11kV and above, and the proliferation of low carbon technologies (LCTs) on low voltage (LV) networks, the demands on distribution networks have changed a great deal. Instead of being passive networks, they are being transformed into active networks, with loads being managed in real-time in order to manage network constraints. This significant new function of Distribution System Operator (DSO) means that the requirements for the monitoring and recording of network parameters have changed significantly, too.

2.1 Development of Smart Networks

With a great deal of the new, embedded generation on the higher voltage networks being based on renewables – mostly wind and solar, an opportunity exists to allow the connection of more capacity than would normally be allowed for by traditional design processes geared towards conventional (fuel-burning) generation. This can be achieved by exploiting the intermittency of renewably energy sources and the relatively low probability that they will all reach full output simultaneously while at the same time further allowing for the natural variation in demand levels.

Allowing these connections – referred to as “alternative” connections, however, relies on the ability to control the associated load, curtailing it when the network is highly loaded and unable to accept the connection’s full output. Alternatively, network constraints could be managed using flexibility services: engaging with other connected customers who are able to operate flexibly and who can be contracted with to alter their generation and/or consumption on instruction.

Regardless of whether constraints are mitigated by using alternative connections, flexibility services, or a combination of both, the need for accurate, reliable real-time data allowing real-time analysis of the network becomes crucial, and significant upgrades to our monitoring equipment are required.

2.2 Improving Network Design

The proliferation of embedded generation and low carbon technologies has also had an impact on the information required for network design purposes. Historically, little more than the maximum demand at a substation was needed to ensure the adequacy of the installed plant. A simple maximum demand indicator could provide this information, although more detailed information is typically now available in the form of historically recorded half-hourly averaged measurements.

Today, however, these recorded measurements are often no longer suitable. In many cases it is not possible to determine the direction of the power flow measurement – when a substation serves only to supply demand, directionality can safely be assumed. Significant embedded renewable generation, however, introduces the possibility of periods of reverse power flow when generation levels are high at the same time as demand levels are low.

Furthermore, the half-hourly averaging that is carried out as standard runs the risk of masking true peak power flows when there is significant variation. While the impact of embedded generation is largely felt on the higher voltage (33kV and above) networks, the increasing uptake of domestic LCTs such as solar panels, plug-in vehicles, heat pumps, and battery storage is driving significant changes in the pattern of demand. This has the biggest impact on the associated local LV networks. In addition to improvements in the real-time monitoring capability of the network, therefore, improvements are also needed in the way in which measurements are taken and recorded for planning and design activities.

2.3 Improving Network Security

The increasing addition of inverter-based technologies such as renewable forms of generation, battery storage and electric vehicles has the potential to significantly impact power quality. Excessive levels of harmonic distortion have detrimental effects on the network, including the possibility of protection systems operating when they shouldn’t, putting potentially large numbers of customers at risk of disconnection.

By monitoring power quality on a continuous basis, the levels of harmonic distortion on the network can be better understood and, therefore, acted upon in order to prevent damage to network assets or to prevent protection mal-operation resulting in significant load loss events.

2.4 Impact on Monitoring Requirements

The ability to effectively run a smart and flexible network requires a high level of real-time network visibility and control, with sufficient monitoring and communication to determine:

- Directional real and reactive power flows at strategic locations on the network;
- Voltage magnitude and phase angle;
- Switchgear status, operations and failures;
- Transformer tap positions;
- Protection operations; and
- Power Quality

Real-time analysis will need this visibility of the network to determine network topology and power flows, so systems can take actions in the required timeframes.

Furthermore, an increasingly complex distribution network will need higher levels of monitoring beyond the current substation boundaries. Data will need to be collected at key network locations and at a higher frequency and granularity, both in relation to real-time system operations and longer term network planning.

The ability to control the network, take actions and react to wider system events through the use of enhanced monitoring solutions will aid our ability to detect issues directly impacting network performance and ensure we maintain a safe and reliable network.

3. Power Flow Visibility

The monitoring equipment installed at a given substation depends on a number of factors such as geographic location and network topology, but is most dependent on the nominal voltage, with the lower voltages having significantly less monitoring. At a Grid Supply Point (GSP), Bulk Supply Point (BSP) or Primary substation most of the required measurement transformers (CTs and VTs), telemetry, and control is already installed, but going down to a distribution substation this is considerably reduced, as the benefits were limited when compared with the associated costs to customers.

However, what is less frequently installed, especially at Primary substations, are the transducers that take current and voltage measurements and convert them to the required, directional real and reactive power flows.

3.1 Existing Monitoring

There are three different types of Power that are applicable to A.C. systems, Apparent Power, Active Power and Reactive Power:

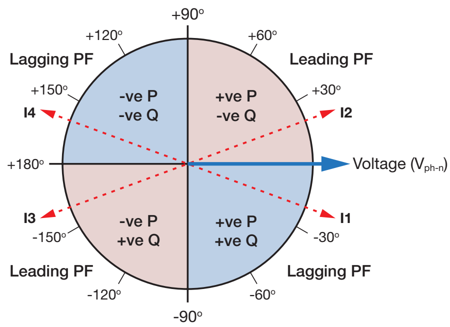
- **Apparent Power** = Voltage x Current and has units of Volt-Amperes (e.g. VA, kVA or MVA).
- **Active Power** = Voltage x Current x COS ϴ, where ϴ is the angle between the Voltage and Current waveforms. Active Power is expressed in Watts (e.g. W, kW or MW).
- **Reactive Power** = Voltage x Current x SIN ϴ, where ϴ is the angle between the Voltage and Current waveforms. Reactive Power is expressed in VARs (e.g. VAr, kVAr or MVAr)

Voltage, Current and Apparent Power by themselves are non-directional quantities and are not assigned a direction. The direction of active and reactive power-flow depends on the relationship between the voltage and current waveform. There are three ways power is determined on the network, with each method giving varying detail on power-flow.

- **Amps with dummy Volts** – This is where no voltage measurement is available, so an assumption of nominal voltage is used. This will give an approximate MVA magnitude, but no directional real or reactive component.
- **Volts and Amps** – This is using measured Volts and Amps to determine power-flow. This will give a true MVA magnitude, but no directional real or reactive component.
- **MW and MVAr** – To get MW and MVAr data requires a volt and amp input into a transducer that can determine the phase angle between the volt and current waveforms, as this determines the direction and magnitude of the real and reactive components.

Figure 1 is a four quadrant diagram showing how the direction and magnitude of real and reactive power can be determined from the phase difference between the Voltage and Current waveforms. To determine this requires a Volts and Amps input into a transducer/device capable of determining the phase angle between the waveforms.

Figure 1: Four Quadrant Diagram - Direction of Power Flow



P = Active Power (kW)

Q = Reactive Power (kVAr)

I1 lags the voltage by approximately 20° and, in this case, the Active Power and Reactive Power are both positive.

I2 leads the voltage by approximately 20° and, in this case, the Active Power is positive and the Reactive Power is negative.

I3 lags the voltage approximately 160° and so, in this case, the Active Power is negative and the Reactive Power is positive.

I4 leads the voltage by approximately 160° and so, in this case, both the Active Power and the Reactive Power are negative.

All of these methods of determining power are utilised to some extent on the network. Amps and dummy Volts are only used where no voltage is available, as it introduces an error where the voltage is not operating at nominal voltage. Operating above nominal voltage is common at most substation busbars, to account for voltage drop at the extremities of the network.

GSP transformers and feeders normally have directional MW and MVAr data available. Monitoring at a BSP transformer is increasingly directional with MW and MVAr metering. All new BSP substations are having it installed as standard and WPD have an active project retrofitting existing BSPs where possible.

3.2 The Importance of Directional Monitoring

The connection of primarily renewable generation has resulted in an increase in locations experiencing reverse power-flow and varying power factors are being seen more and more across the network.

The following example highlights why monitoring just Volts and Amps may no longer be sufficient to design and operate an increasingly complex and unpredictable network. The network represented is a 132/33kV transformer at a BSP.

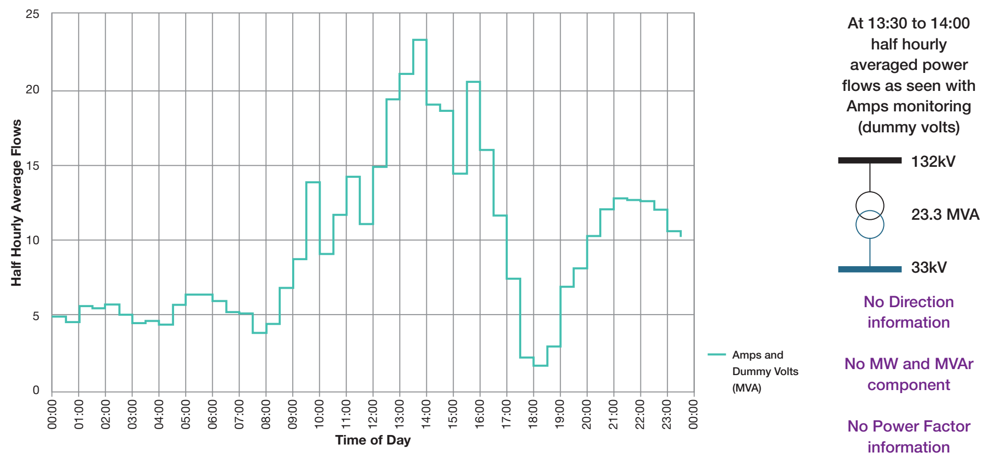


Figure 2:
Power flow represented with Amps and dummy volts metering

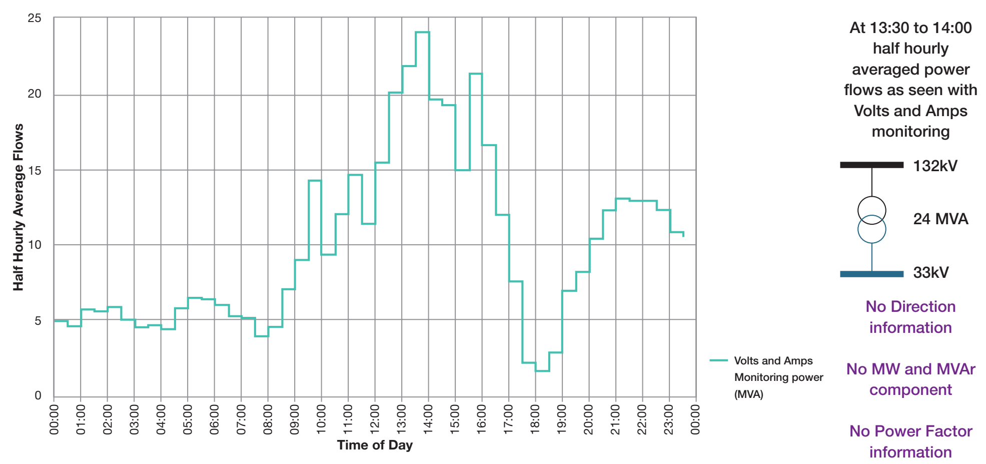


Figure 3:
Power flow represented with Amps and volts metering

3. Power Flow Visibility

Both Figure 2 and Figure 3 are showing MVA values; looking at this data suggests it is a daytime peaking demand, as there is no way of determining the real and reactive magnitudes and direction. The difference in the peak MVA value of 23.3MVA (Amps only monitoring) compared with 24MVA (Volts and Amps) can be attributed to the voltage at the 33kV operating above nominal voltage.

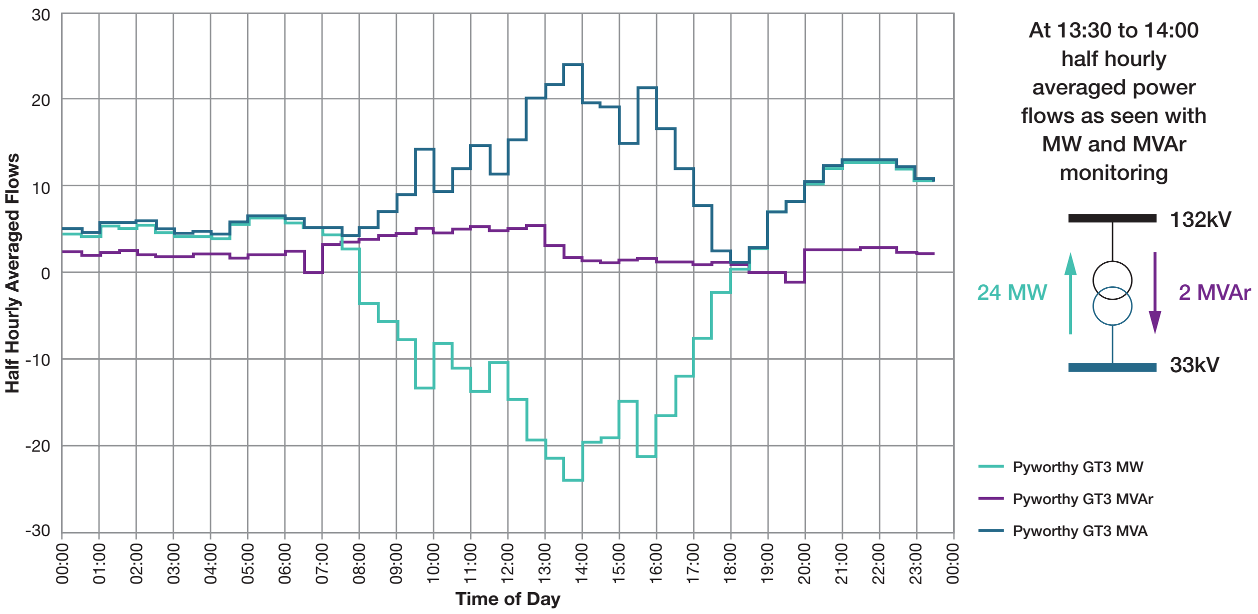


Figure 4: Power flow represented with full 4-quadrant MW and MVAr metering

Figure 4 shows the same transformer on the same day, but with full directional MW and MVAr metering.

This shows a very different picture of the actual flows on the transformer. What is actually happening is reverse real power-flow, in this case predominately caused by solar generation. The power factor is lagging, with 2MVAr flowing into the 33kV network. This information is completely masked with non-directional MVA values.

With the increase in generation installed at 33kV and below, and with the connection of disruptive technologies like batteries the need to understand the real and reactive flows on the network is becoming increasingly important.

This information is necessary for:

- Making informed decisions about switching and network operation;
- Ratings of transformers, as they are dependent on power-flow direction;
- Running real-time analysis like Active Network Management (ANM) to ensure that curtailment requirements are accurately determined; and
- Enabling the network to be correctly represented in power system design software as this is used to determine reinforcement requirements and network constraints at the planning stage.

It is likely that real-time analysis, like that currently used for ANM, will be used to a greater degree in the future as flexibility services are used to manage short duration, seasonal constraints where this provides better value-for-money than traditional reinforcement. Accurate modelling of the network will be required to procure and initiate the correct volume of flexibility services at the right time and right location on the network.

3.3 Measurement Locations

At present, the key aim of our smart systems such as ANM is to manage constraints on the network at 33kV and above. In order to be most effective, the tools used to model the system and its power flows need to be supplied with accurate information at the extremities of the associated networks, in this case the Primary transformers.

In addition to the monitoring at primary transformers, all new generator connections with a capacity of 500kW or more now include a Connection Control Panel (CCP) as standard. This equipment contains the necessary transducer for directional load flow monitoring as well as the necessary interfaces to enable curtailment signals to be sent if the connection is subject to constraint.

Looking ahead to the potential increase in LCT connections at LV and 11kV, there may be further benefits to extending network visibility to cover the 11kV network as well as the 33kV and above. This would also be achieved at primary substations by monitoring of 11kV breakers.

3.4 Work Required to Achieve Full Network Visibility

A detailed assessment of requirements in the South West license area has already been carried out[2]. The amount of work required at each substation will depend on a number of factors.

For visibility of the 33kV and higher voltage networks, most primary transformers already have the required instrument transformers (CTs and VTs) which would enable a multifunction transducer capable of determining direction power flow to be installed where not already present. Multi-transformer sites that do not have busbar VTs will need an additional voltage selection panel installed to enable bar voltage to be determined for any running arrangement.

For additional visibility to cover the 11kV network as well, multifunction transducers would need to be installed for each circuit at the Primary.

The costs for the South West have been estimated as £4.1m for coverage of the 33kV network, with an additional £4.6m required to capture the 11kV network. While detailed studies have not yet been done for WPDs remaining license areas, a simple extrapolation indicates approximately £16m total for 33kV, and total of around £35m for full visibility down to the 11kV network across all four license areas.

[3] WPD Projects South West "Network Monitoring and Visibility", November 2017

3. Power Flow Visibility

3.5 Benefits of Full Network Visibility

While the costs of achieving full network visibility can fairly easily be quantified, the benefits to WPD, specifically, cannot. The precise nature of WPD's DSO function, and the potential financial incentives and/or rewards are under review by OFGEM, and are only likely to be finalised in time for the RIIO-ED2 price review period starting in April 2023. However, there are benefits that can be qualitatively described, along with some quantification of the potential benefits to customers, and the industry at large.

3.5.1 Value of Released Capacity

The primary benefit of improved network visibility will be the capacity that can be safely released to allow the continued growth in the cost efficient connection of renewable generation and LCTs without the need for extensive traditional reinforcement options.

A report on renewable generation statistics produced for BEIS[3] indicates that as at the end of Q3 2019 there was a total installed capacity of 46.9GW of renewables, contributing a total of 28.8TWh of energy during Q3 2019. A crude extrapolation over a full year (assuming that any loss of solar PV over the winter months is made up for by an equivalent increase in wind output) indicates that on average, each gigawatt of installed renewable generation yields 2.46TWh per year. At an average of £50 per MWh (taken from the average of the wholesale day-ahead baseload contracts for winter 2018 and summer 2019), this equates to a total value to the generation industry of £123m per year. It is also worth noting the environmental/societal benefit of this quantity of renewable generation and its contribution to the 2050 "net zero" target for the UK.

With WPD already having issued alternative connection offers with a combined capacity of 2GW, and with systems such as Active Network Management still in limited use, it is clear that there is a great deal of value to be gained from the £35m investment outlined in 4.4 above.

3.5.2 Optimise Operation of "Smart Grid" Systems and Procurement of Flexibility Services

Higher quality of real-time data would allow for greater optimisation of curtailment signals issued to generators on alternative connection agreements. Where curtailment might otherwise have been higher than necessary, this would result in lower levels of curtailment, benefitting customers by reducing the associated lost revenue. In areas where curtailment has been lower than necessary, the benefit would be realised by WPD in the form of lower risks associated with potential asset overloads.

The same improvements in network analysis would also allow greater optimisation of the need for contracted flexibility services.

While the benefits above are very hard to quantify without firm knowledge of the real improvements that could be made with experience, it is possible to illustrate the size of potential savings. Current flexibility contract rates are around £300 per MWh. With 334MW of flexibility capacity currently being sought by WPD, the avoidance of just one hour's worth of full contracted supply would yield a saving of around £100k.

Similarly, the avoidance of 1 hour's full curtailment of the combined 2GW of alternatively connected generators would also yield avoidance of around £100k lost revenue.

[3] National Statistics: UK Renewables July to September 2019

4. Measurement Recording

WPD's Distribution Network Management System (DNMS) software receives instantaneous readings for analogues where there is a change in the monitored value beyond a pre-determined range. This data is displayed on the control diagram and is used to operate the network. It is also used by ANM systems.

This data is not currently recorded for future use because it has not previously been required. What has historically been recorded is a half hourly average value, which is calculated by the DNMS from the instantaneous values. This is used for regulatory reporting and as an input into models to determine network compliance and reinforcement requirements. The granularity of the time averaged data is a trade-off between data processing and accuracy.

When networks were demand driven this granularity of data was the standard, as it gave an accurate representation of network conditions. With the increase of intermittent distributed generation and energy storage connecting to the network, there is a concern that a half hourly averaged value is becoming unrepresentative.

4.1 The Importance of Recording Intervals

The power-flow variation at a given feeder over a half hour period is predominately dependent on the technology mix of demand and generation.

A domestic and commercial demand dominated feeder will typically have less variation across a half hour than an industrial demand or an intermittent generation dominated feeder.

Figure 5 shows the flows on a transformer feeding a demand dominated network. The red lines are showing the half hourly averaged value, with the blue lines showing the second by second variations recorded using a power quality monitor.

This shows the variation from the half hourly average is relatively small. For the half hour between 17:30 and 18:00 the half hourly average is 4.22MW. There was a maximum of 4.33MW and a minimum of 4.07MW; this represents approximately a 3.5% variation from the half hourly averaged value.

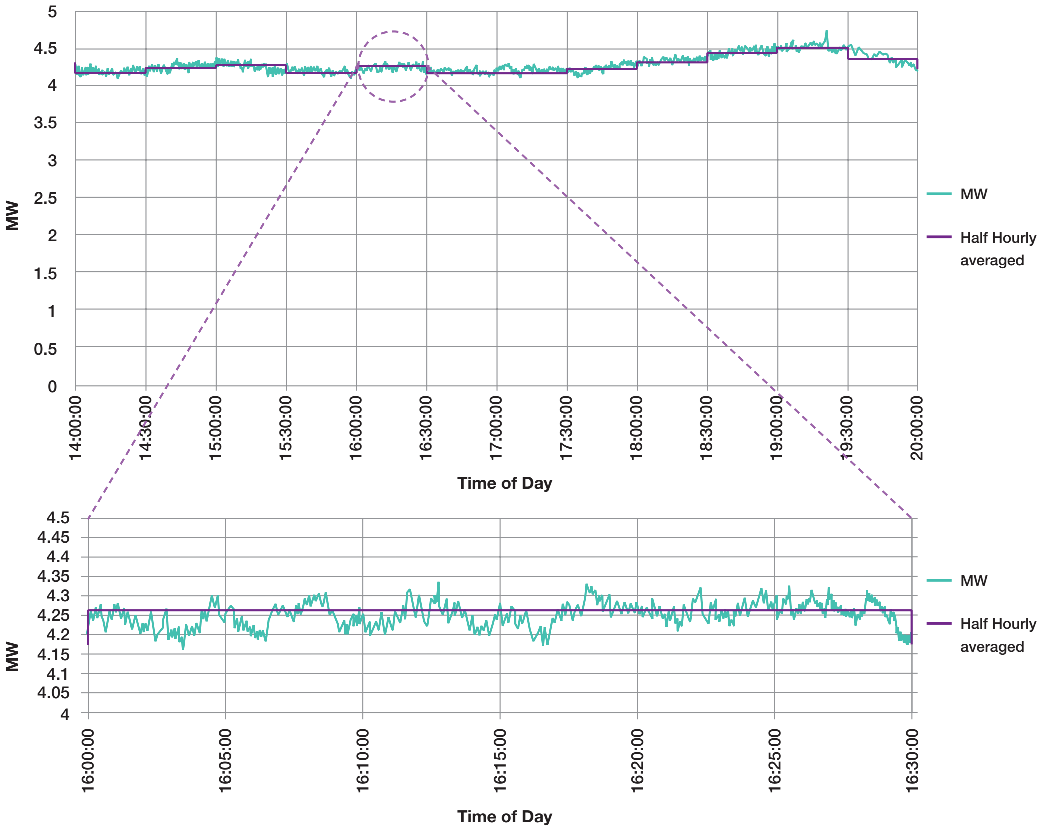


Figure 5:
Comparison of half hourly averaged flows against actual flows on a demand dominated transformer

4. Measurement Recording

Figure 6 shows the variation of real power on a dedicated feeder to a windfarm. This highlights the significant variations seen across a half hour, when compared with the demand dominated feeder in Figure 5.

The largest excursion from the average is almost 50%, highlighting how the increase in intermittent generation is changing the variability of the network, causing half hourly averages to inaccurately represent actual network conditions.

As intermittent generation like PV and storage continue to connect to the network, this variation and inaccuracy will only increase. The second graph in Figure 6 shows the period between 17:30 and 18:00.

It is of particular interest, because it shows how the actual flow is considerably over the half hourly average for almost 10 minutes.

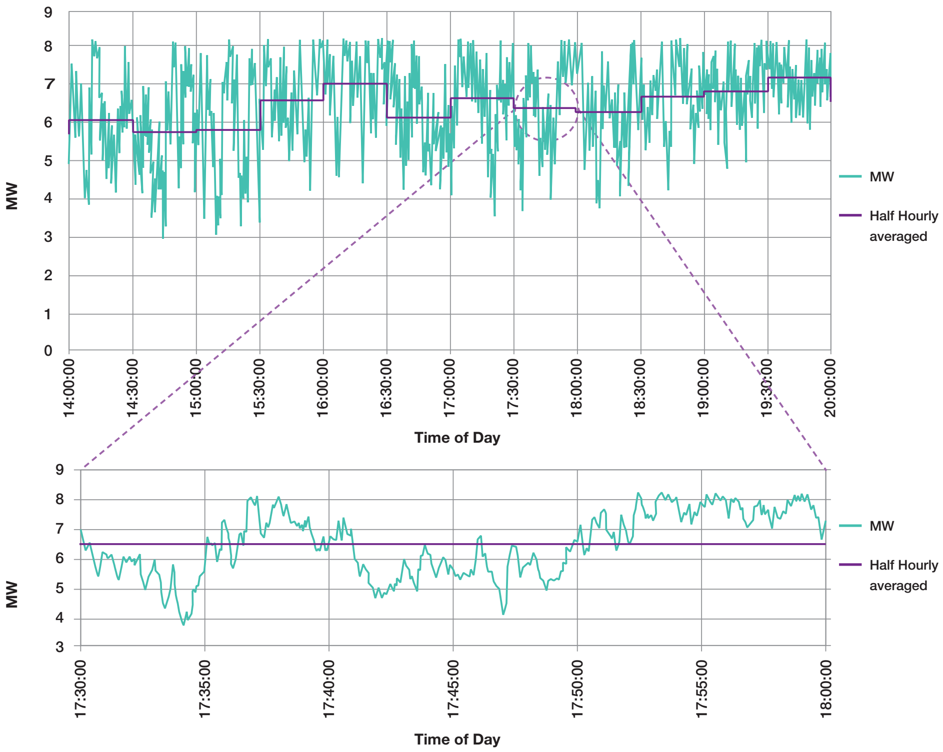


Figure 6:
Comparison of half hourly averaged flows against actual flows on a windfarm feeder

This half hourly average data is used extensively to design the network. This raises the question as to what recording frequency of monitoring will be needed in the future to determine actual peaks and the length that these peaks persist. This needs to be considered along with the coincident peaks of other generation and demands to determine what granularity of averaging is desirable.

Where the most likely network issue is thermal overloads of cables or transformers, then the thermal inertia of these assets means that the minute by minute effect of load variations is considerably dampened. The degree of variation in the loads is a factor in the methodology for setting ratings for overhead lines, and it may be necessary to reassess ratings if the volatility in loadings resulted in higher levels of average heading. Increased variability in loads within a half hour will also make voltage excursions more likely.

This data is increasingly used to calculate generation and demand load factors (coincident factors). This could lead to underestimated load factors; this relates back to the transient limits of the network and what granularity is required to design the network. It is also used to determine the underlying demand on the network. This is calculated by looking at the flows at a given substation and using the half hourly averaged generation data to unmask the underlying demand. If the generation is actually significantly lower at times than the half hourly average, the underlying demand could be underestimated.

4.2 New Data Historian

WPD has recently added the Time Series Data Store (TSDS) to its DNMS. It stores all real time analogue changes (including Amps, Volts, MVAr, MW, MVA and tap position) as well as the time of the change.

This method of recording data does not rely on a pre-set sampling interval in order to capture changes in monitored values, avoiding the unnecessary recording of unchanging values while ensuring that variability is accurately captured.

5. Power Quality

With the primary renewable forms of generation of solar PV and wind turbines, as well battery storage systems and EV chargepoints relying on inverters for connection to the network, power quality is becoming an increasingly important parameter.

Excessive levels of harmonic distortion have detrimental effects on the network: increased RMS currents result in increased thermal stresses, insulation stresses increase as a result of higher instantaneous voltages, and protection equipment can mal-operate if it misinterprets the measured waveforms.

Presently, power quality is monitored only periodically and, due to the monitors themselves, the process is quite labour-intensive and not automated. The Primary Network Power Quality Assessment (PNPQA) innovation project is currently developing an understanding of more sophisticated, automated monitoring equipment.

By monitoring power quality on a continuous basis, the levels of harmonic distortion on the network can be better understood and, therefore, acted upon in order to prevent damage to network assets or to prevent protection mal-operation resulting in significant load loss events.

The benefits of greater investment in power quality monitoring can be substantial. If just one Bulk Supply Point (BSP) outage due to protection mal-operation can be avoided, the financial benefit could be greater than the installation cost of the improved monitoring across the whole of WPD's networks. On the assumption that there are, on average, a total of 35,000 customers connected to a BSP, and with an assumed After Diversity Maximum Demand (ADMD) of 4kW (total average of combined domestic and commercial), a one-hour outage will result in the loss of 140MWh of energy.

A recent project completed by ENW[4] looking at the value of lost load (VOLL) concluded that a weighted average combined domestic/SME figure of £25,300 would be appropriate. This value would indicated that a BSP loss with a one hour restoration time would result in a total cost to customers of about £3.5m.

The PNPQA project documentation indicates that the cost of monitoring a single site would be around £5,500 per site with approximately 60 sites per license area benefitting from the improved monitoring. This puts the total cost of monitoring at £1.32m.

[4] NIA Project ENWL010 – Value of Lost Load to Customers

6. LV Network Demands

Network capacity problems (and potential solutions) are emerging on LV networks, too. Domestic customers are increasingly adopting low carbon technologies (LCTs) such as rooftop solar panels, electric vehicles, and heat pumps. Electric vehicles, in particular, have the potential to add very large levels of demand co-incident with existing periods of maximum demand. They also present the greatest opportunity for flexibility in managing these peak loads.

WPD's aim for the LV networks is, essentially, to reinforce ahead of need. In order to avoid unnecessary work, it is important to correctly identify specific LV networks that actually need reinforcement. To this end we will continue to build on tools already developed for the forecasting of load growth and the identification of LCT locations and network constraints.

Where the potential need for reinforcement is identified, WPD will fit monitoring to the distribution substation to allow actual loads to be assessed. This not only provides verification of modelled information but also provides the basis for the potential deployment of load-management solutions which will allow WPD to mitigate the risk to assets, and to customer supplies, pending the installation of replacement assets.

6.1 Smart Meters

Smart meter data is key for us as it will give us an indication of the status of low voltage feeders without first requiring us to add monitoring systems. Our Data Privacy Plan allows us to use this data, in the form of load profiles derived from aggregated individual customer data, when we make our planning decisions regarding the connection of LCTs.

When this data shows that the network is nearing capacity additional substation monitoring can then be added ensuring the efficient deployment of that equipment and resources and allowing the management of any constraints in real time where possible.

6.2 State Estimation

Smart Meters may not be present at all points of supply on a network and we can use state estimation to plug the gaps in our recorded and monitored data.

For parts of our LV networks which are not operating near their capacity limits this level of estimation is likely to be adequate for us to manage the networks.

It is only when capacities are being reached that we will need to install monitoring at LV feeder level.

6.3 LV Monitoring

Our solution to provide retro-fit monitoring at existing distribution substations was developed through the LCNF Network Templates project. It has now been developed into a business as usual system which uses Rogowski Coils to measure current and direct voltage.

We are developing the provision of LV monitoring as a standard within our current LV fuse cabinet, as the cost of adding this monitoring at the time of manufacturer is small compared to the overall cost of the unit. Adding this as a minimum standard ensures that our new networks are built to be resilient to the requirements of the future. It is expected that LV monitoring will need to be installed at our ground mounted distribution substations first, as these have the largest capacities and supply large groups of customers. We have around 60,000 ground mounted sites but, as explained above, some will be able to operate using just smart meter data and state estimation.

The primary benefit of retro-fitting monitoring to existing sites will be realised through deferring required reinforcement. With a new distribution substation costing around £40k and with an expected life of 40 years, deferring reinforcement for just three years would yield a positive cost benefit for a given site.

Our forecasts for the adoption of Low Carbon Technologies predict that up to 25,000 distribution substations could exceed their demand capacity by the end of the RIIO-ED2 period. When Smart Meter data indicates that a substation would benefit from the enhanced, real time data from active monitoring equipment, we will install this at such sites to confirm and refine our forecasts, as well as to enable further options for constraint management. We also expect that monitoring will defer our expenditure at many of the locations as we can use better information in our models.

For all new substation installations in RIIO-ED2 we will fit monitoring and communications links as standard. Our current standard Low Voltage fuse cabinet is supplied with monitoring rather than traditional "maximum demand" indication. The provision of a communications link to take advantage of this real time data will increase our network visibility at a minimum additional cost.

7. Communications Requirements

We have developed an extensive in-house communications network to control and monitor our electricity network but much of the design was built around older assumptions of a single flow, demand led network topology. It was also built to support the return of half-hourly averages in most cases. The new DSO role and a more active two way power flow increases the communications bandwidth requirements that we require.

7.1 Bulk Supply Points and Primary Sites

Our sites were traditionally linked to our communications network via scanned radio and hill top sites. Whilst the hill top sites were connected via either microwave radio or fibre optic systems, the individual sites were polled.

As volumes of monitoring data increase this polled model creates limitations.

To provide the quality and volume of data required for our DSO role we will need to establish either fibre optic or microwave radio links directly to each substation site. Providing this enhancement to the communications network has the added benefit that it allows our larger substations to become hub sites for communications out to smaller sites.

7.2 Distribution Substations

Our sites have had very limited communications, with links only established where automatic switching operations were required for supply restoration means. Any requirement to provide monitoring from these sites was unusual. Our traditional method of providing communications was to use a simple radio system.

As the number of sites requiring communications increases we will change the way that we provide our solution. We are developing a Long Term Evolution (LTE) system, similar to the technology that is employed in the 5G mobile phone network.

We have also acquired bespoke radio spectrum to allow us our own channels to reach our sites. We would expect to be able to provide a communications link to a distribution substation as simply as if we were just adding a mobile phone to a public network.

8. Innovation

In order to help address the issue of LV network constraints, the Open LV project involves the installation of intelligent substation devices that can support software applications or 'Apps' from multiple vendors on a single device. This provides a low cost hub that, once deployed, can act as a hub: a secure platform that enables intelligent substation devices to be remotely managed and that provides LV network data to community groups and third party organisations. This will facilitate non-traditional business models, such consumer-provided demand side response (DSR), giving WPD more options for managing network constraints.

In addition, the sophisticated sensors and monitors that feed the intelligent system can also be used to provide benefits in finding and restoring faults that result in loss-of-supply incidents to consumers.

The Automatic Location of Arc-faults through Remote Monitoring (ALARM) involves the analysis of current and voltage waveforms to identify the distance to fuse-operating faults, as well as the distance to damage for transient non-fuse-operating "pecking" events that are often the precursors to transitory faults/fuse operations and permanent faults.

In order to provide increased visibility of our higher voltage networks, the OHL Power Pointer project is developing an overhead line-mounted directional fault passage indicator that also provides power flow information. As well as directional power flow monitoring, the aim is to also provide state estimation – using the directional sensors to infer direction through non-directional sensors.

The device will also be able to detect auto-recloser operations, as well as providing directional fault detection, aiding in the timely location and repair of faults and damage on the network.

A further feature of the OHL Power Pointer is the ability to monitor the temperature of the overhead line conductor it is attached to. This information could provide a real-time short-term rating, which could be exploited by systems such as Active Network Management.

The short term rating of an overhead line exploits the thermal capacity of the material itself, with the rating not being dependent on any cooling conditions (such as wind) being available. A simple temperature measurement is all that is needed to provide a rating to cover short-term (around 5-minutes) events.

Although not being actively investigated at present, real-time, dynamic ratings of equipment is an area that WPD aims to investigate. This could involve the fitting of temperature or tension monitors to overhead lines, using distributed temperature sensing on new underground cables, fitting temperature sensors to transformers, and the installation of weather monitoring stations.

Another emerging issue on the higher voltage networks is that of power quality (discussed earlier in this document) – with the rapid increase in inverter-based installations on the network, it is important to understand the impact of harmonics from LCTs throughout primary networks in a systematic way.

The Primary Networks Power Quality Analysis project aims to develop an understanding of the behaviour of the monitoring transducers, to automate the retrieval and analysis of power quality data and to develop a decision support tool for modelling and forecasting the effects of harmonics. This project links with the Harmonic Mitigation project which aims to improve harmonic levels by controlling distributed generation inverters.

Details of all our innovation projects can be found at **www.westernpower.co.uk/innovation**

9. Actions

In summary, WPD will make significant investments in sensors and measurements across its network in order to address the future needs of customers and the industry as a whole:

9.1 Directional Power Flow

WPD will aim for 100% visibility of its 11kV and higher voltage networks by ensuring that directional power flow measurements are available at all of its Primary substations. All new substations now require the necessary instrument transformers and transducers.

In total, approximately £35m will be spent by the end of the RIIO-ED2 price control period, with substations prioritised according to need – those within active ANM zones and/or with significant alternative connections as well as areas of the network being supported by DSR (flexibility) contracts.

While also beneficial to WPD in optimising its network design and reinforcement activities, the largest benefit is likely to be to the industry (and society) as a whole, with the value of generation that would benefit from new connection agreements estimated at £123m across the WPD network.

9.2 Power Quality

Pending the completion of the PNPQA project, WPD will identify the sites on its network with significant numbers of inverter-based connections where power quality is of most concern.

Currently, the estimate is that around 60 sites per license area will benefit from improved monitoring at a cost of installation of £5.5k per site, or around £1.32m across the whole network. This work would be carried out by the end of the RIIO-ED2 price control period.

Power quality monitoring will benefit both WPD and customers by ensuring that levels of harmonic distortion are within acceptable limits, avoiding the risk of equipment damage and power outages due to mal-operation of protection. The value of a single BSP outage is estimated at up to £3.5m, representing an opportunity for significant savings.

9.3 LV Monitoring

Specifications will be developed so that all new or replaced distribution substations will have transformer and feeder monitoring as standard. As well as covering new sites, substations requiring new transformers as a result of new LV connections will also be monitored.

Retro-fitting of existing substation will be carried out according to need, with WPD identifying substations subject to high uptake of LCTs such as Electric Vehicles.

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