Equipment and Methodology for the Planning and Implementation of Dynamic Line Ratings on Overhead Transmission Circuits

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***Abstract*—In past years governments have been incentivising a higher percentage of energy production from renewables. Generation from wind farms is likely to reach 40% of the total energy needs of Northern Ireland (NI) by 2020 [1]. Most of the wind resource is concentrated in the North and West, which are traditionally rural and are therefore poorly electrically interconnected with the East, where the population is most densely concentrated. Future wind farm connections will depend on the ability of the electricity infrastructure to cope with increased currents.**

Large network reinforcement is necessary in the long term but can take years in planning, permissions and construction. For the short-term, the plan is to utilize the existing infrastructure already in place by up-rating the overhead line sections by implementing weather-based dynamic line ratings (DLR).

Building on future work [2, 3, 4] this paper describes the learning achieved two years on from having installed the monitoring equipment on three 110kV overhead lines (OHLs). The paper details the development of the system from initial to more recent generations of equipment. It compares two types of anemometer from field studies and determines the difference in rating achieved. The influence of solar radiation on conductor heating is discussed. The paper describes the progression of the project from research to operation, providing details of plans for integration in to the EMS/SCADA system.

Keywords-Weather-based dynamic line ratings; up-rating without system extensions; integration in to EMS/SCADA system

I. Introduction

Northern Ireland (NI) has a target of 12% of its energy coming from renewables (97% of which is likely to come from wind) by 2012. By the end of 2009 the country had 8% of its quota installed, equating to 306MW. Alternative forms of generation, other than conventional thermal power, present new issues with the existing electricity infrastructure.

The wind resource is heavily concentrated in the West and North but traditionally the majority of the demand is in the East, where it is most densely populated. The problem Northern Ireland Electricity (NIE) faces is transmitting the wind energy from where it is generated to where it is required. Since the West and North are mainly rural, they are weakly interconnected to the rest of the network. The limited routes for wind-generated electricity create critical points in the grid that are likely to overheat and become overloaded in the near future.

NIE, like many Distribution Network Operators (DNOs) use P27 seasonal static ratings [5] to rate overhead lines. These values are conservatively based on 0.5m/s wind speeds but NIE field studies as in Fig. 1 show that even in the lowest wind speed areas values were greater than 0.5m/s for 75% of the year. P27 values are based on seasonal ambient temperatures of 9°C, 20°C, 9°C, 2°C for spring, summer, autumn and winter consecutively, which are rarely experienced throughout any season, as seen in Fig. 2. The P27 standard does not factor solar radiation, but NIE have been better able to model the conductor temperature by factoring solar heating.

As wind farm generation increases there is a large increase in current on the critical overhead lines (OHLs) but since the critical lines are often in the same vicinity as the wind farms the same wind acts as a coolant allowing an increase in the OHL ampacity. Monitoring actual weather conditions along the length of an OHL allows a more accurate calculation of the line rating at any given time. In many cases the OHL will be able to carry much more current than the static rating; providing a quantitative boost in the ampacity of the line without over-heating it. Weather-based dynamic line ratings (DLR) allows up-rating of the network when it is needed most, i.e. when wind speeds are high enough for wind farm generation there is sufficient cooling of the OHLs. The ampacity of the OHL increases during high wind allowing the transmission of more wind energy.

The outline of this paper is as follows: the next section discusses the NI electricity infrastructure pin-pointing the critical areas in the network. Section III addresses the weather-based DLR system used by NIE. This is followed by Section IV which describes NIE's personal experience with the equipment and developments made en route. Section V addresses how NIE plans to integrate the DLR system in to the

Sponsors include Renewable Energy Systems (RES) and Airtricity

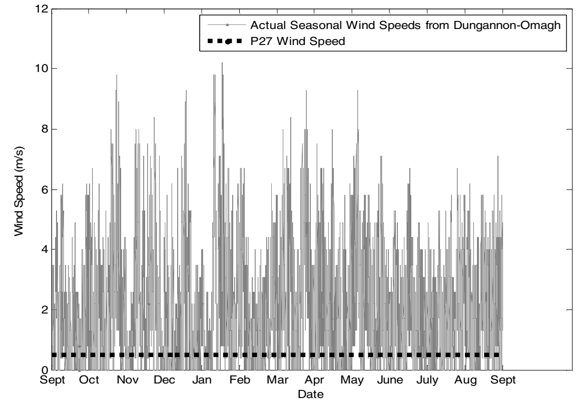

Fig. 1 Comparison of actual seasonal variation of wind for Sept 2008-Aug 2009 versus the conservative P27 assumption for wind speed

Distribution Control Centre (DCC) and the relative operational and running costs of DLR follow.

II. NI Electricity Infrastructure

A. Critical Overhead Lines

In the North and West of the country the OHLs in the vicinity of various wind farms are becoming increasingly more critical. These lines will experience a rise in current during wind generation (which would normally produce a rise in conductor temperature) but the OHL will be cooled from the same wind. The two single circuit 110kV Dungannon-Omagh lines and the single circuit 110kV Kells-Coleraine line, as shown in Fig. 3, are quickly becoming the main electrical interconnections linking the rural North and West to the East of the country.

By 2011 there is expected to be 390MW of wind generation in NI, most of which will at some point feed on to the three fore mentioned OHLs, creating the potential for them to exceed their static ratings under certain contingencies. The worst case contingency the NI network could experience is if one of the Dungannon-Omagh circuits is out of service (OOS) for maintenance while a fault at Coolkeeragh power station (CPS) causes the double circuit 275kV tower line to trip. The current experienced by the Dungannon-Omagh line still in service will increase by 270% in 2011 above normal system operation in 2009 due to the increase in wind generation [4].

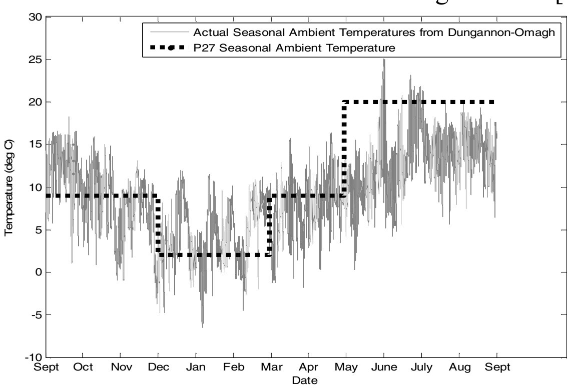

Fig. 2 Comparison of actual seasonal variation of ambient temperature for summer 2009 versus the conservative seasonal P27 assumption for ambient temperature

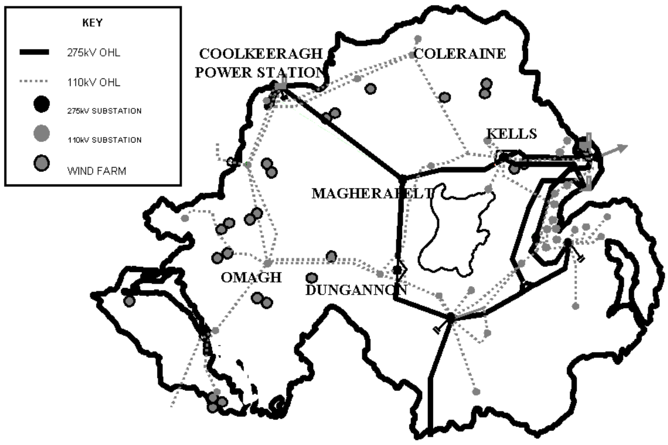

Fig. 3 Map of Northern Ireland transmission grid with wind farm locations up to the end of 2009 superimposed

In order that planned wind farms go in to construction before 2011 the ratings of these OHLs must be reviewed. Weather-based DLR up-rates these lines safely without system extension ensuring the design operating temperature (DOT) of the lines are not exceeded and therefore do not sag below safety clearances (6.4m for 110kV in NI).

B. Critical Points along the OHLs

DLR equipment is installed on selected sites since it is not financially viable to monitor every span along the length of a 40km OHL. Traditionally NIE have monitored ten sites for lines of this length with weather stations and modeled every unmeasured span in between.

Most of the sites chosen in the past have been in low wind speed areas since these are most likely to overheat and therefore limit the ampacity of the whole line (critical points) [4]. In order to model unmeasured spans along the line high and medium wind areas were also chosen. An assessment of the local topography of the land on which the OHLs pass over was performed to determine the sheltering factor, which is accounted for in the DLR calculator.

Weather-based DLR is most suited to transmission lines that pass through flat open spaces with limited bearing changes and sheltering as demonstrated in Germany [6]. However, the terrain in NI is much the opposite. For example the Kells-Coleraine line bears from south-east to north-west, bending considerably in the first quarter section. The bearing of the line in conjunction with the angle of attack of the wind contributes significantly to the cooling effects on the OHL so several sites were chosen to be monitored in this area. A range of measurement nodes with differing elevation were chosen since wind speed and therefore cooling increases with height.

III. The DLR System

At each measurement point, the DLR equipment consists of a weather station, three line sensors, an ‘X-net’ controller and a solar panel. Data are sent via a GPRS mobile provider in real time to a web controller where it can be downloaded remotely from the internet and processed through a ratings calculator to determine the rating of the line at that time. The equipment as

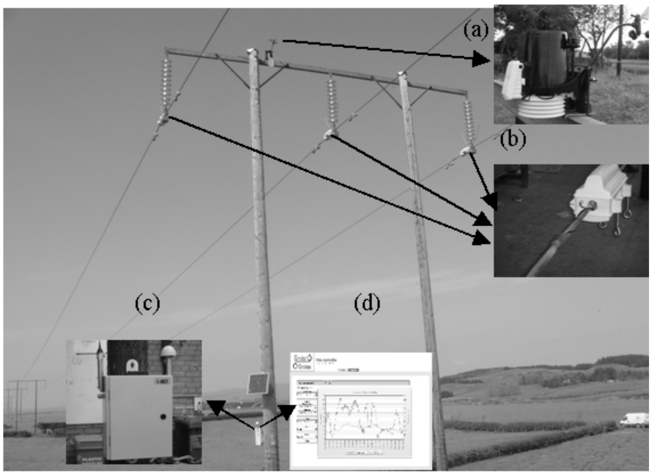

Fig. 4 Photograph of (a) weather station, (b) line mounted sensors, (c) X-NET controller and (d) web controller screen shot

shown in Fig. 4 is fit for purpose, durable and resistant to EMF. The line sensors monitor line current, line temperature and the temperature inside the enclosure. A sensor is fitted to each of the three phases. The 'Davis ProVantage II' weather station monitors wind speed, wind direction, solar radiation and ambient temperature. The weather station is hard-wired to the X-net controller and the line sensors communicate via 868MHz low power radio. The controller is powered by two 12V batteries charged from a 30W solar panel.

A. Ratings Calculator and its Uses

NIE uses the Cigré standard [7] for calculating dynamic ratings.

A calculator, written in 'MATLAB', imports field data, filters it and extrapolates from recent past data to fill in any gaps caused by loss in GPRS or a fault in any of the equipment. The filtered weather data are then inputted along with electrical and physical parameters of the measured spans and the calculator models every unmeasured span.

At unmeasured spans parameters such as wind speed and direction are predicted values and are based on an analysis of local sheltering. Wind speeds are extrapolated between spans using speed-up ratios provided by Renewable Energy Systems (RES). Speed-up ratios model wind speeds between measurement points and take in to account local terrain, sheltering and wind shear. Wind directions at unmeasured sites are also modeled using the calculator. Since the anemometers all face along the direction of the line and not true north, the attack angle of the wind is measured directly at the sites. The derived wind direction at unmeasured spans adjusts for the bearing of the line.

B. Davis Weather Station versus Windsonic Anemometer

The Davis anemometer requires 2m/s to start turning and 1m/s to remain on. It is assumed that the inertia of the anemometer cups can keep them turning after a gust of wind so is not accurate during this time. For this reason an additional ultra-sonic anemometer was installed on each site on the Kells-Coleraine OHL, which is accurate to 0.1m/s and requires no 'turning on' wind speed. There are no moving parts so it is less likely to fail and has better resolution than the Davis.

A study was performed on each measurement point on the Kells-Coleraine OHL to compare the calculated dynamic ratings based on wind speeds from the Davis, Windsonic and P27 standard (constant 0.5m/s wind speed) for spring 2010. Fig. 5 shows the results from one of the measurement points along the OHL.

Both anemometers produced the same trend but the Windsonic has better wind speed resolution (0.1m/s compared with 0.5m/s) and therefore is more accurate. During wind speeds of less than 2m/s the Windsonic created a DLR on average 32A less than the Davis due to the difference in wind speeds recorded since the Davis was not accurate enough at low wind speeds.

Even though the results from both anemometers closely follow the same trend it would be advisable to retro fit Windsonics to the low wind speed areas of the Dungannon-Omagh OHLs. Fine-tuning the ratings calculator to adjust the wind speed from the Davis after a gust of wind at the other measurement points would be advisable.

Note from Fig. 5 that even though the conductor could cope with a DLR of over 1000A, the joints and switch gear could not. Ratings above 750A would never be applied to these particular lines because of these limitations.

C. Factoring Solar Radiation in DLR Calculator

The P27 standard ignores solar radiation and Cigré does not take in to account the solar heat reflected off the earth's surface (albedo). However, NIE recognize the importance of factoring solar heating in to the ratings calculator and so it is calculated more accurately than the equation provided in Cigré taking in to consideration the albedo factor and the latitude of the line, as shown in Equation (1), where P_s is solar heating, α_s is the solar absorptivity of the conductor surface, S is the measured global solar radiation, D is the external diameter of conductor and albedo is the albedo factor.

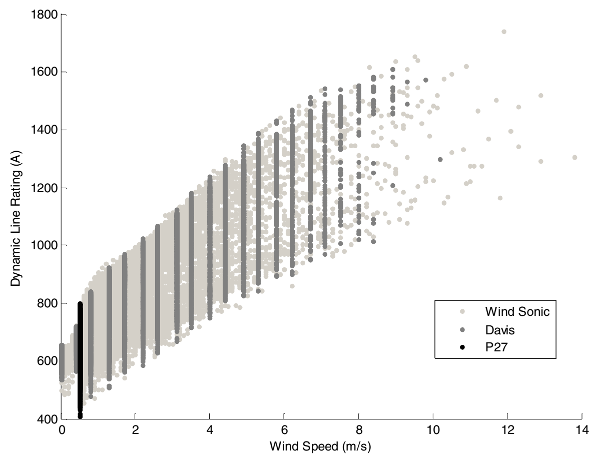

Fig. 5 Scatter plot to show the difference in calculated dynamic line rating using wind speeds from P27 standard (0.5m/s) compared with the Davis anemometer and the Windsonic

$$P_s = \alpha_s SD \text{ x albedo x } (\cos(\text{latitude x } \pi/180))^{-1}. \quad (1)$$

The Cigré standard was applied to field data from summer 2009 after extracting data from during the day. Fig. 6 shows solar heating contributed on average to 7% of the overall heating with a maximum of 10% but NIE's model has shown it to contribute on average 72% with a maximum of 100% of the overall conductor heating. Fig. 7 seconds the importance of factoring solar radiation. The graph shows that the NIE predicted conductor temperature better follows the actual measured temperature, while the green line, which demonstrates no solar factoring, is quite far from the actual.

The reason for the slight difference during the day between the solar-corrected prediction and the actual conductor temperature could be attributed to the pyranometer on the Davis weather station. It measures the vertical component of solar radiation and so using this apparatus in NI, where the sun is never directly overhead, will underrate the solar heating.

Calculating the dynamic rating based on zero solar radiation is not accurate enough. Fig. 8 shows that by factoring solar radiation by NIE's method in (1) the dynamic rating is reduced by up to 80A during the day. This is a significant amount given the dynamic capacity of the OHLs in question (750A) but is necessary to ensure safety clearances are not exceeded.

IV. Development of the Monitoring Equipment

DLR equipment was originally installed in late 2007 on Dungannon-Omagh A and B OHLs (Mark I generation) and on Kells-Coleraine in 2009 (Mark II generation). The developer of the DLR equipment, FMC-Tech has created a number of technical developments between and since the installations due in part to issues that have arisen over the last two and a half years.

DLR equipment is not likely to have the same life-span as other line hardware. It is anticipated that the equipment will remain operational for as long as it is required in the short-term.

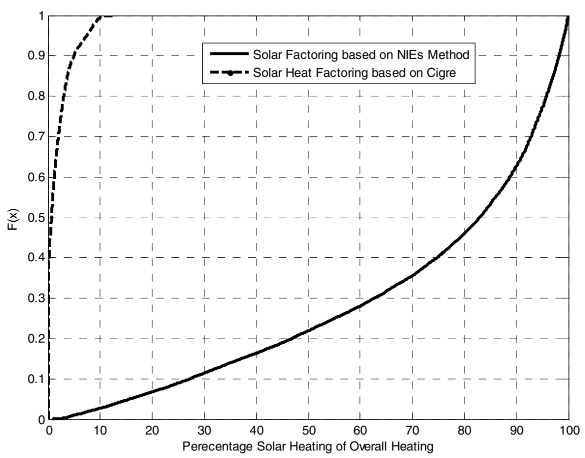

Fig. 6 Difference in using Cigré and NIE's method for factoring solar heating

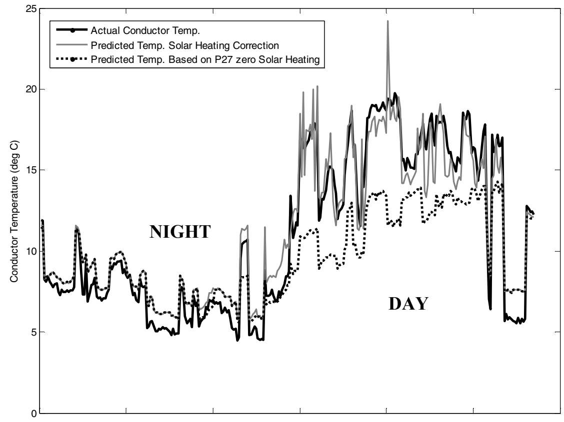

Fig.7 Difference in predicting the conductor temperature using zero solar radiation compared with the more accurate method NIE use

A. *Line Sensors*

The line sensors are powered from the magnetic field produced by the line current. Each of the three sensors per site provides the zero, negative and positive sequence current magnitude and phase. The real component of current filters out the effect of capacitive coupling.

Initial high voltage (HV) testing showed the casing to be a heat sink so an external temperature probe, placed 0.5m away from the casing measures conductor temperature in the Mark I and II versions. FMC-Tech in conjunction with NIE and Queen's University, Belfast has tested a new line sensor design, which incorporates the conductor temperature probe within the enclosure. The new design would be more suited to 'live-line' installations if 'hot-stick' or 'hot-glove' practices were used in the company. Currently in NIE, linesmen do not undertake live-line work over 11kV, but for other organisations live line installation capability is an obvious advantage.

Lightning storms in August 2009 damaged a quarter of sensors on the Kells-Coleraine line. To protect the circuitry in the future an aluminium shield was installed inside the fibre-glass casing.

NIE use the line sensors for validation purposes only since Cigré does not depend on the actual conductor temperature. Instead the ratings calculator inputs the

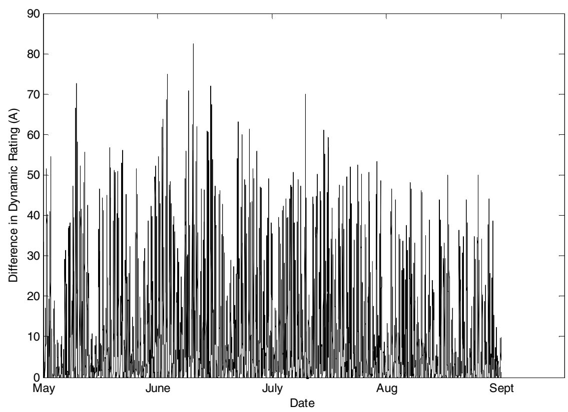

Fig. 8 Difference in using P27 zero solar factoring and NIE's method of calculating solar heating in calculating the Dynamic Line Rating

maximum design operating temperature and derives the dynamic rating based on this temperature.

B. Anemometers

It was noted that the difference in dynamic rating based on the Davis and the Windsonic wind speeds was small; both anemometers recorded accurate wind speeds (over 0.5m/s) to calculate similar dynamic ratings. The main difference between the two is reliability.

The placement of the anemometers (at the top of the pole or tower) means they cannot be reached with out an outage of the line. Since these lines are critical to the NI network, outages are rare and so maintenance is limited, for this reason the anemometers need to be reliable. The Davis anemometer malfunctioned 20% of the time over the last year while the Windsonic only malfunctioned 3% of the time.

The Windsonics experienced a wiring issue, which increased the fault incidence but this was attributed to human error and not a fault with the equipment. The only Windsonic fault NIE experienced was during foggy conditions in early January 2010, which gave incorrect 40m/s wind speed spikes. These were filtered out in the ratings calculator.

The Davis anemometer failed several times due to the mechanical nature of the equipment; dissembling of the cups and displacement of the wind vane were among common issues. Wind speed spikes were recorded many times due to electrical noise between the weather station and the controller. These spikes were filtered out by the ratings calculator instead of shielding the connectors.

C. Controllers

Several significant changes were made to the controllers from the Mark I generation to Mark II. Previously two PCBs were required to communicate between the line sensors (Sensor Network Gateway, SNG controller) and the web controller (X-Net controller), it has since been possible to integrate the functionality onto a single PCB. This reduced building complexity, cabling and the number of connectors used in the unit.

The efficiency of the power supply sections was increased substantially by more than 35%. This is significant considering that the system is powered by rechargeable batteries which are charged through a solar panel.

For installation on the Kells-Coleraine OHL the number of wired communication channels on the controller was increased to accommodate simultaneous communication with the Davis weather station and the Windsonic anemometer.

Other hardware enhancements included increased flash memory size and higher quality of analogue to digital conversion.

Most controller problems in the past have been due to software bugs, which FMC-Tech have addressed. The Mark II system has been developed to include remote firmware updates, which provides better diagnostics of equipment faults and the ability to repair them off site. It also provides the ability to add other features post deployment such as local analysis of data and applying various averaging strategies to produce samples every five minutes. By ‘future-proofing’ the system in this way the software can be maintained centrally to avoid numerous equipment versions in the field and minimises maintenance costs.

D. GPRS

NIE changed GPRS mobile service providers on the Dungannon-Omagh lines but several sites had low signal strength on the new provider. In areas of low coverage voice calls take precedence over data packets sent, this resulted in choppy data being received from the measurement points. NIE and FMC-Tech worked closely with the mobile network provider to correct this.

V. Integration

In the initial stages of the project DLR was intended for research purposes to better educate engineers on the impact of weather on OHL ratings in Northern Ireland. As the project has progressed NIE are actively planning for incorporation of DLR into the Distribution Control Centre (DCC). A diagrammatic representation of the communications is shown in Fig. 9. The system architecture allows FMC-Tech and NIE research engineers to access data remotely as well as providing control engineers with information to plan and adjust dispatch of generation based on local weather conditions.

Data will be received from measurement points via GPRS and sent over the internet as before. A firewalled link will then send the data to the DCC, which can be accessed by the System Operator for Northern Ireland (SONI) in the EMS/SCADA system via an Inter-control Centre Protocol (ICCP) link. Currently data are held on a public Access Point Name (APN) but security assessments have suggested this may need to be made private to prevent rogue users accessing the system.

For this project to be used in normal day-to-day network planning and operation a review of the equipment is required. Common issues with monitoring equipment were with the line sensors affected by lightning and that the moving parts of the Davis weather stations are subject to failure. A major issue is loss of GPRS connection near Omagh.

The industrial DLR system should make regular automatic maintenance checks on equipment subject to failure to allow quick deployment of teams to fix problems.

VI. Cost of Installing and Operating DLR

Installing DLR is relatively inexpensive compared to building new lines. The cost of operating DLR on an OHL for five years is approximately 3% of that incurred in restringing the same line with a higher temperature conductor. In NIE’s case network extension is inevitable so the cost is only differed for a few years to provide time to build the new OHLs.

Procuring and installing the DLR system costs 85% of the total expenditure, while corporate GPRS charges equate to 7% and maintenance (pending a maintenance contract being set up

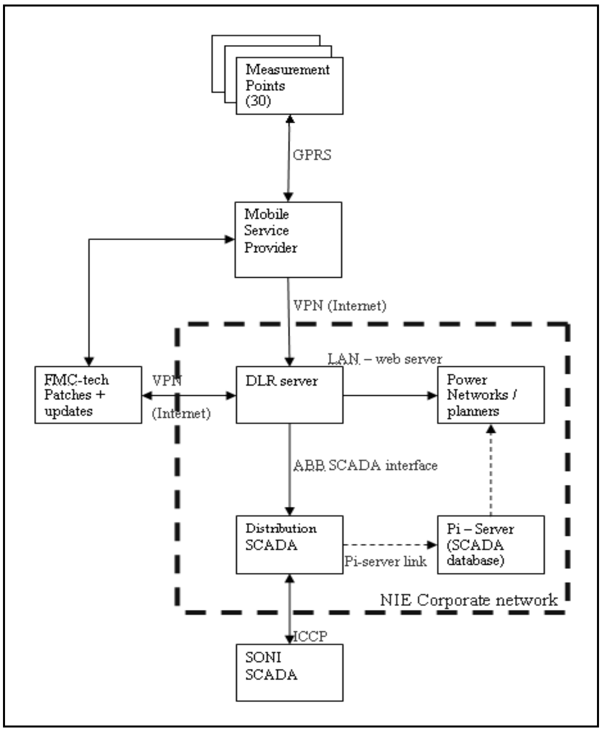

Fig. 9 System architecture for control centre integration of DLR

between NIE and FMC-Tech) will contribute to 8% of the overall cost.

VII. Future Work

The advancements made in the DLR system offer the possibility to extend knowledge to other OHLs in the critical electricity network. It is anticipated that NIE will instrument a 33kV OHL with DLR equipment where a wind farm extension is being built to avoid building a new OHL to it. This would save time and money and prevent an unnecessary line being built.

Gaps in the data of certain measurement points have been caused by temporary loss of GPRS signal. Currently the DLR calculator fills in small gaps but the longer the gaps the less reliable the extrapolations. It is imperative that the operational DLR system is reliable to prevent resorting to back to the static rating. NIE are planning to provide a confidence level in the DLR for the control engineer to allow him/her to make an informed decision on deployment of generation based on how reliable the DLR is.

Before the DLR system can be integrated in to the Distribution Control Centre NIE and the system operator must be certain the data are received securely. NIE are in the process of procuring a private server to contain the data bases (currently on FMC-Tech's third party server) to retain network control integrity. Meetings have been held with security consultants to determine the best move forward.

NIE are planning to provide DLR forecasting 15 minutes to 4 hours in advance. Two methods of forecasting being considered are: (1) weather persistence forecasting, which predicts weather patterns from historical weather databases or (2) predicting wind farm output and correlating this to the OHLs to predict the DLR.

VIII. Conclusions

In the near future it is anticipated that wind generation will be limited by the supporting electricity infrastructure. As wind speeds increase, wind farm generation rises causing an increase in current on the transmission line network. Under certain contingencies several 110kV overhead lines become the critical interconnection between the source of wind generation and the load. It has been noted that the wind producing large generation also cools the OHLs in the area, allowing them to carry more current than they are statically rated for.

NIE have successfully instrumented three 110kV OHLs with DLR equipment. A reliable, accurate DLR calculator has been created to extrapolate between measurement points to model unmeasured points along the lines.

It is proposed that low wind speed measurement points on Dungannon-Omagh A and B be retrofitted with Windsonics.

NIE have proven the need for factoring solar radiation in calculating accurate DLR.

NIE have concluded that DLR provides extra head room when it is needed most i.e. when the wind is high enough for wind farm generation and is planning for control-room integration of DLR by the end of 2010.

Acknowledgments

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