Dynamic Network Rating for Low Carbon Distribution Network Operation—A U.K. Application

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***Abstract*—Dynamic asset rating (DAR) is one of the number of techniques that could be used to facilitate low carbon electricity network operation. Previous work has looked at this technique from an asset perspective. This paper focuses, instead, from a network perspective by proposing a dynamic network rating (DNR) approach. The models available for use with DAR are discussed and compared using measured load and weather data from a trial network area within Milton Keynes in the central area of the U.K. This paper then uses the most appropriate model to investigate, through a network case study, the potential gains in dynamic rating compared to static rating for the different network assets—transformers, overhead lines, and cables. This will inform the network operator of the potential DNR gains on an 11-kV network with all assets present and highlight the limiting assets within each season.**

***Index Terms*—Asset life management, distribution network, dynamic asset rating (DAR), dynamic network rating (DNR), low carbon network operation.**

NOMENCLATURE

I	Currents (A).
K	Current ratios (actual value/rated value).
R	Transformer loss ratios (rated loss/no-load loss).
R_e	Cable electrical resistance (Ω).
R_t	Cable thermal resistance (m^2K/W).
T	Temperatures (°C).
ΔT	Temperature rises (K).
W_d	Cable dielectric loss (W).
λ	Cable loss ratios.
τ	Time constants.
a, soil	Ambient and soil value subscripts.
c	Conductor value subscript.
hs, o	Hot-spot and oil value subscript.
r	Rated value subscript.
s	Steady-state value subscript.
OHL	Overhead line.
TX	Transformer.
UGC	Underground cable.

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I. INTRODUCTION

THE COST and limited flexibility of traditional approaches to 11-kV network reinforcement threaten to constrain the uptake of low carbon technologies. In the U.K., to enable distribution network operators (DNOs) to develop new approaches, office of gas, and electricity markets (Ofgem) (a U.K. national regulatory authority) has released £500 m of funding—low carbon network fund [1] for DNOs to trial innovative techniques and share the learning with the rest of the industry. Project flexible approaches to low carbon optimized networks (FALCON) [2] is funded via this Ofgem initiative to DNO western power distribution plc. (WPD), and aims to facilitate the uptake of low carbon technologies by delivering faster and cheaper connections to the 11-kV network by reducing traditional reinforcement requirements. The trial will provide learning on the use of real-time data to inform network planning rather than traditional indicators such as total demand and engineering guidelines. The learning obtained throughout the project will be shared with other DNOs and the wider industry.

One of the techniques under study is the dynamic asset rating (DAR) for transformers, overhead lines, and cables within a network to help with asset life management. The technique looks to maximize network loading. The increased passage of current through an asset increases its losses, namely the copper loss, which manifests itself as heat. The heat generated can have notable effects if the asset is allowed to exceed the manufacturers' recommended thermal rating. Once the thermal rating has been exceeded degradation of the insulation (for transformers and cables), or reduced safety clearance (for overhead lines) occurs resulting in possible failure. Therefore, thermal ampacity (maximum current that can pass through an asset before the temperature limits are reached) needs to be obtained by monitoring or estimating conductor temperatures and comparing with temperature limits to ensure no breach which may lead to additional degradation. Monitored environmental and loading data will be used to calculate "real-time" asset loading, allowing for higher ampacity for limited periods rather than the current "static rating" current used by DNOs. With the benefit of on-line weather monitoring, the dynamic rating, or ampacity can be calculated. This process is also known as dynamic thermal rating.

Research and practical tests have been carried out on DAR for individual assets such as transformers, overhead lines, and cables as described in Section II. This paper builds on that work to look at the application of DAR modeling of a dynamic network rating (DNR) containing all of these asset types. This process is novel in terms of managing the rating of a network as a whole compared to managing on an asset-by-asset basis. This type of network management lends itself to future integration with automatic load transfer techniques to alter the location of the load to optimize the network based on the DNR. This paper is organized as follows. Asset DAR techniques are discussed and compared in Section II. In Section III, the concept of DNR is proposed. Using FALCON project trial area data, simulations have been carried out to calculate the DNR over the period of a year in Section IV. Findings and potential application issues are presented in the conclusion in Section V.

II. DAR

The attentions around DAR for transmission systems can be tracked back to the 1980s [3]. The main aim of a real-time application is to take advantage of environmental impacts, e.g., low-ambient temperatures to load an asset above its nameplate/static rating without causing excessive overheating [4]. This is particularly useful in meeting peak winter U.K. demand. Condition monitoring should be undertaken with sensors, online monitoring, and intelligent tools, to maximize and safely utilize the potential benefits. However, the challenges for applications to distribution systems are lack of weather data, equipment for thermal state monitoring, developing fit-for-purpose thermal models, and lack of asset specific data where old asset test certificates have been lost or parameters have changed with time. The models are the basis for the dynamic rating calculations and important for the network rating assessment.

A. Transformer DAR

Power transformers are generally the most expensive components in distribution networks. Cost savings and deferred replacement of transformers subject to loading constraints could be achieved if transformers can be operated beyond their nameplate ratings for certain periods. Other published work to date has focused on dealing with overloading, i.e., loading above the nameplate rating [5], or highly fluctuating load profiles, such as for wind turbine transformers [6].

The practice of using transformer DAR is to comprehend the thermal effects that oil and winding temperatures have on the life of insulation. The highest winding temperature known as the hot-spot temperature is located around the windings but difficult to locate and is a function of transformer design and cooling functionality, ambient air temperature, oil temperature, winding losses amongst others. This makes the hot-spot temperature difficult to measure with any degree of certainty. Although direct measurement methods have already been proposed [7], they can only be applied to newly built units, for which the manufacturer installed limited number of technically advanced measuring facilities (for instance sensors with fiber-optic cables). Therefore, the hot-spot temperature may only be computed for most applications. An implementation of transformer DAR in distribution networks in New Zealand was reported in 2012 [8]. This was based on implementing the International Electrotechnical Commission (IEC) model described below with limited validation using a winding temperature indicator. This is a good example of an asset rating implementation primarily for short-term overloading applications.

1) Modeling: The industrial standards model transformer thermal responses by estimating the hot-spot temperature of windings. This is generically represented by top-oil temperature rise and hot-spot temperature rise on top of the ambient temperature

$$T_{\text{hs}} = T_o + \Delta T_{\text{hs}} = T_a + \Delta T_o + \Delta T_{\text{hs}} \quad (1)$$

where T denotes temperatures, ΔT denotes temperature rises subscript o refers to oil values, subscript hs refers to hot-spot values, and a refers to ambient values.

Based on the hot-spot temperature models, consumption of transformer life (loss of this paper insulation life, unit value at 98 °C for nonthermally upgraded paper; 110 °C for thermally upgraded paper) can be estimated. In this paper, models were compared from the international guides for loading mineral-oil-immersed transformers: IEEE C57.91 [9], and IEC 60076-7 [10]. In terms of mathematical models, all these models consider using exponential function (for both the top-oil and winding hot-spot temperatures) for transients between initial and ultimate temperatures. In IEC 60076-7, a double-exponential model is proposed to improve the calculation accuracy. In particular, for IEC 60076-7, it is mentioned that the exponential model is primarily designed for "step increase followed by a step decrease and so on." The IEC 60076-7 also presented a differential equation model, which is fit-for-purpose for real-time application. The models were programmed into standard form to put in MATLAB as shown

$$\frac{dT_o}{dt} = -\frac{1}{k_{11}\tau_o}T_o + \frac{1}{k_{11}\tau_o}T_a + \frac{1}{k_{11}\tau_o}\Delta T_{or}\left(\frac{1+K^2R}{1+R}\right)^x \quad (2)$$

$$\frac{d\Delta T_{\text{hs1}}}{dt} = -\frac{1}{k_{22}\tau_w}\Delta T_{\text{hs1}} + \frac{1}{k_{22}\tau_w}k_{21}K^y\Delta T_{or} \quad (3)$$

$$\frac{d\Delta T_{\text{hs2}}}{dt} = -\frac{k_{22}}{\tau_o}\Delta T_{\text{hs2}} + \frac{k_{22}}{\tau_o}\left(k_{21}-1\right)K^y\Delta T_{or} \quad (4)$$

where K is the load factor (load current/rated current), subscript r refers to rated values. Other factors used within the formula, e.g., x, y, k_{11}, k_{21}, and k_{22} have been determined empirically and can be found in the IEC 60076-7 document [10].

A comparison example between the models is shown in Fig. 1 to compare the models and validate the coding. This shows the hot-spot temperature for a week's worth of data with the highest yearly temperature, where "IEC exp" and "IEC dif" denote IEC exponential and differential models, respectively. The differences between models are within 5 °C. This is within the error range of 10 °C from experimental results of oil temperature measurement and model calculation in [11]. IEC dif is the most conservative model which gives the highest temperatures. Therefore, this model was chosen to as the basis for the DNR modeling.

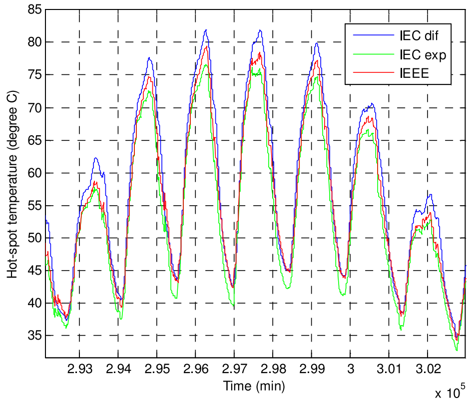

Fig. 1. Hot-spot temperature calculation with different models (7 days).

B. Overhead Line DAR

The static ratings of overhead lines have been calculated in standard energy networks association (ENA) (the U.K. and Ireland energy network regulator) engineering recommendation (ER) P27 [12] to ensure that conductor temperature remains within set tolerances. To ensure public safety, estimates of seasonal weather have been used to set the static ratings in the DNO network design manual [13]. In most cases, the thermal limit is defined by ground clearance (sag of the conductor) (not thermal degradation of insulation or conductor melt temperatures as in cables or other equipment). In the U.K., for distribution systems built prior to 1970, the electricity supply regulations limited the rated temperature of overhead lines to 50 °C. Some more recent lines have been limited to higher temperatures (up to 75 °C) due to the introduction of lighter conductors with higher strength/weight ratios. ENA ER P27 gives ratings at 50 °C, 65 °C, and 75 °C. Other effects of conductor temperature include: 1) the possibility of grease melt; 2) effect on joints; and 3) conductor annealing resulting in loss of mechanical strength of aluminum overhead lines [14], [15].

1) Modeling: There are three well-known standards proposing models to be used for determining the rating of bare overhead line conductors: IEC/TR 61597, IEEE 738-1993, and International Council on Large Electric Systems (CIGRE) working group 22.12. A comparison of the output of each of the models has been reported [16]. For network dynamic ratings, the CIGRE model has been used as recommended by IEC and widely used in the U.K. Both the differential and exponential models [17] were considered.

The thermal steady-states are defined by considering heat balance of heat gain from joule, magnetic, solar, and corona heating; heat loss from convective, radiative, and evaporative cooling [17]. Then, transients between steady-states are estimated by exponential functions

$$\text{Heating} \quad T_c = T_s^{(\text{ult})} - \left(T_s^{(\text{ult})} - T_s^{(\text{ini})}\right) e^{-\frac{t}{\tau_{\text{heating}}}} \tag{5}$$

$$\text{Cooling} \quad T_c = \frac{T_s^{(\text{ini})}}{P_1}\left[P_2 + (P_1 - P_2) e^{-\frac{t}{\tau_{\text{cooling}}}}\right] \tag{6}$$

where T denotes temperatures, subscript c refers to conductor transient values, subscript s refers to steady-state values, superscript ini, ult refers to initial and ultimate steady-state values of current calculation step. P_1 and P_2 are the heating powers before and after the cooling period. τ_{heating} and τ_{cooling} are the time-varying heating and cooling time constants [17]. The code was validated against the Alstom P341 relay [18] data and the static rating under the same conditions.

C. Underground Cable DAR

The static calculated current ratings of underground cables are based on the temperature rise of the cable insulation (90 °C for polymeric insulation and 65 °C or 75 °C for this paper). To avoid insulation breakdown leading to cable failure, a static summer and winter current rating and a cyclic summer and winter rating are employed by the ENA ER P17 [19]. These values are de-rated when the cable is ducted or in close proximity to other cables. The ratings contained within P17 are limited to a fixed number of cable types and are typically calculated using average values for soil characteristics, taking the thermal resistivity of soil as a set seasonal value. Although this is fine for a generalized case that will fit the large majority of cables on the U.K. distribution network, it does not allow the full realization of individual cables full current carrying capability.

1) Modeling: Industrial models of underground power cable are detailed in IEC 60853-1 (cyclic and emergency ratings of cables) [20] and IEC 60287-1 (calculation of cable rating) [21]. The model used within this paper was based on the equations in [21] for the case where drying out of the soil does not occur or the cables are in air. The permissible current rating of an ac cable can be derived from the expression for the temperature rise above ambient temperature

$$\Delta T = \left(I^2 R_e + \frac{1}{2} W_d\right) R_{t1} + \left[I^2 R_e (1 + \lambda_1) + W_d\right] n R_{t2} + \left[I^2 R_e (1 + \lambda_1 + \lambda_2) + W_d\right] n (R_{t3} + R_{t4}) \tag{7}$$

where ΔT is the conductor temperature rise above ambient, I is the current in one conductor, R_e is the ac electrical resistance per length at maximum operating temperature, W_d is the dielectric loss per unit length. R_{t1} is the thermal resistance between conductor and sheath, R_{t2} is the thermal resistance between sheath and armor, R_{t3} and R_{t4} are the thermal resistances of the external serving and the surface to surrounding medium, n is the number of load carrying conductors, and λ_1 is the ratio of losses in the metal sheath to conductor losses while λ_2 is the ratio of losses in the armoring to conductor losses.

A finite element model using the finite element method magnetics (FEMM) v4.2 program was used to validate the rating computed in the MATLAB model and the DNO specified rating as the cable type was not explicitly mentioned in ENA ER P17. This was done by comparing conductor temperature for a fixed current at fixed temperature and soil conditions. Fig. 2 shows the finite element model of a ducted paper insulated corrugated aluminum sheath (PICAS) 185 mm^2 cable and the external temperature of the conductor under a 230 A sustained rated current at 15 °C soil temperature and 0.8 Km/W soil resistivity which produces an external

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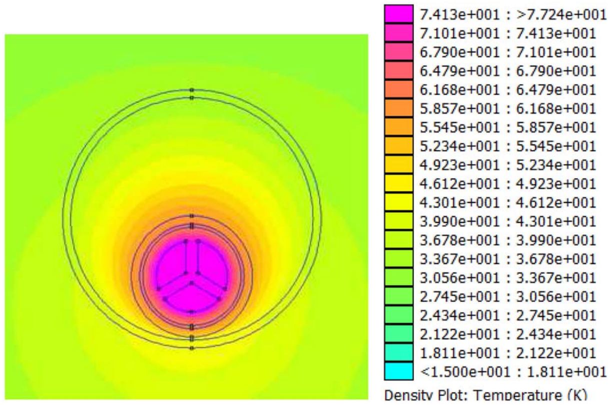

Fig. 2. FEMM plot of 11-kV PICAS 185 mm^2 ducted cable.

conductor temperature of 70 °C to tie up with the rating used in the MATLAB DAR analysis.

The cables were analyzed as both ducted (to take into account possible road crossings) and un-ducted to explore the difference in network dynamic rating. However, the cables were assumed to be ungrouped. Grouping of cables further reduces the rating and it is important for a network operator to know in advance if the cables are grouped prior to implementing DAR.

III. DNR

As far as the authors are aware there has only been one industrial application of DAR in distribution systems carried out in the U.K. in the past five years [22]–[25]. The field trial of each asset is on a section of 33-kV Scottish power energy networks considering connection of an offshore wind farm (each asset was analyzed separately). Alstom developed the P341 relay as part of that project in an attempt to monitor individual assets [18] and part of the larger FALCON project will look to test the accuracy of this device against measured asset temperature and the thermal models.

Michiorri *et al.* [26] discussed system ratings considering distributed generation accommodation. Although all types of assets were included in this literature, the network dynamic rating was not identified or analyzed. In this paper, the maximum dynamic loading of an 11-kV network has been studied. Moreover, not only are asset ratings considered but these are compared to determine network rating within a network analysis tool. A DNR approach is proposed as shown in Fig. 3.

For each asset, MATLAB models in Section II was implemented to carry out component thermal analysis. With predicted load, environmental, operational data, and limit constraint requirements of either specified temperature or loss-of-life the models were used to calculate maximum dynamic rating. The DAR results along with predicted load data and circuit data were fed into the network model, where load flow analysis, and asset constraint analysis were carried out for both static and DAR constraints. This process is iterated until all the time intervals of a year (or a specified period) have been gone through for the predicted load profile. For each time interval iteration, the maximum network loading at the primary at which an asset reaches its static rating compared to its DAR is

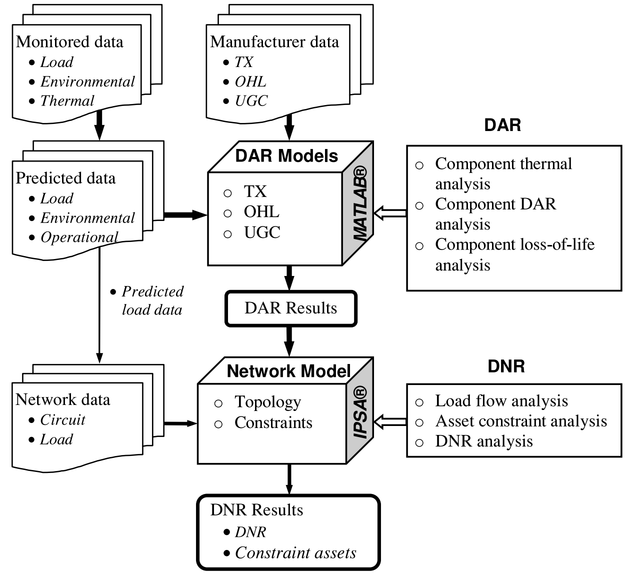

Fig. 3. Overview of the proposed DNR process.

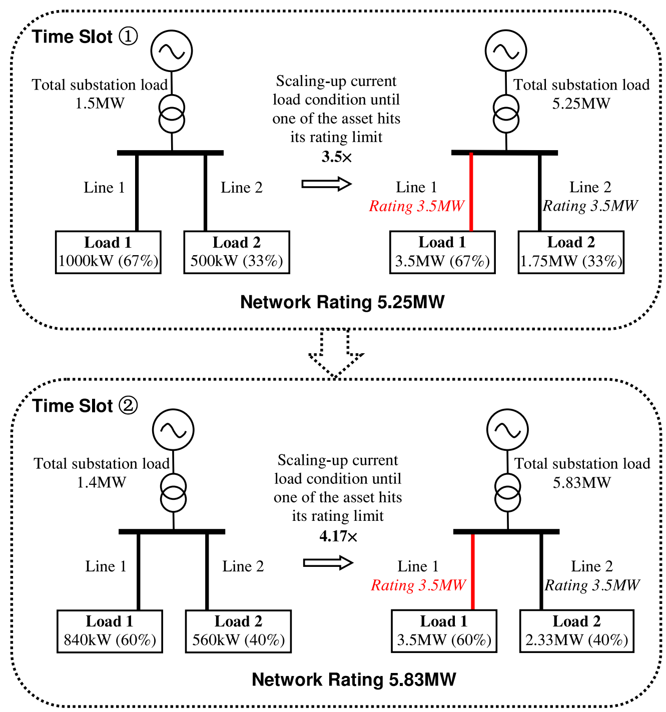

Fig. 4. Network rating calculation example.

recorded. Then, the total network rating (defined as the total current through the primary transformers at constant voltage) is recorded as the DNR at this time point. The outcome of DNR will be the network ratings over the whole period with a list of the constrained assets.

The process is further explained with the example in Fig. 4; for the first time slot (iteration 1), the original load distribution along the two feeder lines is 67% (1000 kW) and 33% (500 kW) each. This load condition is scaled-up until one of the asset hits its rating limit, i.e., line 1 in red which has a rating of 3.5 MW (scaling factor of 3.5). Therefore, the total substation load is 5.25 MW, which is defined as the

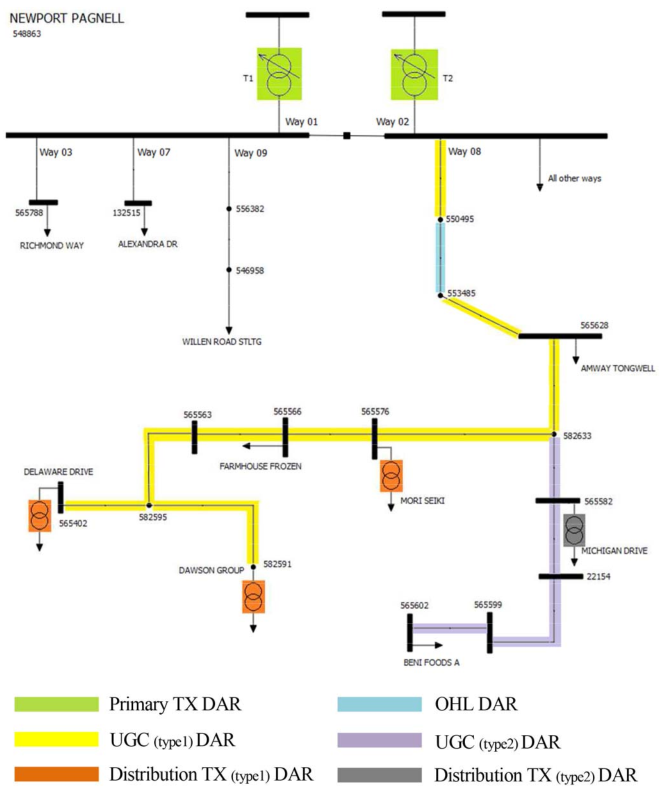

Fig. 5. Trial network schematic with DAR assets highlighted.

static network rating at this time period. For the next time slot (iteration 2), the feeder load and the load distribution are different, 60% (840 kW) and 40% (560 kW) for lines 1 and 2, respectively. If the load is scaled-up until line 1 hits its rating of 3.5 MW again (scaling factor 4.17) then the total substation load is 5.83 MW, which is the new static network rating at this time slot. To calculate the dynamic rating, not only does the load distribution of the feeders change, but the rating of the line (or other assets) also changes.

IV. DAR/DNR Simulation Results and Discussion

A. Project Trial Area and Assets

The trial network considered in this paper is from an area within Milton Keynes. The test network covers six different asset types starting at Newport Pagnell substation: primary ground mounted 33 kV/11 kV transformers, 11 kV overhead conductors, two types of 11 kV underground cables and two types of distribution transformers. The network schematic is shown in Fig. 5 with the DAR assets highlighted.

Feeder load data from 2012 along with an estimated secondary load split provided by the DNO was used with corresponding weather data from the Met Office. MATLAB (R2011a) was used to implement the algorithms of the various DAR models. IPSA 2.3 is then used to undertake the network analysis. DNR is implemented by Python scripting in IPSA to input DAR results from MATLAB.

B. Transformer DAR

The primary transformers of the network are at Newport Pagnell substation. They are 33 kV/11 kV-12/19/24 MVA transformers, with cooling type oil natural air natural (ONAN)/oil forced air forced (OFAF). The rating of the transformer is dependent on the cooling adopted. From their test certificate, the rated current is 209.9 A primary, 602.5 A secondary for ONAN cooling, and 332.4 A primary and 953.9 A secondary OFAF cooling. No-load loss: 6610 W (at 0.8 pf regulation), full-load loss: 71052 W on tap 9, 68537 W on tap 1 and 77045 W on tap 17.

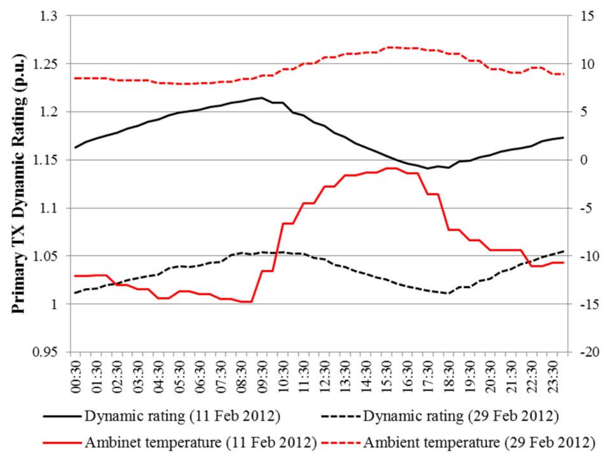

Fig. 6. Example of dynamic rating for unit loss-of-life operation (110 °C limit) with OFAF cooling for 2 days in February 2012.

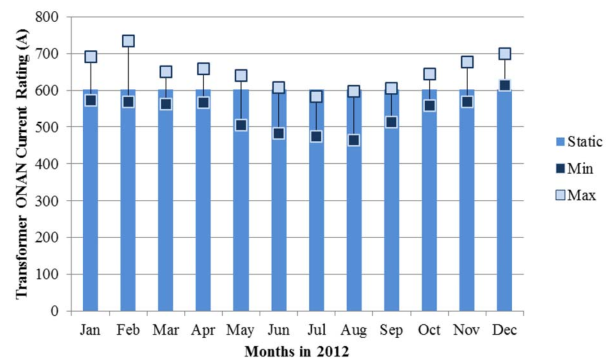

Fig. 7. Primary transformer dynamic rating limits under ONAN cooling for unit loss-of-life operation (110 °C limit).

Standards typically state that 110 °C is the unit life winding temperature for thermally upgraded paper. This means that the winding temperature can reach 110 °C without there being any noticeable additional loss-of-life. Using this information in conjunction with the IEC differential model, the maximum load current in conjunction with the weather conditions for a time step period has been used to determine the maximum loading on the transformer compared to the static rating for ONAN and OFAF cooling applied constantly. Fig. 6 shows two days in February 2012 that have extreme temperatures to indicate the degree of variation in the DAR over the course of the day and the variability over a month. The maximum and minimum dynamic rating for each month is then shown in Figs. 7 and 8, which show the scope of dynamic rating for the two cooling types for each month compared to the static rating.

Investigating the effect of continuous loading at 19 MVA compared to a dynamic rating (with temperature hot-spot limit

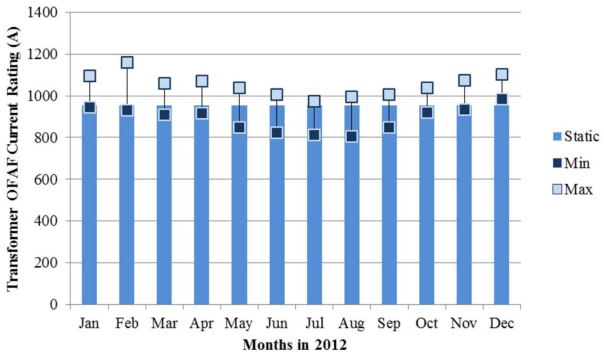

Fig. 8. Primary transformer dynamic rating limits under OFAF cooling for unit loss-of-life operation (110 °C limit).

set to 110 °C) shows that there is scope to run at up to 20% higher continuous current in the winter months. However, under high ambient temperature conditions this dynamic rating may also reduce in the summer months. Peak load in 2012 occurred in February, and modeled dynamic ratings indicated a good margin due to low temperatures. Due to the thermal capacity of the system an increased dynamic overload on the transformer could be applied for several hours. Based on modeling of continuous load and looking closer at the data, on a month-by-month data (both with and without forced cooling) gives an idea as to where gains in dynamic rating may be obtained. January to May and October to December offer gains in dynamic rating on some if not all of the days of the month.

As the ambient temperature increases there is a much more marked effect on the shape of the modeled temperature curve from March to October to mimic the ambient temperature variation. This suggests a slight advantage at morning load pick up, but no advantage at peak load period. However, the curves from this analysis for June to September suggest that no additional increase in dynamic rating is likely even at night and in fact there may even be a drop in the static rating required.

C. Overhead Line DAR

The section of overhead line in Way8 feeder to Amway Tongwell was analyzed as part of the network. This line is an aluminum-conductor steel-reinforced Dingo line with cross sectional area of 150 mm^2. The static rating of the line in summer is 382 A. One of the key points to note is that the data for wind speed and solar radiation is of poor granularity and was provided by the MET office as wind speed (mean and peak value) each 24 h period and the solar radiation was given as a total daily amount of energy received over a meter square area. To deal with this in the modeling, the wind speed was set to the constant mean value and the solar radiation was assumed to fall over an 8 h period in early afternoon (so that the impact of solar radiation at peak load could be assessed with a value that approximates to a typical peak summer day). This reduces the accuracy of the modeling for a particular 30-min period in time. However, the values averaged over time will be representative.

Fig. 9 is an example of how the calculated dynamic rating of the line changes for different weather conditions by

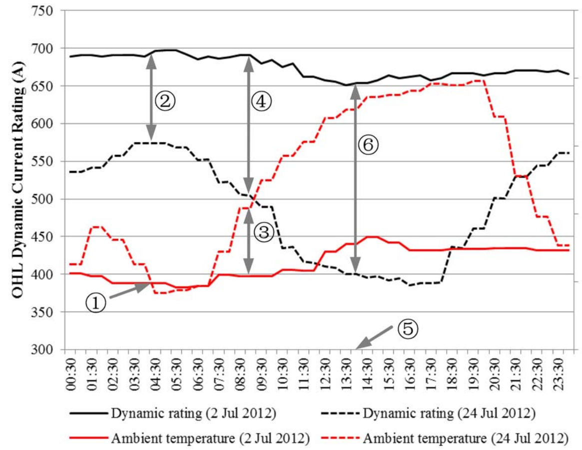

Fig. 9. Example of overhead line (OHL) dynamic rating with weather conditions for 2 days in July 2012.

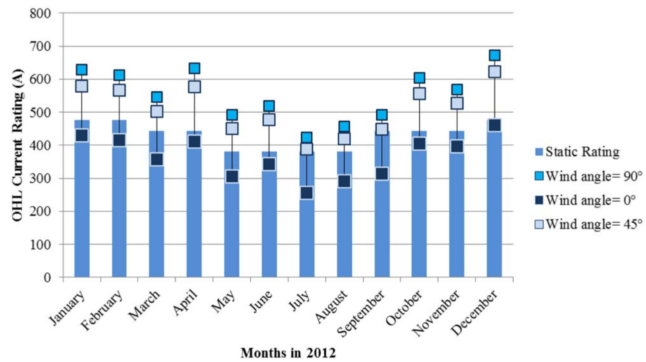

Fig. 10. OHL dynamic ratings with weather conditions including the effect of wind angle.

comparing two different days in July, 2nd and 24th. July 2nd is an unseasonably chilly day with a 9-knott wind and low amount of solar radiation. July 24th is a hot sunny day with a 7-knott wind. Within Fig. 8 a number of points can be noted: point ① on the graph (overnight) shows an instant in time when the solar radiation is zero for both days and the ambient temperature is equal. At this point, the difference in dynamic rating is a function of the wind speed. July 2nd which has a higher wind speed to cool the line therefore has a greater dynamic capacity (difference of 120 A) as shown by point ② on the curve. At point ③ on the graph, the ambient temperature of July 24th is 5 °C greater than that of July 2nd. Point ④ on the graph shows that the difference in dynamic rating between the two curves has increased to 170 A. At point ⑤ on the graph, the ambient temperature and solar radiation on July 24th is higher than July 2nd. This acts to alter the difference in dynamic capacity between the two curves even further as shown at point ⑥ where the range is now 250 A. The DAR for the overhead line on July 24th approaches the static rating as ambient conditions approach the nominal conditions used in the calculating the static summer rating. There is a significant variation in dynamic capacity over the course of a day and during a month. Fig. 10 shows a monthly plot of dynamic ratings compared to static ratings including the effect of wind angle on this margin.

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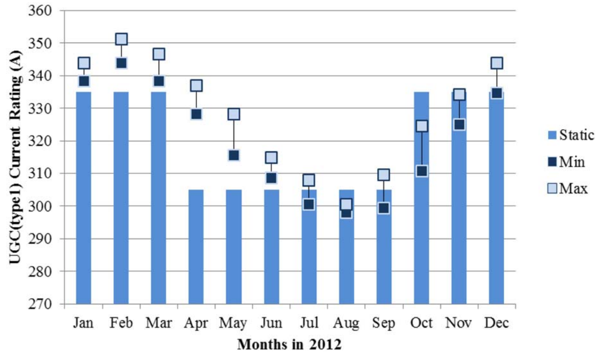

Fig. 11. DAR of the underground cable (UGC) (type 1).

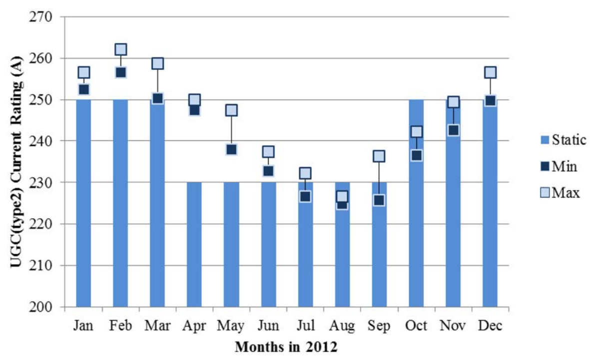

Fig. 12. DAR of the UGC (type 2).

The time constants on the overhead lines are in the order of 10 min. This means that the line will quickly reach a steady-state condition within a 30-min time period. However, it also means that variations over a small time scale will impact ampacity but may not be recorded if 30-min averages are used. Wind angle can have a key effect on the cooling of the line. Along the length of the line, it is likely that the wind angle will vary considerably. A value of 45° is usually chosen and this value (in the absence of solar power) used in the IEC models with the P27 fixed ambient temperature and wind speed gives the same static rating as the DNO network design manual [13]. Ampacity of the line over the period of a year is very varied. Within the modeling undertaken, there appears to be good ampacity gains on both a daily and a seasonal basis. Within the course of a 24 h period, the ampacity is higher overnight time reflecting the lower ambient temperatures. On a seasonal basis, there appears to be a gain in the winter months. However, on hot sunny days with low wind speed in the summer months, a reduction in ampacity may also be necessary.

D. Underground Cable DAR

There are two types of underground cables in this paper—these are 11-kV 3 core sector shaped aluminum conductor, paper insulated corrugated aluminum sheath (Al-PICAS) cables with cross-sectional areas of 300 mm^2 (type 1) and 185 mm^2 (type 2), respectively. The time constant relating to the change in soil temperature is significantly higher than 24 h, and therefore the daily soil temperature and the DAR of the cables can be assumed to be fixed over each 24 h period.

TABLE I
DNR Scenario Studies

Scenarios	OHL at wind angle 45°	OHL at wind angle 0°	UGC ducted	Distribution transformers	Primary transformers ONAN
UGC un-ducted Without distribution transformers Primary transformers OFAF	(a)	(b)			
OHL at wind angle 45° Without distribution transformers Primary transformers OFAF			(c)		
OHL at wind angle 45° UGC un-ducted Primary transformers OFAF				(d)	
OHL at wind angle 45° UGC un-ducted Without distribution transformers					(e)

TABLE II
Constraint Asset Values

Constraint asset	Constraint asset value
Primary TX	1
UGC (type 1)	2
OHL	3
Distribution TX (type 1)	4
Distribution TX (type 2)	5

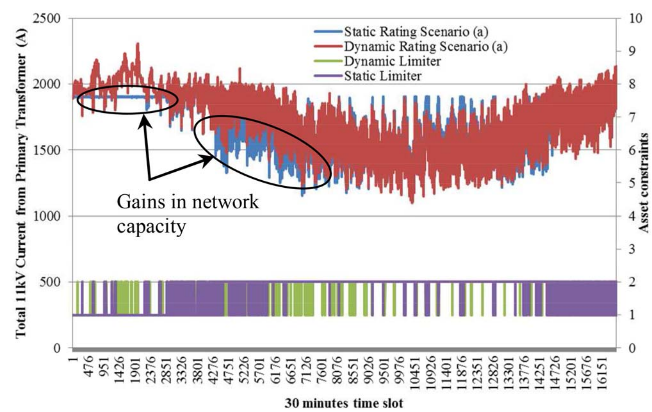

Fig. 13. DNR of the circuit under scenario (a) (OFAF cooling, un-ducted cable, wind angle 45°).

The effect of this long time constant is apparent when the dynamic and static ratings for sustained current are compared in Figs. 11 and 12. There are clearly areas where dynamic rating is above the cyclic rating which show where benefit may be obtained. However, a reduction in rating may also be needed if conditions are extreme (if the soil temperature is greater than the seasonal static value).

E. DNR

The following DNR scenario studies were undertaken as shown in Table I over the period of a year to determine the constraining asset on the network and how the network loading compares to the static ratings. These have been designed to fully explore the effect of: UGC ducted/un-ducted,

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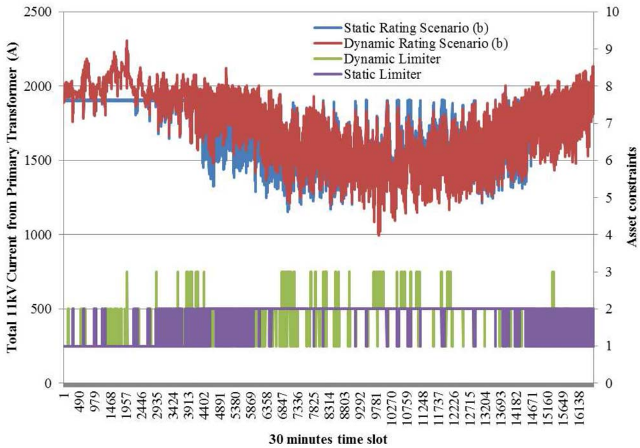

Fig. 14. DNR of the circuit under scenario (b) (OFAF cooling, un-ducted cable, wind angle 0°).

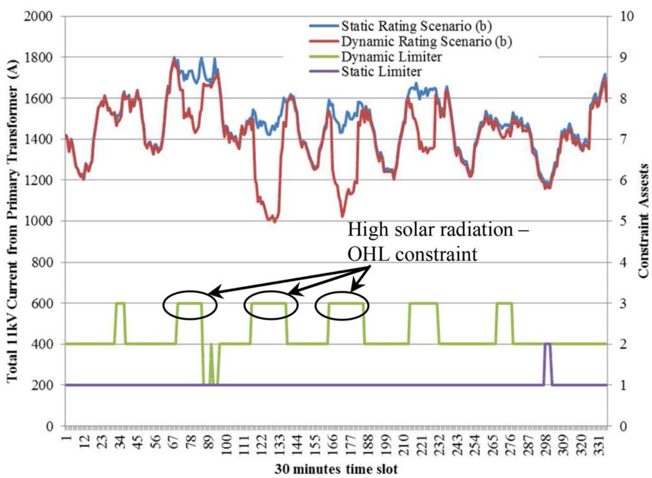

Fig. 15. DNR of the circuit under scenario (b) for a week in July to show the effect of low wind angle and high solar radiation on OHL rating as a constraint.

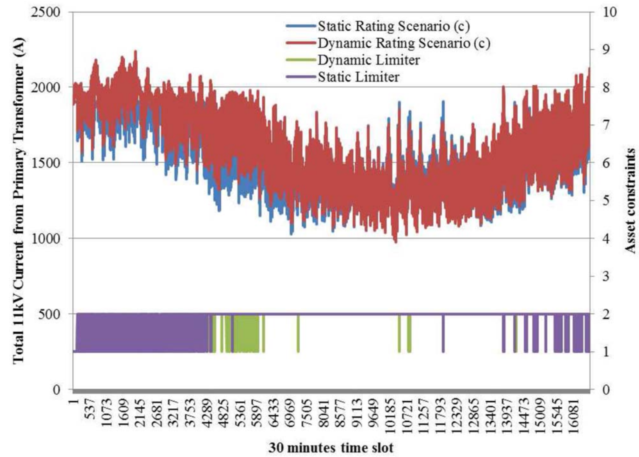

Fig. 16. DNR of the circuit under scenario (c) (OFAF cooling, ducted cable, wind angle 45°).

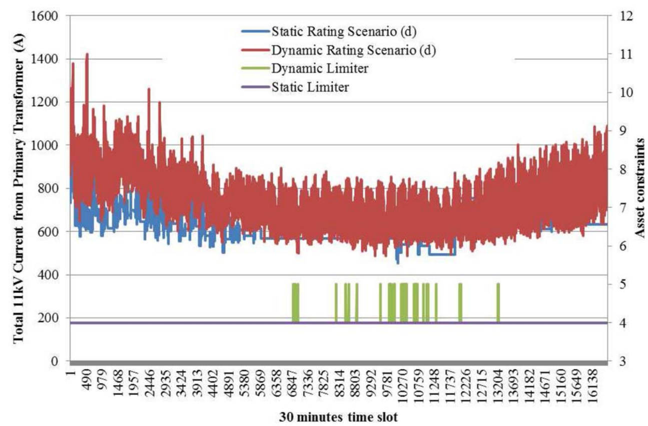

Fig. 17. DNR of the circuit under scenario (d) (OFAF cooling, ducted cable, wind angle 45° with distribution transformers).

with/without distribution transformers, primary transformer OFAF/ONAN, OHL wind angle variation where data uncertainty exists. All the constraining assets have been allocated a number which allows them to be tracked in the following graphs. Table II shows which number refers to which asset.

Fig. 13 shows the static and DNR over the course of a year under scenario (a). The static rating is largely constrained by the primary transformers in winter and by the underground cable from the primary feeder (type 1) in the summer months. The dynamic rating is similarly constrained but there are clear gains in rating during winter and spring when the static rating of the transformer is mostly lower than the dynamic rating (as per Figs. 7 and 8). However, in summer, the dynamic rating is lower than the static rating because the constraint is tied to the type 1 cable and from Fig. 11 the soil temperature is higher than that used to calculate the static value resulting in a reduction in dynamic rating.

Unfortunately, a wind direction measurement was unavailable during 2012. The value of wind angle delta used to produced Fig. 13 was set to 45° which is a common value used within the standards. However, the worst case scenario exists when the wind angle is equal to 0° in which case there is no wind cooling effect in the network. Fig. 14 shows the effect on the DNR when a wind angle of 0° is used to generate the dynamic rating. As can be seen, there are now times within the year where the network can also be constrained by the wind angle (asset constraint value is 3). However, a closer look at this shows that the asset is only constrained by the wind angle when this coincides with a period of solar radiation as shown in Fig. 15.

A cable within a duct has a lower rating than a direct laid cable. Fig. 16 shows the effect of the cable being laid in a duct. Comparing this to Fig. 13 (the un-ducted case), it shows that the cable is now the main constraint in the network, as opposed to the primary transformer, especially in the summer months. The dynamic rating of the cable offers gains to network dynamic rating in the winter and spring but not the summer or autumn. The overall network rating is reduced by up to 20% compared to when the cable is not ducted.

The distribution transformer model requires more information than readily available, e.g., weight of oil and no-load losses. Therefore, typical industrial values have been used which adds uncertainty into the calculation. Fig. 17 shows the impact on the network of including the ratings of typical distribution transformers into the calculations. It is apparent

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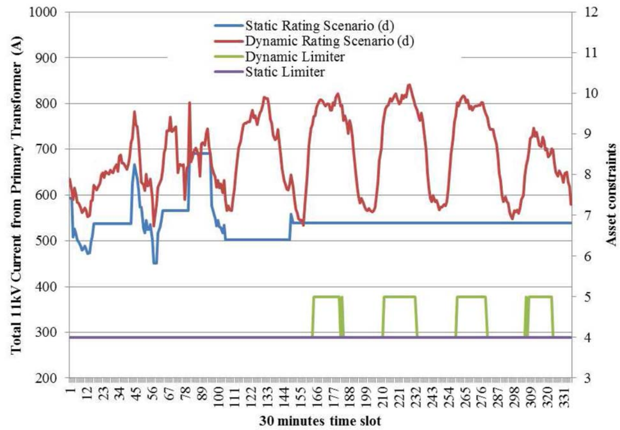

Fig. 18. DNR of the circuit under scenario (d) for a week in July to show the effect of distribution transformer as a constraint.

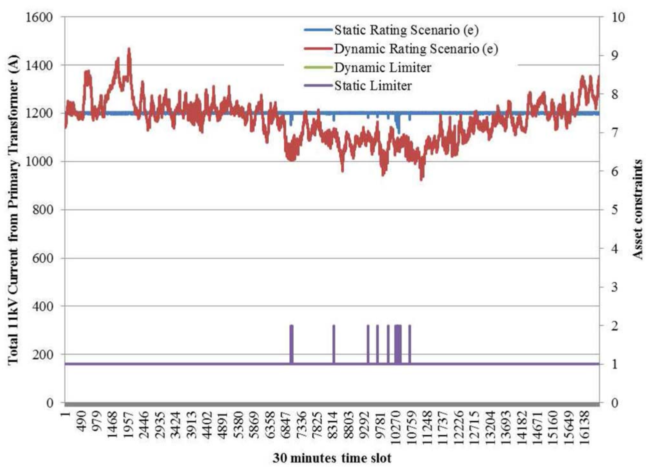

Fig. 19. DNR of the circuit under scenario (e) (ONAN cooling, ducted cable, wind angle 45°).

TABLE III
MEAN AND STANDARD DEVIATION VALUES OF SEASONAL STATIC AND DYNAMIC RATINGS

Scenario	Winter Ratings (A)				Spring Ratings (A)			
	Static		Dynamic		Static		Dynamic	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
(a)	1896	33	1999	98	1728	171	1834	152
(b)	1896	33	1999	98	1728	171	1828	161
(c)	1820	117	1927	140	1556	185	1682	183
(d)	688	86	876	109	597	47	743	83
(e)	1201	2	1262	67	1202	2	1189	58
Scenario	Summer Ratings (A)				Autumn Ratings (A)			
	Static		Dynamic		Static		Dynamic	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
(a)	1526	157	1525	155	1655	190	1653	192
(b)	1526	157	1514	162	1655	190	1652	193
(c)	1361	142	1363	146	1471	184	1484	193
(d)	562	49	689	88	700	73	740	105
(e)	1202	4	1079	47	1202	2	1171	59

that there is a drop in network dynamic rating compared to Fig. 13. This indicates that the least monitored part of the network in terms of past research potentially offers the biggest network constraint.

Fig. 18 shows a close-up of a week in the summer, where the constraint is switching between two different distribution transformers. The reason the network loading values are not constant for a constant static rating of transformer is because the load at each substation is varying with respect to time and if a substation takes a higher proportion of the current then it has less available capacity.

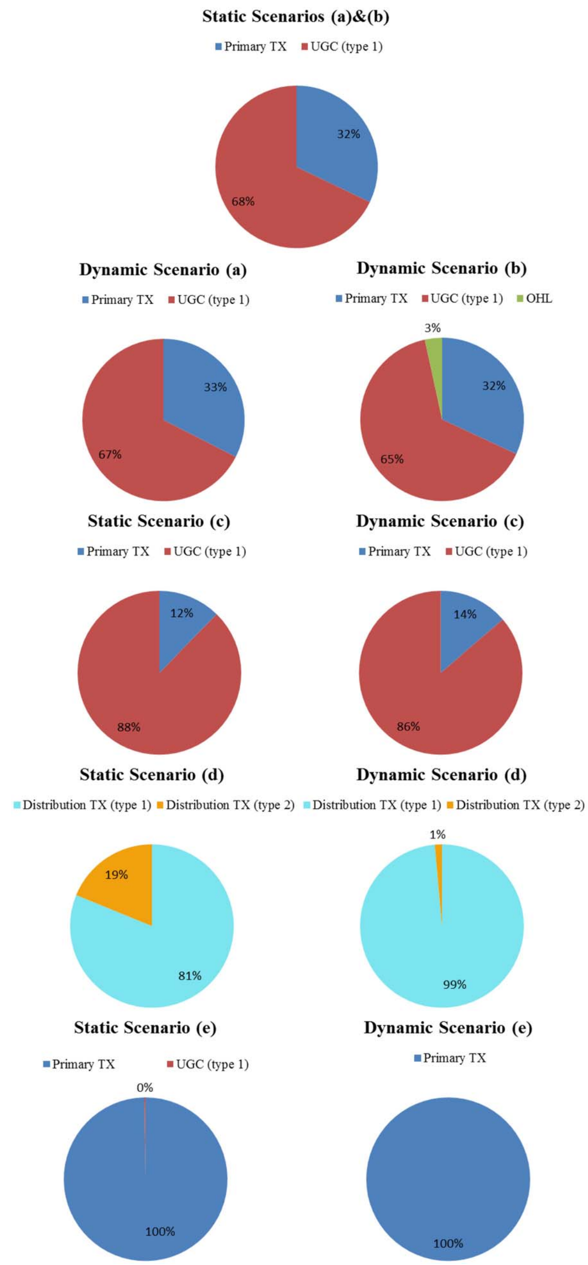

Fig. 20. Summary of the constraining assets under each scenario.

A last issue which could potentially affect the DNR is the issue of primary transformer cooling (all distribution transformers on this network are ONAN). If there are issues with the cooling, then the primary transformer will need to run under ONAN as shown in Fig. 19. This, then, becomes the constraining asset for the majority of the year, especially in summer when the dynamic rating may be less than the static rating (see Fig. 7). This results in a DNR decrease of around a third compared to Fig. 13.

A summary of mean and standard deviation values of seasonal static and dynamic ratings is shown in Table III which gives an indication of average gains/losses in network loading between static and dynamic ratings. During winter and spring, all the dynamic mean values are higher than those of using static ratings. The highest mean value increase from static to dynamic can be up to 188 A. This is for scenario (d) in winter when low ambient temperature is advantageous for the operation of constraining distribution transformers. However, during summer and autumn, most of the dynamic mean values are very close and may even be slightly lower than the static values. The highest mean value decrease from dynamic to static can be up to 123 A. This is for scenario (e) in summer when the primary transformers are operating at highest ambient temperatures but with ONAN cooling only. For almost all the cases, the standard deviation values of dynamic ratings are higher than those of static ratings. This is reasonable as more varying factors are considered for each DAR hence the higher result fluctuation.

V. Conclusion

A new DNR approach has been presented which looks in detail at the DNR using results from DAR calculations. Fig. 20 shows charts to summarize the percentage of time each asset is constrained under each of the scenarios studied. From these charts, it can be seen that the constraining network asset types are similar between static and DARs. Within this network, there are only a small number of assets which set the loading limit of the network. For example, there are 23 assets in the network of the type that can be monitored; however, the results show that of these assets it is only necessary to monitor up to five of these in order to understand the dynamic rating of the network.

The most constrained asset appears to be a couple of distribution transformers. In practice, the increase of load in a network would result an increased number of distribution substations/transformers rather than simply increasing the load on existing units. Another significant asset in the network is the primary transformers, even with cooling present, the primary transformer can be the main constraint within the winter months. The cable closest to the substation which carries the highest load has been found to be the constraining asset within the summer and autumn months. However, a low wind angle and wind speed on a sunny day could worsen this network rating.

To summarize, the dynamic rating offers clear gains to network operators in terms of network loading in the winter months (when peak loading occurs) but may be lower than the static rating on hot sunny days. It is also not necessary to monitor every asset within a network and careful use of modeling can point toward monitoring those assets that offer the biggest constraints.

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