Meshing Radial Networks at 11kV

B. Ruben, A. Cross, *Member, IEEE*, D. Strickland, M. Aten, *Member IEEE,* R. Ferris

***Abstract*-- This project evaluates the benefits of meshing existing 11kV radial networks in order to reduce losses and maximise the connection of low carbon distributed generation. These networks are often arranged as radial feeders with normally-open links between two of the feeders; the link is closed only to enable continuity of supply to an isolated portion of a feeder following a fault on the network. However, this link could also be closed permanently thus operating the network as a meshed topology under non-faulted conditions. The study will look at loss savings and the addition of distributed generation on a typical network under three different scenarios; traditional radial feeders, fixed meshed network and a dynamic meshed network. The networks are compared in terms of feeder losses, capacity, voltage regulation and fault levels.**

***Index Terms*-- Distributed generation, meshed network, network losses, radial network.**

I. Introduction

The UK's government's energy objectives are to deliver 15% renewable energy by 2020 and an 80% reduction in CO_2 by 2050. To achieve these objectives, low-carbon distributed generators (DGs) like wind power generators, PV modules or micro combined heat and power (micro CHP) generators have the potential to become increasingly common in distribution networks. Connection of DGs to existing 11 kV distribution networks poses certain technical difficulties because they were designed originally to just feed loads. Therefore new approaches to network design need to be explored.

The main objective of the work described in this paper was to evaluate the benefits of meshing existing 11kV networks, which are perceived to be:

- Permanently meshing two radial feeders balances their load and increases diversity. This is expected to result in reduced feeder conductor (I^2R) losses, and thus a reduction in CO_2 emissions.
- The network connection costs for DGs can be decreased, in some scenarios where meshing may defer investment of a new cable or line. If more network capacity can be made available to connect low carbon distributed generation, then this brings the benefits of reducing CO_2 omissions by offsetting fossil fuel generation and may increase revenue from network usage charges.

In addition, if the meshing scheme incorporates so-called smart grid units (SGUs), which consist of three intelligent circuit breakers arranged in a "T" connected to the feeder nodes, there will be further benefits such as:

- By locating the SGUs at each HV/LV substation, there will be an increase in the availability of supply to customers. This will reduce customer minutes lost (CMLs) and associated distribution network operator (DNO) penalties.
- SGUs can be used to dynamically change the meshing configuration, for example by moving the normally open-point, or switch between radial/meshed operation depending on which mode is optimum.

Existing studies have been carried out to quantify the advantages and disadvantages of DG connections in networks and to understand the technical solutions necessary to overcome these problems [1-3]. Some of the key issues that need addressing when connecting distributed generation are:

- Reverse Power flow, which may be a problem for some older tap changers.
- Excessive fault current levels
- Inadvertent islanding mode
- Voltage regulation and violations
- Loss impacts
- Power Quality effects
- Protection and reliability

Within the literature a number of different terminologies are used to represent the same basic concept. The switch from a radial to a meshed network may be referred to as network reconfiguration, meshing or looping. Simulation work on loss impacts [4,5] by meshing indicate that closing the normally open-points on radial substations fed from the same primary substation offers around 1% saving on losses. Losses by adding distributed generation [6,7] may be either negative or positive depending on conditions at the time of the study.

Existing studies show that once a meshed network is adopted, the additional fault level contribution from adding DG is not significantly higher. However protection co-ordination can be more complicated [8]. The disadvantages in fault level contribution are offset by increases in network stability [9] and reliability [10,11].

Three main automation solutions have been suggested for use on distribution networks; network re-configuration, active

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B Ruben, A Cross and D Strickland are with the Department of Engineering and Applied Science, Aston University, UK (e-mail: b.ruben@aston.ac.uk, a.cross@aston.ac.uk, d.strickland@aston.ac.uk).

M Aten is with E.ON New Build & Technology Ltd (e-mail: martin.aten@eon.com).

R. Ferris is with Western Power Distribution (e-mail Robert.ferris@central-networks.co.uk)

generation control and voltage control. This paper is primarily concerned with network reconfiguration. Much of the work on re-configuration has been on post-fault, some of which includes losses as an input to the process. However, a number of papers have looked at optimisation techniques to reconfigure the network to reduce losses both with and without added DG including across different primary substations [12]. These techniques may be implemented either manually or automatically. Typically some form of load flow analysis is undertaken and optimisation is used to find the best radial configuration [13,14]. The most simple of these is to simulate the meshing of the network and determine where the lowest current is and open the switch at this point assuming no network violations. Loss savings of between up to 10% are typically quoted within the studies both with and without DG for the different techniques.

In addition to reconfiguring the network to reduce losses, many studies have investigated spare network capacity and look at optimally siting or sizing DG Units using techniques ranging from impact indexes to analytical approaches and metaheuristics, to linear and non-linear programming as summarised in [15]. The conclusion from these studies was that the 33/11kV thermal ratings of the transformers were the limiting factors to increased DG penetration.

More complex meshing techniques utilising power electronic devices have been proposed, for example by using a Static Synchronous Series Compensator [16], and so-called soft, normally-open points [17], which help overcome some of the potential problems regarding the control of real/reactive power across the normally-open point. However, this could be potentially expensive and it is not clear whether this offers any advantage over intelligent SGUs operating dynamically.

Section II of this paper begins with a discussion of radial and meshed network configurations at 11 kV. This is followed in section III by an analytic study of a radial/meshed circuit, which derives a useful mathematical expression for the ratio of the meshed and radial conduction losses. This equation also gives insight into how individual circuit parameters affect the overall feeder losses. Section IV describes the methodology used to assess the meshed/radial networks, whilst section V presents the results from circuit simulations of three sections of an 11 kV distribution network within the UK. Section V explores the use of dynamic meshing to reduce meshed/radial losses, whilst the next two sections VI and VII, use simulation to look at the impact of introducing DG into the network.

II. Feeder Configurations

A. Radial network configuration

The general network configurations for 11kV distribution systems are radial, with normal open points between two feeders to allow connection with another feeder during a forced outage or maintenance. From a ‘primary’ substation, a number of 11kV feeders run to different loads in the system.

A ‘50% utilisation’ network design is most common at 11kV, which means that there are two feeders in parallel each having the capacity to supply its own peak demand plus the peak demand of the other feeder when the normally open point is closed (Fig. 1a).

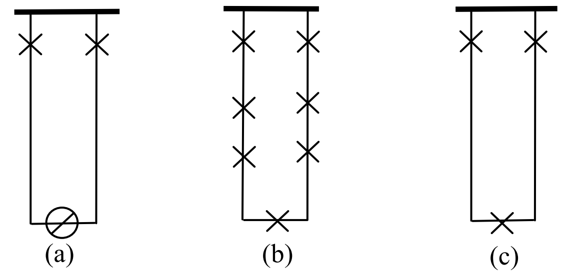

Fig. 1 Network Feeder with 50% utilisation in radial and meshed configurations.

The design aspects of a radial network without DG are relatively simple to analyse as the flow of current is in one direction only. The fault level and voltages monotonically decrease along the feeder as the distance increases from the substation. For protection, only one circuit breaker with an over-current protection relay is needed per feeder, which makes radial networks very attractive in terms of protection costs. With DG, the fault level and voltage profiles are no longer monotonic. In terms of protection, the DG is self-protected, which nullifies its contribution toward feeder faults.

B. Meshed network configuration

A meshed network will aggregate variations in both load and generation, and can increase reliability by providing multiple routes from supply to the load points. The main drawbacks are that fault levels are increased, and protection arrangements are more complicated and costly. Meshed networks have been implemented at voltage levels of 132kV and above and 33kV feeders are often paralleled via 33/11kV transformers which limits the fault level increase due to the impedance of the transformer. Meshed networks at 11 kV as shown in Fig. 1b, are employed in some large UK cities where the link between two parallel feeders is permanently closed. Additional circuit breakers are located at each 11kV/LV secondary substation so that fast unit protection can be applied to each cable segment between these substations. This increases the reliability of the network, but it has the drawback of increased costs due to the additional circuit breakers, and protection equipment.

Another possible and cheaper implementation of a meshed network is to have just one additional circuit breaker at the link point as shown in Fig. 1c. The circuit breaker would need an over-current trip relay that should be graded to operate before the main feeder circuit breakers located at the primary substation. In this way, if a fault occurs in one feeder, the disruption to the other feeder is minimised to a very short interval, so that ‘customer minutes lost’ are not increased compared with a radial feeder arrangement. A directional over-current trip relay would be needed only if there are already other circuit breakers along the radial feeder.

III. Losses in Radial and Meshed Feeders

A mathematical analysis of two radial/meshed feeders was carried out in order to derive an expression for the ratio of the feeder cable conduction losses in meshed and radial configurations. The equivalent circuit for a two feeder network is shown in Fig. 2, where the isolator at the normally open-point is used to switch between radial a meshed configurations. Each of the two feeders has a number of loads $N_{1,2}$ where the j^{th} load, which is positioned at distance d_{1j} and d_{2j} along a feeder, draws a current i_{L1j} and i_{L2j} respectively. It is assumed that load currents for each feeder have the same phase angle $\phi_{1,2}$, with respect to some arbitrary reference. The feeder input currents when in radial mode are denoted i_{1in} and i_{2in} respectively.

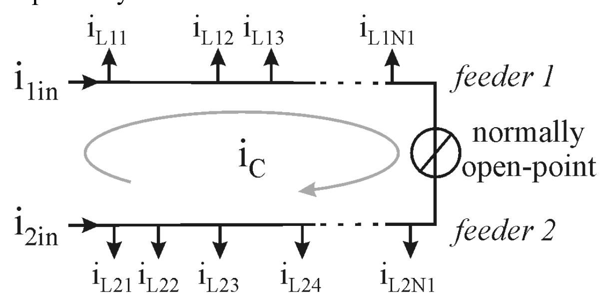

Fig. 2 Equivalent circuit of a two-feeder network.

In radial mode the total network feeder losses are given by,

$$3\sum_{f=1}^{2} r_f \sum_{j=1}^{N_f} I_{Lfj}\, d_{fj}\left[2\sum_{k=j}^{N_f} I_{Lfj} - I_{Lji}\right] \tag{1}$$

where r_f is the resistance per unit length of the f^{th} feeder, and capitalised current symbols correspond to current magnitudes. Feeders with a variable resistance per-unit length along the feeder can be modelled by simply scaling the distances d_{1j}, d_{2j} by an appropriate factor. When the isolator switch is closed for meshed mode, a circulating current i_C is superimposed on the original radial feeder currents where,

$$i_C = \frac{-z_1 e^{j\phi_1}\sum_{i=1}^{N_1} I_{L1i} d_{1i} + z_2 e^{j\phi_2}\sum_{i=1}^{N_2} I_{L2i} d_{2i}}{Z_1 + Z_2} \tag{2}$$

$z_{1,2}$ being the feeder impedances per-unit length and $Z_{1,2}$ the total impedances of the feeders up to the normally open-point for feeder 1 and 2 respectively. It can be shown that the change in losses when going from radial to meshed configurations is then given by,

$$3I_C\left(\sum_{f=1}^{2}(-1)^{f-1}2r_f\cos\left(\angle i_C - \phi_{3-f}\right)\sum_{j=1}^{N_f} I_{Lfj}\, d_{fj} + R_f I_C\right) \tag{3}$$

where R_f is the real part of $Z_{1,2}$ respectively. The ratio of meshed to radial losses is then simply the sum of (1) and (3), divided by (1). These equations are quite complex due to the summation terms, and give no insight into the effect of individual parameters on meshed/radial losses. Therefore a statistical approach was used to simplify these loss equations by making the following assumptions,

- The feeder load currents have a uniform, random spatial distribution along each feeder.
- Load current magnitudes have a uniform, random distribution, but their sum is constrained to be equal to the feeder radial input currents I_{1in} and I_{2in}.
- The change in node voltages along a feeder is small between meshed and radial configurations - the load currents i_{Lj} therefore remain unchanged.
- The load currents for the two feeders have the same phase angles $\phi_1 = \phi_2$.

Under these assumptions the expressions for the expected or average, radial and meshed losses can be derived from equations (1)-(3). The random variables that represent spatial position and load current in (1)-(3), form convex combinations of ordered random variables [18], where the terms are ordered according to their position along a feeder. From the central limit theorem, the distributions for both radial and meshed losses tend toward normal for increasing $N_{1,2}$. Furthermore, the ratio of the meshed to radial losses is a ratio distribution, which has a much narrower spread of points than those of the individual radial and meshed losses, and the ratio of the average meshed/radial losses tends toward the median of this ratio distribution. The expression for the expected meshed to radial loss ratio is given by,

$$1 - F_{k=1} + F_{k\neq 1} \tag{4}$$

where,

$$F_{k=1} = \frac{(ir-1)^2}{4(1+r)\left(N_{n2} + N_{n1} i^2 r\right)}$$

$$F_{k\neq 1} = \frac{k_{t2}^2 r^2 (1+i)^2 (k-1)^2}{4(1+r)\left(N_{n2} + N_{n1} i^2 r\right)\left((1+r)^2 + k_{t2}^2 (1+kr)^2\right)} \tag{5}$$

$i = I_{1in}/I_{2in}$, $r = R_1/R_2$, $k = k_{t1}/k_{t2}$, $kt_{1,2}$ being the X/R ratio for feeders 1 and 2 respectively and $N_{n1,2} = (1+N_{1,2})/(1+3N_{1,2})$.

The term $F_{k\neq1}$ is equal to zero when the feeders have equal X/R ratios, and the ratio of meshed to radial losses is then given by $1-F_{k=1}$. Under these conditions it can be seen that the meshed losses are always less than or equal to the radial losses by the factor $F_{k=1}$. Note that when $i=1/r$ the meshed and radial losses are equal, and there is no reduction in losses between the two topologies. However, if $k\neq1$, then $F_{k\neq1}>0$, which means that if the feeders have unequal X/R ratios, the benefits of meshing are reduced. In particular, if $i=1/r$ and $k\neq1$, there is actually an increase in overall losses when meshing. An example of such a scenario is when feeders consist of a mix of underground cables and overhead lines.

Note that for $N_1,N_2>>1$, the terms $N_{n1,2}\rightarrow1/3$, and equations (4) is then identical to that obtained when assuming the feeder input currents $I_{1,2in}$ are distributed with an ideal, continuous uniform density along the feeders.

In order to demonstrate the distribution of the radial and meshed losses, a Monte-Carlo analysis of a typical network was carried out and the results are shown in Fig. 3 where i=0.83, N_1=6, N_2=10, r=5/3, k=1/2, k_{t2}=4, I_{2in}=100 A and R_2=0.3 Ω.

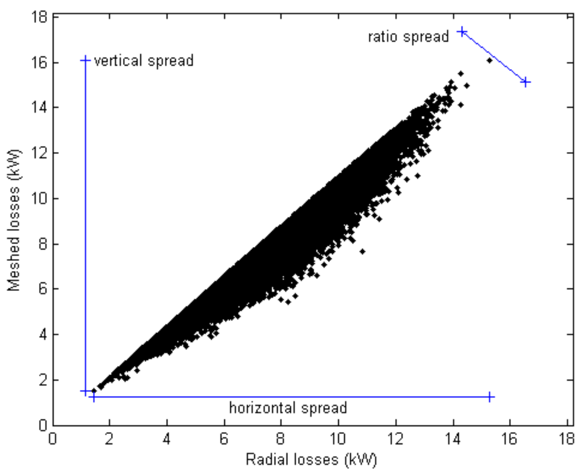

Fig. 3 Monte-Carlo analysis of radial and meshed losses.

Fig. 3 shows that whilst the spread of the individual radial and meshed losses is quite large, as indicated by the horizontal and vertical extent of the scattering, the distribution of the ratio of the losses is relatively small, as can be seen by the spread of the distribution across a 1:1 trajectory. This indicates that the random distribution of load along a feeder has a common effect on losses for both the radial and meshed configurations.

In order to establish the conditions for maximum loss savings when meshing, the plots of the meshed to radial losses from equation (4) are shown in Fig. 4 for i=0.2→5 and r=0.2→5 and k=1. It can be seen from the figure that the greatest loss savings are obtained when i and r are both larger than unity or, both i and r approach zero. For example, loss savings of around 50% can be obtained at the extreme values of i = r = 0.2 or i = r = 5. However, these scenarios are very rare in practice as they correspond to highly unbalanced radial feeder input currents and/or impedances. The examples of rural, suburban and urban feeders that have been studied in this paper show that values of i and r are much closer to unity, with typical values of i = r =0.5 or i = r = 2. Under these conditions the reduction in losses is then reduced to around 25%. In addition for unbalanced feeder X/R ratios, k≠1, the benefits are reduced further.

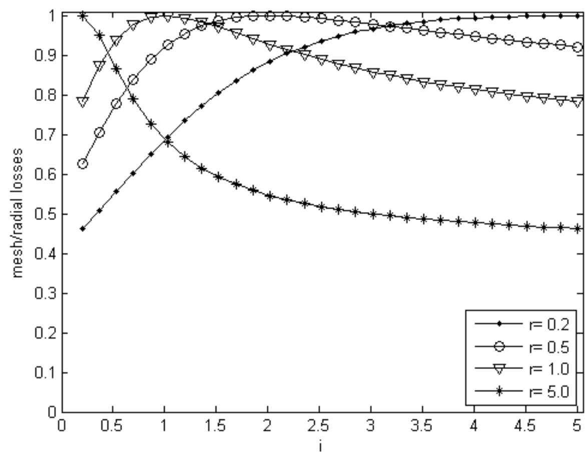

Fig. 4 Plots of $1-F_{k=1}$, .for i=0.2→5 and r=0.2→5

The equation for the ratio of meshed to radial losses (4) can be conveniently used to rapidly identify feeders that may give loss savings when meshed.

IV. Calculation Methodology

Power system simulation was used to assess the behaviour of meshing in terms of:

- Feeder conduction losses
- System fault level
- Voltage regulation
- Potential for DG penetration

Models were implemented in the software package IPSA for an 11kV network in central England. A total of three networks with different size and loading levels were chosen for the study, that correspond to urban, suburban and rural regions around the city. Actual sub-station feeder input current measured at half-hourly intervals was imported into IPSA using the Python scripting language to allow an accurate calculation of losses over a 12 month period.

An existing technique based on Loss Load Factors is commonly used to calculate network losses for time-varying load profiles. This method can be used for radial networks but not for the meshed networks here due to the unknown circulating current i_C – Fig. 2, that flows around the mesh.

Since only the measured data of the feeder input current is recorded by the DNO, this current has to be apportioned appropriately to each load along the feeder using an extrapolating technique. A standard method is to distribute the load along the length of the feeder by proportioning the total load based on the rating of the step-down transformer at each load take-off point. This was the method used in these studies for the IPSA simulations. In addition, all loads were assumed to operate at a power factor of 0.95.

V. Loss Calculation Results

The peak and average yearly losses were calculated using IPSA simulations and are shown in Table I and II respectively.

In addition, losses were also calculated using intermediate, expressions from the statistical analysis along with the ratio of the losses (4) and these are also shown in the tables:

TABLE I
PEAK LOSSES CALCULATED USING IPSA AND STATISTICAL EQUATIONS

	Method	Radial loss peak load (kW)	Mesh loss peak load (kW)	Meshed: Radial loss ratio
Urban	IPSA	15.43	15.33	**0.99**
	Statistical	8.72	8.56	**0.98**
Suburban	IPSA	52.09	38.59	**0.74**
	Statistical	31.00	22.94	**0.74**
Rural	IPSA	31.75	32.67	**1.03**
	Statistical	22.24	22.90	**1.03**

TABLE II
AVERAGE YEARLY LOSSES AND AVERAGE RATIO CALCULATED USING IPSA AND STATISTICAL EQUATIONS

	Method	Annual radial loss (MWh)	Annual mesh loss (MWh)	Meshed: Radial loss ratio
Urban	IPSA	39.90	37.10	**0.93**
	Statistical	37.73	35.14	**0.93**
Suburban	IPSA	99.55	63.53	**0.64**
	Statistical	112.27	77.48	**0.69**
Rural	IPSA	35.06	32.91	**0.94**
	Statistical	46.88	42.41	**0.90**

Tables I and II show that whilst in some cases there is quite a large error between the simulated absolute loss calculations and the statistical equations, there is very good agreement between the meshed/radial ratios. The difference in absolute losses between the two methods is to be expected as the statistical method is based on the average loss, whereas the actual loss represents just one sample from a wide-range of values, shown by the distribution in Fig. 3. However, the ratio of losses has a much narrower distribution and results in a much closer agreement between the two methods.

Assuming that the average carbon dioxide emission for UK grid is 0.502 kg CO_2/kWh according to DEFRA UK, the amount of annual CO_2 reduction that is represented by Table II is approximately 1, 17 and 1 tonne for urban, suburban and rural networks respectively. These results equate to a fairly modest savings in losses. Note that the larger loss reduction in the suburban network is not generic for all suburban networks but due to a relatively high unbalance in loss between the two feeders in this case.

It can be seen from Table I, that the rural network gives an increase in losses when meshed at peak load. This is due to the unequal X/R ratios of the two feeders, which are a mixture of cable and overhead line. However, the overall annual losses are lower when meshed. This is because the peak load for the network is dominated by a large, single industrial plant, which has a very intermittent duty. When the plant is operating, the meshed losses are greater than the radial, whereas when the plant is not operational, for example during evenings and weekends, the radial losses are greater than the meshed.

VI. DYNAMIC NETWORK OPERATION

In terms of losses it can sometimes be advantageous to operate a meshed network in a radial configuration depending upon the instantaneous loading on the network at any particular time. Two scenarios are discussed:

1. When the radial losses are lower than those for the meshed network - this can happen on feeders having unbalanced X/R ratios. This solution requires a circuit breaker at the normally open-point.

2. Permanently operating the feeders as a radial configuration but dynamically moving the normally open-point - the loss savings can be potentially as much as those for meshing. However, the network retains the benefits associated with a radial network, such as ease of protection. This scenario assumes that the network is fitted with multiple SGUs

The first scenario can be demonstrated by examining the rural network data from the previous section. The rural network has unbalanced feeder X/R ratios, k= 0.5287, and when the large industrial load is operating, the meshed losses are then greater than the radial losses. This is shown by the annual meshed/radial loss ratio against time plot Fig. 5, where the meshed/radial loss ratio exceeds unity.

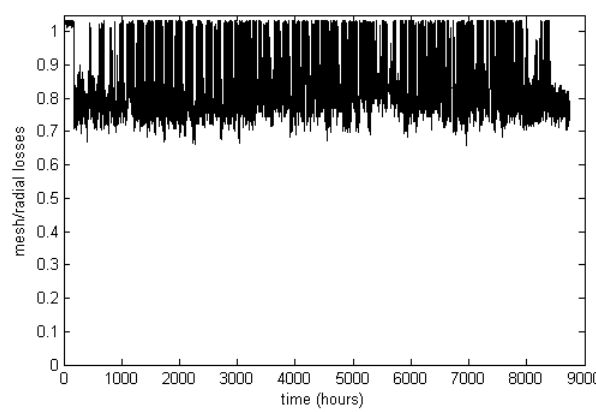

Fig. 5 Half-hourly meshed/radial loss ratio for rural network over one year

In a dynamic meshed scheme, a system controller uses equation (4), to estimate when the meshed/radial ratio is greater than unity. To do this the controller would need a measurement of the current at the normally-open point when meshed in order to calculate the ratio i. If this scheme was implemented on the rural network, the meshed/radial loss ratio would be as shown in Fig. 6.

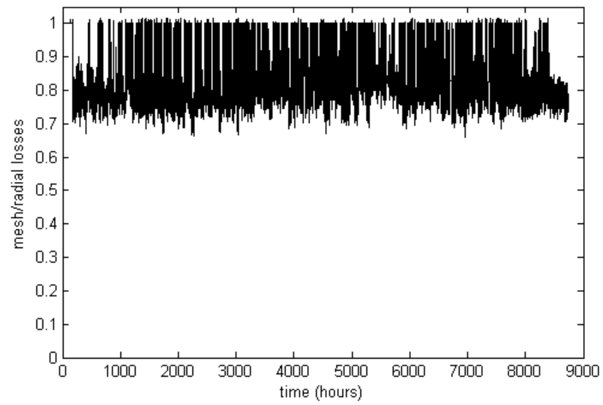

Fig. 6 Half-hourly meshed/radial loss ratio for rural network over one year, which dynamic meshing

It can be seen from Fig. 6 that the ratio is now clipped at approximately unity. The difference between the annual losses for the permanently meshed network and the dynamic meshed network for these two figures is approximately 276 kWh. This loss saving is very small, which this is due to the peculiar characteristic of the industrial load in the network. However this example does demonstrate the principle of dynamic meshing.

The second scenario implements a movable open-point. The optimum location of the open-point is at a point along a feeder where the total meshed current is zero. In practice, this point would probably lie between two switches – SGUs – and therefore only a sub-optimal solution would be achieved.

For example, in the suburban network, the position of the optimum normally open-point, current zero, is shown in Fig. 7. However this point is located at some distance from the normally open-point that currently exists in this network.

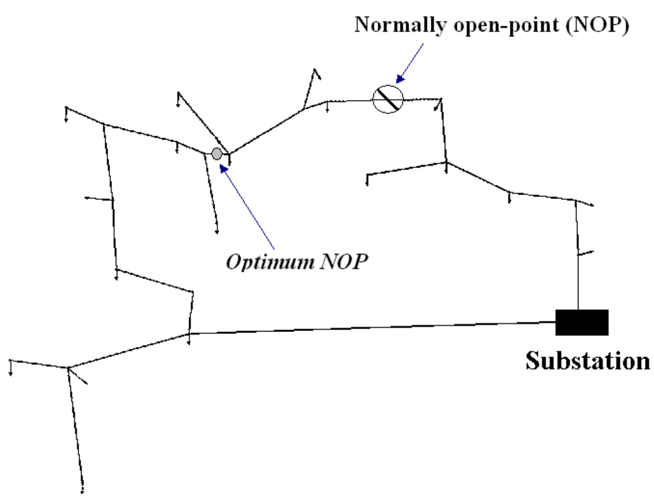

Fig. 7 Suburban network with optimum NOP

If a movable open-point could be implemented on this network and the open-point moved to either side of the optimum position shown in Fig. 7, the difference in losses between this configuration and a meshed network is several tens of Watts and therefore negligible.

In this system, the SGUs would provide measurements of the mesh current between nodes in order that the optimum open-point could be identified from the current minimum.

This example also highlights the fact that even if meshing was not implemented, this particular suburban network would benefit from simply relocating the existing isolator.

VII. Connection of Distributed Generation

Whilst simply meshing existing radial feeders having just loads doesn't appear to give significant loss and thus CO_2 reductions, the connection of low-carbon, renewable DG would have a significant impact. The following sections discuss the issues surrounding DG connections in terms of losses, feeder capacity, voltage limits and fault levels for both radial and meshed networks. The main criterion for determining these values is that the network has to operate without thermal overloading of conductors and maintain system voltage level. The following cases were considered for adding DG using IPSA simulations:

1) DG is connected at the end of one radial feeder
2) DG is connected at the middle of one radial feeder

The maximum DG that can be connected before cable overloading occurs was calculated at maximum and minimum demands according to measurements. The voltage rise constraint was also checked at the same demand levels, with the criteria that the voltage should not exceed 1.06 pu anywhere along the 11 kV line due to connection of DG. It was assumed that the voltage at the primary substation was 1.04 pu which is common practice today, but somewhat onerous for the voltage rise constraint, and in practice it may be possible to lower this voltage. This should however not impact whether more DG can be connected in a meshed, rather than a radial configuration. In all cases it was assumed that the DG runs at unity power factor, which is common practice, and fault levels were not the limiting factor to connect DG.

A. Case 1 – DG at the end of one feeder

In this case DG was connected at the end of one of two selected radial feeders and the maximum DG that can be connected in both radial and meshed configuration was derived. This scenario is quite representative in so far that DG connected to an 11kV network is often concentrated in one location, rather than having many DGs connected at different points to two nearby feeders.

In this scenario, significant more DG - average 81% - can be connected by meshing the two feeders for different networks considered: results are shown in Fig.3 for connecting DG to one feeder (F1). In the urban network the maximum DG is determined by thermal loading constraints. There are no voltage constraints, because of the relatively short cable distances, and associated low impedance. In the suburban network, the DG penetration is constrained due to thermal overloading in one feeder (F1), and due to voltage rise in the other feeder (F2, not shown in Fig. 8). This is related to the currently selected normal open-point between the two feeders, causing significantly longer cable distance and thus larger impedance between the primary substation and the DG.

In the rural network the maximum DG is constrained by voltage rise in both feeders. This can be explained by the long cable and overhead line distances, and resulting high impedance between the primary substation and the DG, which is quite common for rural networks.

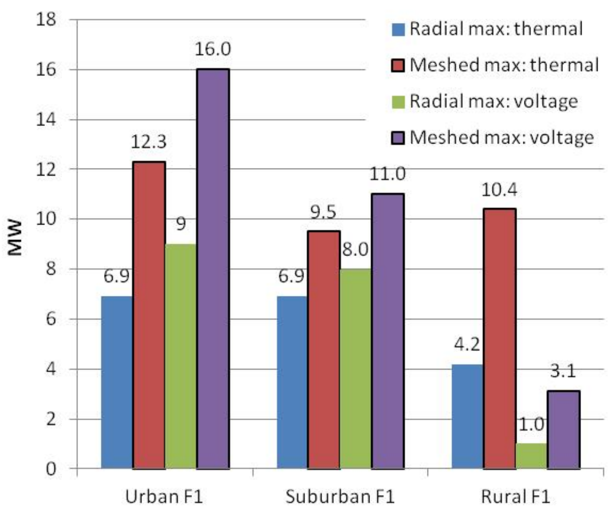

Fig. 8 Maximum allowable DG at the end of feeder 1 at minimum load, based on thermal and voltage constraints

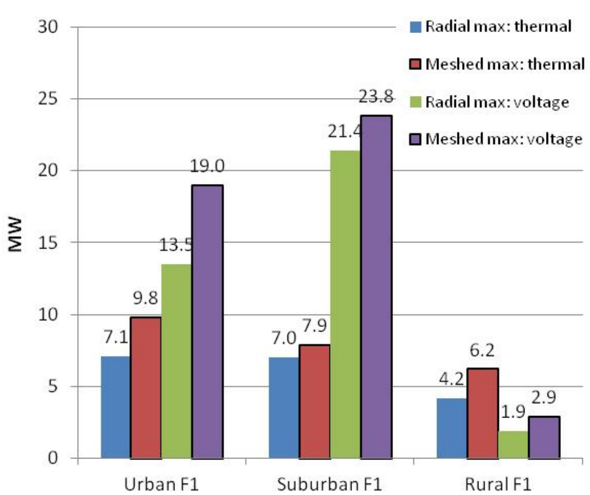

Fig. 9 Maximum allowable DG at the middle of feeder 1 at minimum load, based on thermal and voltage constraints

B. Case 2 – DG at the middle of one radial feeder

This scenario is similar to the one in the previous section but DG is connected at the middle of one radial feeder. The results given in Fig. 9 (showing feeder 1 only) illustrate again that by meshing more DG can be connected, but the gain (average 33%) is much smaller than in the previous scenario.

Where maximum DG is connected on both feeders there is no additional benefit to be obtained by meshing.

VIII. Fault Level Analysis

Fault levels were calculated in IPSA to evaluate to what degree and where fault levels increase when meshing two radial feeders connected to the same primary substation, with and without DG. The peak make fault current was calculated at 10 ms and the symmetrical RMS break fault current at 50 ms which is the typical minimum time delay incurred by the protection relay(s) plus the breaker opening time. The fault current contribution was assumed according to a wind turbine generator (DFIG: Doubly Fed Induction Generator).

The DG was assumed to be connected at the end of the primary feeders, with the maximum allowable DG capacity according to the thermal overloading constraints identified. The voltage rise constraints were not applied, as this would have been more benign for the fault levels, whereas the voltage rise constraints may be overcome, for example by decreasing the voltage at the primary substation using the tapchanger or VAr compensation.

Although the fault levels increase somewhat by connecting DG using meshed feeders, a similar increase can be expected if a line or cable would be upgraded, thus decreasing the impedance. Fig. 10 shows the RMS fault levels at 50 ms along two suburban feeders showing the increase in fault level for both meshing and increased DG.

In all networks the following trends are similar: meshing the two feeders increases the fault levels more at the secondary substations, the further they are located from the primary substation. By adding DG, the fault levels are increased, more so in meshed configuration, but the fault levels near or at the primary substation are not much increased due to meshing.

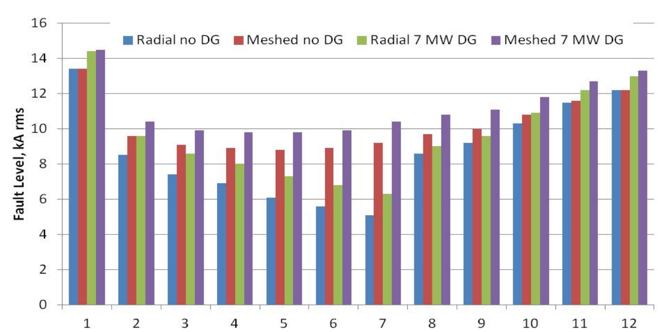

Fig. 10 Suburban RMS fault levels with and without DG

IX. Conclusions

This paper has used a case-study approach and mathematical analysis to help determine whether or not there is a case for meshing an 11kV distribution network either permanently or dynamically.

A statistical based analysis of the feeder losses was carried out and compared against detailed IPSA simulations of three representative networks: urban, suburban and rural. There was good agreement between the mathematical equation and the IPSA results for the ratio of meshed to radial losses. Both methods predicted fairly modest reductions in losses for all three networks, having just loads. The mathematical analysis predicted a potential increase in losses when meshing feeders with unbalanced X/R ratios and this was validated by the IPSA simulations of the rural network. Two dynamic meshing strategies were discussed, and again, the benefits of these schemes appeared to give very small reductions in losses based on the examples used.

A more significant benefit that meshing can offer is that it may facilitate the connection of more low carbon generation by providing a second export route in certain scenarios, thus saving on line and cable upgrades. Preliminary results also indicate that there may be significant cost savings from reductions in feeder losses when meshing a network with DG connected to one feeder. Whether these cost savings will outweigh the costs of more complex protection required for meshing depends on network specifics and size and location of DG. Details of studies on this will be part of a future publication, which will also include the statistical analysis of such a network.

Although the fault levels increase somewhat by connecting DG using meshed feeders, a similar increase can be expected if a line or cable would be upgraded, thus decreasing the impedance. In all networks the following trends are similar: meshing the two feeders increases the fault levels more at the secondary substations, the further they are located from the primary substation. By adding DG, the fault levels are increased, more so in meshed configuration, but the fault levels near or at the primary substation are not much increased due to meshing.

The loss calculations that have been carried out in this study have been confined to a sample of three 11 kV feeder pairs. However the work could be extended to assess the overall impact of meshing large numbers of feeder pairs using the techniques described in this paper.

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XI. Biographies

Benedict Ruben is a Knowledge Transfer Partnership Associate at Aston University, working in the field of electrical power distribution engineering. At present he is located at E.ON New Build & Technology Centre, in Ratcliffe on Soar, UK.

Andrew Cross (M’2005) is a Lecturer and member of Aston’s Electrical Power Engineering and Power Electronics Group since Sep 2008. He has over 12 years experience working in industry at GEC Industrial Controls, Ultra Electronics, Alstom Power Conversion and Areva T&D.

Dani Strickland is a Lecturer and member of Aston’s Electrical Power Engineering and Power Electronics Group since Jan 2010. She has over 10 years experience in industry working at both Rolls Royce Fuel Cell Systems Ltd and Eon as a Power and Control Engineer.

Martin Aten (M’1995) started his industrial career in 1995 and since 2006 he is employed by E.ON New Build and Technology in Ratcliffe on Soar, UK, carrying out network studies and research in electrical power systems

Robert Ferris is the Innovation and Development Manager for Western Power Distribution (previously Central Networks). He graduated from Aston University with a degree in Electrical and Electronic Engineering and has over thirty year experience of working in the UK’s Electricity Distribution Industry. In his career he has undertaken a variety of technical roles and has been the Company’s Overhead Line Specialist, Automation Task Force Manager, Protection and Automation Manager, and the Asset Manager.