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<td>Publication date</td>
<td>2008-07</td>
</tr>
<tr>
<td>Item record/more information</td>
<td><a href="http://hdl.handle.net/10197/3206">http://hdl.handle.net/10197/3206</a></td>
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Minimum Cost Curtailment for Distributed Generation Voltage Management

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Abstract - The penetration of DG is increasing on distribution networks across the world. As a result, networks are being pushed closer to their operating limits. In particular, voltage rise has been identified as a key barrier to further DG capacity. Active management of the voltage constraint may be possible, leading to a form of constraint management at distribution level for the first time. Here a novel method is proposed, which minimises the cost of curtailment. It takes advantage of the dispatchable capability of certain forms of DG, such as biomass, hydro or landfill gas. There are a number of well established methods for congestion management on the transmission network. A number of these are applied to voltage management on the distribution network and used for comparison with the new minimum cost method. The variability of voltage sensitivities and market prices is also investigated, with their impact on the cost of curtailment quantified.

Keywords - Power distribution operation, Energy resources, Dispersed storage and generation, Costs.

1 Introduction

Historically, distribution networks have been passive systems used only for the delivery of energy to the consumer. With the advent of distributed generation (DG), the role of distribution networks is changing. They are now employed for the delivery and harvesting of energy. A number of well established constraints place limits on the permissible capacity of DG [1, 2]. The voltage constraint, in particular, has previously been identified as often being the limiting constraint to further DG capacity [3]. Traditionally, network operators have offered firm access to prospective generators. The amount of firm access granted under the connection agreement to a distributed generator is the level of output at which they can always operate without violating any of the constraints on the network. Non firm access refers to output greater than this amount, at which generators may be allowed operate dependent on the system conditions throughout the year. The introduction of non firm access will lead to some form active control of DG, whereby control actions will be required to bring the system back within limits from time to time.

Previous work has shown the scope for non firm energy beyond the strict constraint limits and has optimised the allocation of this non firm energy, such that the constraint breaches are reduced and hence the energy harvested is increased [4]. Congestion management is well established on transmission networks, with existing schemes in place [5, 6]. However, given their traditionally passive nature, constraint management on distribution networks is much more unusual.

In [7], methods to estimate the amount of wind power that could be installed in areas with congestion problems are presented. The methods are applied to the Swedish transmission network and the cost of the spilled energy is determined. Other work has focused on the coordination of wind and hydro plant, with the hydro plant being used as storage. The objective was to maximise the generator’s profit and to smooth out the combined output of the generators [8]. In [9], the operation of a proposed active management scheme is investigated on the Orkney islands in Scotland. The feasibility and benefits of non firm access are highlighted as are the potentially complex operational issues surrounding the implementation of such a scheme. In [10], the issue of the operation of curtailment on the distribution network is addressed, with a number of curtailment methods compared and the calculation of voltage sensitivities examined. The influence of losses on the curtailment rules is addressed. Previous work has examined the impact of distributed resources on congestion management on the transmission network in terms of contribution factors [11]. In [12], the use of customer side generation to provide congestion relief on the transmission system is examined. Other work has focused on the reliability worth of DG [13] and the consideration of an optimal operating strategy for DG on an hourly basis. Other operational issues have been investigated such as in [14], where a Monte Carlo simulation is employed to assess the impact of all possible DG operation conditions on the system. In [15], the operational issues of using multiple DG sources for voltage support are examined with a number of recommendations made.

In this paper, the curtailment of DG as a method of relieving voltage rise on the distribution system is investigated. A number of existing methods employed for congestion management on the transmission network are implemented for voltage management on the distribution system. A novel minimum cost curtailment method is proposed that utilises the ability of some forms of DG to re-dispatch. The amount of curtailment required is calculated based not only on the voltage sensitivity of the DG buses, but also on the cost of curtailment of the DG. The cost of curtailment of a generator is dependent on the capability of the generation to ramp up and down while maintaining their annual energy output. By taking account of this capability of certain generators the amount of non dispatchable generation spilled through curtailment can be substantially reduced.
Section 2 describes a novel minimum cost curtailment method that takes account of the dispatchable capability of some forms of DG. Section 3 describes some of the existing congestion management methods used on transmission networks and how they can be applied to distribution systems for voltage management. The calculation of the voltage sensitivities and description of the test system is given in Section 4. Results and discussion are given in Section 5, with conclusions given in Section 7.

2 Minimum Cost Curtailment

This method minimises the cost of a voltage management scheme. This method facilitates an overall increase in energy output from DG by avoiding the spilling of energy by non-dispatchable generation, which in turn reduces the cost of curtailment. It utilises voltage sensitivities to calculate the contribution of each generator to the voltage rise. The cost of curtailment for each generator is also determined and is used to allocate the required curtailment between the generators such that the overall cost is minimised.

2.1 Voltage Sensitivities

Due to the low X/R ratio in distribution networks, the magnitudes of bus voltages are more dependent on the active power injections in the system than in the transmission system which tends to have higher X/R ratios. Voltage sensitivities are employed here to identify the contribution of each generator to the constraint limits. Traditionally, voltage control on distribution networks is done by reactive power control or tap changing transformers. Active power curtailment is proposed here as an alternative method, which can be used if the alternative methods are unavailable or have been exhausted. The voltage sensitivities are used to calculate the amount of curtailment required by each generator.

Given a specific operating point, the Jacobian matrix used in Newton-Raphson load flow methods can reflect the sensitivities of bus voltage changes to power changes. In [16], the sensitivities of voltage to the P or Q injections from distributed generations were analysed. In summary, for all the PQ mode buses (including load buses and those buses with distributed generators attached which are operating at the power factor mode), the bus voltage sensitivities to the active and reactive power injections, \( \frac{\partial V}{\partial P} \) and \( \frac{\partial V}{\partial Q} \), can be calculated from Equation (1).

\[
\frac{\Delta V}{\Delta \theta} = J^{-1} \left[ \begin{array}{c} \Delta P \\ \Delta Q \end{array} \right] = \left[ \begin{array}{cc} \frac{\partial V}{\partial P} & \frac{\partial V}{\partial Q} \\ \frac{\partial \theta}{\partial P} & \frac{\partial \theta}{\partial Q} \end{array} \right] * \left[ \begin{array}{c} \Delta P \\ \Delta Q \end{array} \right]
\]

(1)

Where \( V \) is the vector of nodal voltages, \( \theta \) is the vector of voltage angles and \( J \) is the Jacobian matrix given by Equation (2).

\[
J = \left[ \begin{array}{cc} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial Q} \\ \frac{\partial \theta}{\partial P} & \frac{\partial \theta}{\partial Q} \end{array} \right]
\]

(2)

The variable nature of load and DG means that power flows in the network will vary frequently. The Jacobian matrix in Equation (2) is dependent on the operating condition and will change accordingly. Hence, the sensitivity matrix in Equation (2) will also change with the operating condition, leading to a significant variation in the sensitivity values. These variable sensitivities are employed in the methodology and their impact examined in Section 5.

2.2 Cost of Curtailment

The cost of curtailment of each generator is calculated and used in conjunction with the voltage sensitivities to calculate how much energy should be curtailed. The result is the amount of curtailment that leads to the minimum overall cost. The cost of curtailment is dependent on a number of factors. Firstly, it is dependent on whether the plant is dispatchable or not. In the case of non-dispatchable generation, such as wind, the Generation Marginal Cost (GMC) is equal to the system marginal cost (\( \text{€}/\text{MWh} \)), i.e. the market price at that time. A dispatchable generator, such as biomass, can redispacht itself to accommodate some of the curtailment for ‘free’.

There is a limit to this ‘free’ curtailment, dependent on the plant availability, load factor and magnitude and frequency of constraint breaches. The amount of curtailment that a dispatchable generator can accommodate can be calculated based on the generation load factor and plant availability. The average amount of curtailment required over a year can be estimated reasonably well through simulation of the network. It is impossible to predict ahead of time exactly when instances of overvoltage will occur. However, the total amount of constraint breaches over a year can be assumed to be a relatively stable value from year to year, given the predictable nature of both the load and overall DG energy output. As such, the calculation of the GMC is based on historical levels of required curtailment. The calculation of the generation marginal cost of the \( l \)th energy resource (GMC\(_l\)) is given in Equation (3).

\[
\text{GMC}_l = \frac{\text{CurtReq}_l - \text{FreeCurt}_l}{\text{CurtReq}_l} MP + \text{CycleCost}_l \forall M.
\]

(3)

Where CurtReq and FreeCurt give the amount of energy to be curtailed and the amount of energy that can be accommodated for free in terms of energy alone respectively. MP gives the price paid to the generator in the market and M is the set of all available energy resources. CycleCost\(_l\) is the cost of cycling and is explained below. If FreeCurt is greater than CurtReq, then the generator can accommodate more curtailment than is required and GMC\(_l\) is equal to the cycling cost. It can be seen that in the case of non-dispatchable generation where generally FreeCurt = 0, GMC\(_{\text{Wind}}\) = MP + CycleCost\(_{\text{Wind}}\). In the case of a dispatchable generator, it can be seen that the GMC will be based on the fraction of CurtReq that can be accommodated for free. FreeCurt is determined by analysing the dispatchable generator’s historical output profile. An estimate of CurtReq can be determined based on the magnitude of overvoltage experienced historically. The generators could be compensated for any errors in this
The operation marginal cost of the $l$th values, given by $\mu_l$, activity the tailment is assigned for a specific time period. It is evident with cycling a LFG generator, which could also be associated with cycling a biomass generator is calculated here. Similarly there is a cost associated with cycling a LFG generator, which could also be calculated in a similar fashion. Wind turbines are designed to take on more of the curtailment then the stress on the unit comes. Hence, if a dispatchable generator is required to come. The overvoltage, given by $\Delta V_i$, is divided between the contributing generators. $\beta$ is used to attribute the proportion of the voltage rise to each generator based on cost, but $\mu$ is still required to curtail the generators by their allotted amount. This leads to Equation (6) which gives the total amount of curtailment required for a voltage breach at the $i$th bus.

$$P_{\text{Curtail}} = \sum_{l=1}^{M} \frac{\text{Prop}_l \Delta V_{i}}{\mu_{ij}}, \quad i \forall N.$$  \hspace{1cm} (6)

Where $P_{\text{Curtail}}$ is the amount of curtailment at the $j$th bus for a voltage breach at the $i$th bus.

### 2.4 Operating Constraints of Plant

The basis of the minimum cost method is that the dispatchable generation can accommodate the required energy by cycling up and down. As detailed in [20], in a competitive market a generator with a limited amount of fuel may be contracted to supply a certain amount of electricity at various times throughout the day. If the price is low, the generator could purchase electricity from the market, store its fuel and produce its own electricity at a later stage for an increased price. This is akin to the situation described above with dispatchable plant deferring production to avoid the non dispatchable generation from spilling energy and then increasing its output at a later stage, thus maintaining its projected total output. There are a number of dispatchable distributed generators that would have the capability to operate in this manner; biomass, LFG and hydro. All three have a limited energy resource and will have a projected total output for the year. In the case of hydro this will be affected by the amount of rainfall. The annual output of a landfill gas (LFG) plant is dependent on the rate of the landfill gas generation at the site. This gas is collected in a system of pipes on site and pumped to a nearby gas turbine [21]. There are a number of types of biomass plant, but in the case of an industrial residue plant, the output of the generator may be influenced by the operating schedule of the site it serves and also on the availability of its fuel. As result these plants will not be completely flexible and may not be able to adopt a profit maximising strategy. This is also relevant for combined heat and power (CHP) plant.

### 3 Existing Curtailment Methods

There are a number of established methods for curtailting generators on the transmission system. Three of the most relevant, which are also given in [22], are applied to the distribution system here and are given below. They all employ voltage sensitivities to calculate the required amount of curtailment. They are used in Section 5 for comparison with the new curtailment method developed.
in Section 2. They are represented graphically by the two generator case shown in Figure 1.

![Figure 1: Different curtailment methods for two generator case](image)

The limit of the generation operation is given by the constant voltage line for bus A (in bold). Above this line, the voltage at A exceeds its maximum permissible value. This line is given by Equation (7).

\[
\mu_{AA} P_A + \mu_{AB} P_B + V_{Base} = V_{Max}
\]

(7)

Where \(\mu_{AA}\) gives the voltage sensitivity (kV/MW) of bus A to generation connected at bus B, \(P_A\) gives the output (MW) of the generator connected at bus A and \(\mu_{AB}\) gives the voltage sensitivity of bus A to generation connected at bus B. \(P_B\) gives the output (MW) of the generator connected at bus A. \(V_{Base}\) gives the voltage (kV) when there is no generation connected and \(V_{Max}\) gives the maximum permissible voltage. In the two generator case shown, the generators are operating above this limit and are required to curtail their output to bring the voltage back within its limit. The minimum energy method involves the curtailment of the generator that has the highest voltage sensitivity. The minimum distance curtails the generators such that the geometric distance between the current operating point and the constant voltage line is minimised. Thirdly, the proportional method curtails the generators according to their individual contribution to the voltage rise. Each of these methods is described in more detail below.

3.1 Minimum Energy Curtailment

This method entails curtailling the generator that contributes most to the voltage rise. Hence, the voltage can be restored to within the limits with the least amount of curtailed energy. This method is described by Equation (8), where the sum of the curtailed energy at all buses is minimised.

\[
\text{Min} \sum_{j=1}^{N} P_{\text{Curtail}} \quad (8)
\]

From Equation (8) the energy curtailed is minimised by selecting the maximum voltage sensitivity (\(\mu_{ij}\)) for the \(i\)th bus. The calculation of the curtailment is shown in Equation (9).

\[
P_{\text{Curtail}} = \frac{\Delta V_i}{\mu_{ij}} \quad i \forall N.
\]

(9)

Where \(P_{\text{Curtail}}\) (MWh) is the amount of energy that is curtailed at the \(j\)th bus. \(\Delta V_i\) gives the magnitude of the overvoltage at the \(i\)th bus. \(\mu_{ij}\) is the voltage sensitivity (kV/MW) of the \(i\)th bus to generation at the \(j\)th bus. In terms of voltage, the generator that has the highest voltage contribution to the \(i\)th bus will be generation connected at the \(i\)th bus (i.e. \(j = i\)). If there is no generation or not enough generation connected at the \(i\)th bus then the next highest value is used in Equation (9) or a combination thereof.

3.2 Minimum Distance Curtailment

This method minimises the distance from the initial operating point to the constant voltage line in Figure 1. This can be expressed mathematically by Equation (10) which minimises the sum of the squared cartesian coordinates of distance. This method curtails the generation on the basis of their respective voltage sensitivities. It is done independently of their own output levels at the time of curtailment.

\[
\text{Min} \sum_{j=1}^{N} P_{\text{Curtail}}^2 \quad (10)
\]

The generalised form of this method is given by Equation (11) which gives the total amount of curtailment \(P_{\text{Curtail}}\) required at the \(j\)th bus for a voltage constraint breach at the \(i\)th bus. Each generator is represented by its associated voltage sensitivity value.

\[
P_{\text{Curtail}} = \left(\frac{\Delta V_i}{\sum_{k=1}^{M} \sum_{p=1}^{N} \mu_{ikp}^2} \right) \quad i \forall N. \quad (11)
\]

The main drawback of the minimum distance curtailment method is that the amount of curtailment of each generator is calculated independent of the generator’s operating points. In a case where two generators have the same voltage sensitivity, but one of the generators has a power output four times greater than the other generator, the generators would be curtailed by the same amount even though one generator is responsible for 80% of the total voltage rise.

3.3 Proportional Curtailment

Another method of curtailment is to curtail each generator contributing to the voltage rise proportionally, i.e. if a generator contributes to 25% of the voltage rise then it takes 25% of the curtailment required.

\[
\text{Prop} = \frac{\mu_{ij} P_{ij}}{\Delta V_i} \quad i \forall N, \ j \forall N, \ l \forall M. \quad (12)
\]

Where \(\Delta V_i\) is again the magnitude of the overvoltage at the \(i\)th bus. Equation (12) is similar to Equation (5), with the difference being that the voltage rise is allocated between the generators using the voltage sensitivity (\(\mu\)) rather than the modified voltage sensitivity \(\beta\) employed in the minimum cost methodology. This value for \(\text{Prop}\) is then substituted into the previous expression for \(P_{\text{Curtail}}\) in Equation (6). In the case where the cost of curtailment of the generators is equal, the proportional method is equivalent to the minimum cost method.
4 Test System & Data

A sample section of network is modelled and simulated to compare the performance of the minimum cost method against the performance of the other methods. The network section analysed is a typical rural section of the Irish 38kV distribution network, shown in Figure 2. To assess the impact of the various curtailment methods, a DG scenario is analysed to assess the scope for optimisation of DG operation. Annual simulations are carried out to compare the performance of the various curtailment methods. The simulations consist of load flow calculations carried out for half hourly data. The data used in the simulations includes actual historical active and reactive power profiles for each of the energy resources and loads, along with data on frequency of N-1 outages and the sending voltage at the transmission station. The generation and load profiles were employed for the simulation were obtained from [23, 24]. The power factor of DG is taken as fixed, as is the case with DG in the UK and Ireland.

![38kV 7 bus radial distribution network diagram](image)

Figure 2: 38kV 7 bus radial distribution network diagram

The sensitivity of the bus voltages to increasing generation ($\mu_{ij}$) is determined for minimum load levels, all with a power factor of 0.95. It is evident from the network topology in Figure 2 that the voltage at some buses will be independent of generation at other buses. Table 1 shows the voltage sensitivity of each bus to power injections at all the buses under normal feeding conditions, rounded to four decimal places. The buses with the highest sensitivities and interdependence can be identified as buses C & D. The maximum allowable voltage is 1.1pu, the generation is curtailed such that the voltage is brought back to 1.095pu in the case of overvoltage.

<table>
<thead>
<tr>
<th>Bus</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0437</td>
<td>0.0272</td>
<td>0.154</td>
<td>0.118</td>
<td>0.0754</td>
<td>0.0415</td>
<td>0.105</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>0.0437</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0</td>
<td>0.154</td>
<td>0.1258</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>0</td>
<td>0.118</td>
<td>0.1354</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0754</td>
<td>0.2089</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>G</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1: Bus Voltage Sensitivities $\mu_{ij}$ (kV/MW)

5 Results & Discussion

Results are shown here evaluating the performance of the minimum cost curtailment method with direct comparison to the curtailment methods described in Section 3. The network shown in Figure 2 was simulated over a given year and the amount and cost of energy curtailed under each of the methods compared. For the case simulated a 12MW wind generator was connected at bus C and a 6.5MW biomass plant was chosen as the dispatchable generator and was connected at bus D. The wind and biomass generators have load factors of 0.35 and 0.85 respectively. The results are dependent on the sizing and siting of the generation. These allocations are chosen to give an illustrative example of the impact of each of the curtailment methods.

$CurtailReq$ is calculated to be 2.439MWh based on the historical minimum cost curtailment requirement and $FreeCurtail$ is calculated to be 2.051MWh based on the historical operating profile of the biomass plant. Both figures are based on constraint breaches at bus C. The cycling cost was estimated to be approximately €12 per MWh [19]. A number of rules were drawn up for the reschedule of the dispatchable generation. The rules only permit the generator to ramp up when the load is above a certain level, the wind generation is below a certain level and the generator is available. These rules ensure that when the generator ramps up its output, it does not result in new constraint breaches and that the reschedule is done in a realistic manner.

There are a number of practical issues that should be considered when examining potential curtailment methods. As mentioned in Section 2 the voltage sensitivities are dependent on the operating conditions and will vary over the year. Another issue to be considered is the impact of the market price. The market price will vary throughout the year and the impact of a variable market price is also assessed here. To this end, a number of scenarios are tested utilising averaged and real time data. All of the methods compared below use the same costing structure.
5.1 Variable Voltage Sensitivities

From Equation 2, it can be seen that there will be a variation in the bus voltage sensitivities dependent on the operating condition. The impact of these variations are assessed here by using sensitivity values that are recalculated throughout the year. The variance of the voltage sensitivity is dependent how the operating conditions vary at each bus throughout the year, hence, the amount and type of generation connected at each bus will have a significant impact on it. For this case the market price is set to its average value for the year. Table 2 shows the new amounts of curtailed energy under the different curtailment methods when the varying voltage sensitivities are employed.

Table 2: Curtailed Energy (MWh) with Variable Voltage Sensitivities

<table>
<thead>
<tr>
<th>V.V.S.</th>
<th>Bio</th>
<th>Wind</th>
<th>Total</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Energy</td>
<td>0</td>
<td>1,810.1</td>
<td>1,810.1</td>
<td>99,011</td>
</tr>
<tr>
<td>Min. Dist.</td>
<td>901.6</td>
<td>1,014.7</td>
<td>1,919.3</td>
<td>85,034</td>
</tr>
<tr>
<td>Proportional</td>
<td>981.8</td>
<td>943.6</td>
<td>1,925.3</td>
<td>83,767</td>
</tr>
<tr>
<td>Min. Cost</td>
<td>1,239.4</td>
<td>714.7</td>
<td>1,954.0</td>
<td>68,839</td>
</tr>
</tbody>
</table>

It can be seen that, in terms of energy, the minimum energy curtailment method has the least amount of energy curtailed, with the minimum cost method incurring the most curtailment. However, given that the energy curtailed under the minimum energy method is wind energy, it is the most expensive option. The other methods are cheaper because they employ the dispatchable generator, in this case biomass, to initially curtail the energy. The energy is not lost because the biomass generator regains this energy at a later stage. The biomass plant was redispached throughout the year and it was found that it could successfully accommodate its allotted level of curtailment, by ramping up its output whenever it was permitted, based on the rules described in Section 2.4. The redispach rules successfully ensured that no new overvoltages occurred when unit ramped up its output. The impact of the GMC can be seen in Table 2 with the cheaper biomass curtailment being employed much more in the minimum cost approach. This leads to a 24.4% reduction in cost over the minimum energy method for the case shown.

5.2 Variable Market Price

In a real market situation the price paid to generators varies throughout the day. Depending on when the dispatchable generator ramps up or down its output may affect the price they get paid for their energy. Market price data for each half hour of a given year was obtained from the transmission system operator in Ireland [23]. In this case, a variable market price is included. The voltage sensitivities are fixed to the values shown in Table 1.

Table 3 shows the impact of a variable market price on the cost of curtailment over the year. The market price is not taken account of in the three methods outlined in Section 3. However, in the minimum cost method, it is used in the calculation of the energy to be curtailed by the respective generators. As seen in Figure 3, the curtailment generally occurs in the early hours of the morning when the load is low, corresponding to times when the market price tends to be lower than the average market price previously employed. In addition, due the redispach rules in Section 2.4, the times when the biomass generation redispaches, is restricted to times of somewhat higher load, generally during the day. The market price tends to be higher than average at these times. Both of these factors combine to give the saving in cost that occurs when accurate pricing information is employed. These Tables shows that in this case the use of an average price leads to considerable overestimation of the cost of curtailment. In a case where the market price was higher at the times of curtailment than at times of redispach, the generator may experience an increase in cost through the use of accurate pricing.

Table 3: Curtailed Energy (MWh) with Variable Market Price

<table>
<thead>
<tr>
<th>V. V. S.</th>
<th>Bio</th>
<th>Wind</th>
<th>Total</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Energy</td>
<td>0</td>
<td>1,869.3</td>
<td>1,869.3</td>
<td>89,846</td>
</tr>
<tr>
<td>Min. Dist.</td>
<td>902.5</td>
<td>1,177.8</td>
<td>2,080.2</td>
<td>70,131</td>
</tr>
<tr>
<td>Proportional</td>
<td>1,083.3</td>
<td>1,039.2</td>
<td>2,122.5</td>
<td>66,222</td>
</tr>
<tr>
<td>Min. Cost</td>
<td>1,392.9</td>
<td>802.0</td>
<td>2,194.9</td>
<td>61,266</td>
</tr>
</tbody>
</table>

Figure 3: Comparison of Biomass Output Profiles

Figure 3 shows a comparison between the original biomass output profile and the redispach profile over a sample period of the year. The impact of the redispach can be seen with the redispach profile reducing its output when required and ramping up when possible to regain the curtailed energy.
meeting their own electricity demand and who can actually export power onto the network. There are a number of questions surrounding each of these capabilities, with each providing its own challenges to the planning and operation of the network. A comprehensive integrated approach which examines both the supply and demand side distributed resources in tandem will be the focus of our future work.

7 Conclusion

The advent of non-firm access to distribution network will require new methods of distribution operation. A minimum cost curtailment method for DG voltage management is proposed here that facilitates an increase in energy output from DG by avoiding the spilling of energy by non-dispatchable generation, which in turn reduces the cost of curtailment. The implementation of this method has been demonstrated for a full year simulation. Three existing curtailment methods, that have been traditionally used for congestion management on the transmission system, are applied here to voltage management on the distribution system for comparison with the minimum cost method. The new curtailment method minimises the cost of curtailment for the generators. It has been shown here that a significant saving is possible if the flexibility of the available dispatchable generation is utilised. Variable voltage sensitivities have been calculated and their impact has been demonstrated with a reduction in curtailed energy over the year when accurate values are used. The impact of online market prices has also been assessed with a reduction in the cost of curtailment occurring.

Acknowledgments

The authors gratefully acknowledge ESB Networks and Eirgrid for the data provided and their colleagues in the Electricity Research Centre, in particular Eleanor Denny, for their help with this work.

Appendix

Table 4: Test System Data

<table>
<thead>
<tr>
<th>Lines</th>
<th>R (Ω)</th>
<th>X (Ω)</th>
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</thead>
<tbody>
<tr>
<td>Tx-A</td>
<td>1.19</td>
<td>1.176</td>
</tr>
<tr>
<td>Tx-B</td>
<td>0.18</td>
<td>0.53</td>
</tr>
<tr>
<td>Tx-E</td>
<td>3.36</td>
<td>3.53</td>
</tr>
<tr>
<td>Tx-G</td>
<td>5.59</td>
<td>5.88</td>
</tr>
<tr>
<td>A-B</td>
<td>5.97</td>
<td>6.27</td>
</tr>
<tr>
<td>B-C</td>
<td>9.32</td>
<td>9.80</td>
</tr>
<tr>
<td>C-D</td>
<td>2.074</td>
<td>6.052</td>
</tr>
<tr>
<td>E-F</td>
<td>10.44</td>
<td>10.98</td>
</tr>
<tr>
<td>E-G</td>
<td>3.65</td>
<td>8.90</td>
</tr>
</tbody>
</table>
REFERENCES


