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# TABLE OF CONTENT

INTRODUCTION TO ANM4L ............................................................................................... 5

DOCUMENT INFORMATION ............................................................................................... 6

1 PURPOSE OF ANM ALGORITHMS ............................................................................. 7
  1.1 Voltage and current limits .......................................................................................... 7
  1.2 Controllable resources .............................................................................................. 7

2 ANM ALGORITHM FOR VOLTAGE LIMITATION ....................................................... 8
  2.1 Voltage Changes in Distribution Networks ............................................................... 8
  2.2 Control Strategies .................................................................................................... 9
  2.3 ANM Voltage Limitation Algorithm for Renewable Energy Sources ................. 11
  2.4 ANM Voltage Limitation Algorithm for Loads ....................................................... 12

3 ANM ALGORITHM FOR CONGESTION MANAGEMENT ......................................... 12
  3.1 Congestion in distribution networks ........................................................................ 12
  3.2 Control Strategies ................................................................................................... 13
  3.3 ANM Algorithm for Congestion Management ....................................................... 14
  3.4 ANM Algorithm for Reactive Power Management ............................................... 15

4 ALGORITHM SIMULATION AND TESTING .............................................................. 15
  4.1 Test System ............................................................................................................ 15
  4.2 Simulation Environment .......................................................................................... 17
  4.3 ANM Voltage Limitation Algorithm Performance ............................................... 17
  4.4 ANM Congestion Management Algorithm Performance ..................................... 21
  4.5 ANM Reactive Power Management Algorithm Performance .............................. 23

5 FURTHER DEVELOPMENT OF ANM ALGORITHMS ........................................... 24
  5.1 Algorithm Data Availability and Financial Solutions ......................................... 25
  5.2 Combining ANM Algorithms ............................................................................... 25

6 CONCLUSIONS ......................................................................................................... 30

7 REFERENCES ............................................................................................................ 31
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Co-creating with partners that help to understand the needs of relevant stakeholders, we team up with intermediaries to provide an innovation eco-system supporting consortia for research, innovation, technical development, piloting and demonstration activities. These co-operations pave the way towards implementation in real-life environments and market introduction.

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INTRODUCTION TO ANM4L

The ANM4L (Active network management for all) project, anm4l.eu, will develop solutions to enable integration of renewables with the agility required from developments in demand and production.

Alternatives to traditional network expansion are needed to ensure sustainable development of the power grids. New technologies, methods, and markets are emerging to provide increased flexibility in consumption, generation, and power transfer capacity.

ANM4L aims at demonstrating innovative active network management (ANM) solutions to increase integration of renewable energy sources (RES) in electricity distribution systems.

ANM solutions will consider management of active and reactive power to avoid overload situations, maintain voltages within limits, minimize the need of RES curtailment, and enable further RES uptake even above the theoretical design limit of the electricity network.

Core research and development activities include development of:

- Active network management methods for local energy systems.
- Business models to provide decision support for market players.
- An integrated toolbox to support the planning and operation of the distribution system.

The toolbox, methods and business models for ANM will be demonstrated in Sweden and Hungary. The project will also prepare solutions and recommendations for replication in other local and regional energy systems.

The ANM4L project is an international cooperation with a consortium consisting of partners in Sweden, Germany and Hungary:

- RISE Research Institutes of Sweden (coordinator)
- Municipality of Borgholm
- Lumenaza GmbH
- Lund University
- RWTH Aachen University
- E.ON Energidistribution AB
- E.ON Észak-dunántúli Áramhálózati Zrt
- E.ON Group Innovation GmbH
DOCUMENT INFORMATION

This deliverable is part of Work package 3 (WP3): ANM methods for congestion and voltage management.

The main objective of WP3 is to develop ANM algorithms and to integrate them in operational planning and investment planning.

This document outlines the developed ANM algorithms.
1 PURPOSE OF ANM ALGORITHMS

Present distribution networks are generally designed to supply consumers with electricity. The Active Network Management control algorithms in this work are developed with the aim to manage two fundamental issues related to the growing presence of renewable energy sources in radial distribution networks, namely excessive voltage levels and excessive current usually called congestion. To ensure operation within network limits for voltage and current, the algorithms rely on flexibility resources which allows for control of both active (P) and reactive (Q) power. Details and characteristics of such resources are treated in [1].

1.1 Voltage and current limits

Voltages in electricity networks change more or less with variations in generation and consumption. In public distribution systems in Europe, the standard EN 50160 formulates requirements on the voltage supplied to customers at LV (Low Voltage <1000 V) and MV (Medium Voltage 1-35 kV) level. For slow variations captured by 10 min averages, the deviations from the nominal value should be within ±10% for 95% of a week. This serves as a minimum requirement, and many distribution system operators (DSOs) aim at keeping the voltage magnitude within a narrower range.

Current in all sorts of electric equipment contribute to heating of the equipment through Joule losses. It is obvious that excessive currents cause immediate damage while low currents have no impact at all. Between these extremes, long term exposure to high currents causes aging of insulation material and reduces the lifetime of the equipment. For all equipment, manufacturers define a rated current, which is the maximum current that can be allowed continuously while maintaining normal lifetime. For cables, the heating is the main concern, but for overhead lines the elongation caused by the heating is more important as insufficient clearance below a line is a matter of electrical safety. For transformers, the rating is normally expressed in MVA; which is a product of rated current and voltage.

1.2 Controllable resources

Both active and reactive power contribute to voltage deviations and they both contribute to congestion. This means that to mitigate these problems it is of interest to control both active and reactive power. The extent to which this is practical differs between different devices and in this work the following assumptions are made:

**Photovoltaic (PV) units** always use an inverter to inject active power into the grid. Using an external signal, this active power can be reduced – at most down to zero. The reactive power is specified by the grid code but is considered available for control. While the control of active and reactive power is independent, the active and reactive current components are parts of the total current, which is limited by the current rating of the inverter. Both active and reactive power are considered continuously variable; no discrete values are considered.

**Wind turbine generators** today use an inverter-based grid interface like the PV units. In terms of control, they are treated in the same way.
Consumption mainly draws active power but may also draw an associated amount of reactive power. In this work, only the active power is assumed continuously controllable.

Battery energy storage are inverter-based and can be considered a variation of PV, with variable reactive power but with the difference that active power can be reversed.

2 ANM ALGORITHM FOR VOLTAGE LIMITATION

Even though the ANM algorithms for voltage limitation and congestion management are similar, the two issues are different, and they are here treated separately. This chapter explains the issue of overvoltage, discusses control strategy aspects that have been considered and describes three versions of the voltage limitation algorithm. In the first version reactive power is controlled using feedback, in the second using constant power factor and in the third it is excluded.

2.1 Voltage Changes in Distribution Networks

Traditionally, distribution networks are built to maintain sufficiently high voltage at maximum load. In this case, voltage is highest at the feeding transformer and decreases along the feeder. For a single load drawing active power $P$ and reactive power $Q$ at the end of the feeder, the decrease $\Delta V$ is approximately:

$$\Delta V \approx \frac{RP}{V} + \frac{XQ}{V},$$

where $R$ and $X$ are series resistance and reactance respectively of the line between transformer and feeder end. The same expression applies in the opposite case with a single generating unit at the feeder end, injecting $P$ and $Q$. Here $\Delta V$ is an increase in voltage, see Figure 1.

Figure 1. In an unloaded radial distribution feeder, adding generation of active power $P$ raises the voltage by $\Delta V$. Here $P$ is added at the midpoint (green) or at the end of the feeder (blue). Consumption can be considered as negative generation.

Intermediate points on the feeder have $R$ and $X$ in proportion to the distance from the feeder head. At the midpoint of the feeder, $R$ and $X$ thus take half the end point...
values. In other words, the voltage rise at the midpoint caused by e.g. a certain PV generation $P$ is only half what the same $P$ would cause at the feeder end, see green and blue cases in Figure 1. The same expression for $\Delta V$ applies for countermeasures in terms of active and reactive power $P$ and $Q$. These also have more impact the greater $R$ and $X$ are. To summarize, high voltage is most likely to happen at the end of the feeder, and this is also where countermeasures are most effective.

To reduce the voltage at the end of the feeder the flow of active power towards the transformer can be reduced. It can be done by reducing the net $P$ injected by either curtailing renewable energy sources or by increasing power consumption and battery charging rates. An alternative to adjusting active power towards the transformer is to increase the reactive power absorption at the feeder end, which is straightforward with connected converter-interfaced generation units.

As can be deduced from the equation above, the efficacy of each method is determined by the $X/R$ ratio of the line impedance: Relatively large resistance $R$ favours active power control while large reactance $X$ suggests the use of reactive power control. For a given voltage level, the $X/R$ ratio is determined by the line or cable type and cross-section area. European distribution networks exhibit large variations in $X/R$ ratios, ranging from 0.1-1.4 in low voltage (0.4 kV) networks to 0.5-2.5 in medium voltage (20 kV) networks [2].

The choice of control method is also a matter of costs. While curtailment of renewable energy sources in many cases is effective to mitigate overvoltage, it is also associated with some loss in revenue for the producer, see [1]. It might be preferable to instead utilise reactive power to a larger extent, as its use is not related to any significant costs, see [1]. At the same time, the availability of reactive power is largely restricted by the active power production which means achieving large $P$ production and large $Q$ consumption simultaneously gives a high inverter current. It is therefore possible only through oversizing the converter, normally a costly investment. An alternative way to reduce the feeder voltage level without curtailing renewable power production is to increase the consumption of active power using flexible loads or initiating charging of battery energy storage devices. While transformer tap changers are the most important means to adjust voltage today, their control mainly focuses on avoiding undervoltage. This is left unaffected and tap changers are excluded in this report.

### 2.2 Control Strategies

A wide range of voltage limitation control strategies involving active and/or reactive power have been proposed in literature (some examples can be found in [3], [4], [5]). Other key aspects that are typically considered are:

- Level of coordination and communication between controlled flexibility resources,
- availability of real-time measurements or reliance on state estimation, and
- complexity of network integration and implementation.
As explained, the voltage problem is local in the sense that where voltage deviates most, is also where a change of power gives the largest voltage change. Purely local control strategies are thus an attractive and straight-forward approach, which also allows for simple and cost-effective “plug-and-play” implementation. The drawback is that the lack of coordination – through real-time communication or manual parameter adjustments – makes any optimization of control actions unrealistic and consequently the use of available resources becomes less efficient.

While optimization techniques can be used to maximize grid utilisation, these practically imply communication and coordination between assets. The added operation complexity for the implementation of an optimal control scheme raises the threshold for when such a solution can be financially and technologically motivated. In practice, integration of renewable energy sources is a continuous process. When penetration of wind power or solar electricity reach high levels, the usual margins in grid capacity motivated by uncertainty in power flows cannot be upheld anymore. The major contribution from ANM is then to first extend the range of safe operation – effectively exploiting the margins by permitting larger power flows. The shift from requiring margins to safely using the margins can best be started with a simple solution that focuses on not exceeding limits.

Another reason for starting simple is that the development of RES technology is impacted by several factors outside the control of distribution system operators, complicating forecasting of future voltage flexibility needs. Local “plug-and-play” solutions have the advantage that they can develop together with new distributed generator units. This view is reflected by the popularity of local droop-like Volt-Var or Volt-Watt control schemes in various grid codes [6], [7].

The development of the voltage limitation algorithms in the ANM4L project has been carried out with the intention that the control schemes should be:

- easily deployable,
- scalable, and
- adaptable to different network topologies.

Thus, local solutions have been favoured. Another important objective has been to go beyond static Volt-Var or Volt-Watt schemes to improve utilisation of flexibility resources. The development approach can be summarised by four core principles, namely

- Local control with local voltage measurements.
- Increasing grid utilisation through safe operation up to voltage limits.
- At any time, use engage the flexibility resources that offer the most effectiveness at least cost. Typically reactive power as the first control action, and curtailment of generation or increase of active power consumption when reactive power is insufficient.
2.3 ANM Voltage Limitation Algorithm for Renewable Energy Sources

The algorithms for local voltage limitation control are well suited for implementation in RES inverter control software. This would yield a plug-and-play solution that makes it impossible to exceed the maximum voltage limit. This could be specified by a connection requirement, just like existing local solutions like fixed power factor or the Volt-Var or Volt-Watt control schemes mentioned above.

The ANM voltage limitation algorithm is based on a PI controller, see Figure 2, for each individual resource. While PI controllers traditionally act to bring the measured quantity to a reference value, the controller here only acts when the measured quantity is above the reference value.

![Figure 2. Q+P local voltage limitation control block diagram.](image)

This is achieved by the asymmetric output limits $Q_{\text{min}}=-Q_{\text{max}}$ and 0 of the PI controller that permits the controller to only reduce voltage. This is done by ordering the generator to draw reactive power from the grid. If $-Q_{\text{max}}$ is reached without voltage being returned below $V_{\text{max}}$, the controller starts to curtail the generation by reducing the active generation by $\Delta P$. The converter current is limited to the rated current, corresponding to the MVA rating $S_{\text{rated}}$ of the converter. Due to the higher value of active power, it is given priority over reactive power that is limited by the remaining capacity.

The above algorithm remains passive until the voltage is above $V_{\text{max}}$. In networks where the algorithm is used in several units along a feeder, this is an advantage as long as voltage is acceptable everywhere and as long as the reactive power does not saturate anywhere. But when reactive power capability saturates at one point, curtailment starts there before all other reactive power resources have been depleted which is undesirable.

A better strategy draws reactive power before the voltage limit has been reached. One option for this is to draw reactive power in proportion to the generated active power, yielding constant power factor $\cos \phi$. This makes great sense as selecting the power factor that gives $Q/P = -R/X$ cancels the voltage rise completely, see the expression for $\Delta V$ above. But as $R$ is usually greater than $X$ in LV networks, it means that more reactive power should be drawn than active power should be delivered. This implies a very large converter and also requires knowledge of $R$ and $X$. A reasonable choice is a more modest $Q/P=0.5$ corresponding to a power factor of 0.9.
The voltage limitation algorithm using constant power factor is seen in Figure 3. In this case reactive power is drawn in proportion to active power and when voltage reaches $V_{\text{max}}$ it starts curtailing active power. This gives more room for active power and the power factor could go even lower, but this is not implemented yet.

![Figure 3. Constant power factor local voltage limitation control block diagram](image)

### 2.4 ANM Voltage Limitation Algorithm for Loads

If only active power can be controlled, the scheme is simplified, see Figure 4. Note that generation and consumption have opposite effect on voltage, so in case of overvoltage the algorithm will increase load.

![Figure 4. Active power load local voltage limitation control block diagram](image)

### 3 ANM ALGORITHM FOR CONGESTION MANAGEMENT

This chapter explains the issue of congestion management, discusses control strategy aspects which have been considered and describes the congestion managements algorithm. This algorithm can easily be modified to control of reactive power to limit only reactive power flow, which is also described.

#### 3.1 Congestion in distribution networks

Congestion in distribution networks occur when too much power or – equivalently – current is sent through a transformer or line, see Figure 5. The transformer or line is then overloaded leading to excessive heating and in the case of overhead lines to insufficient clearance between line and ground. The rated line currents and transformer MVA ratings are usually selected to provide margin to maximum consumption, but the network situation regarding consumption and production may change considerably during their lifetime. An important issue in deciding maximum consumption is if the peak of individual consumers coincide and yield a relatively high total peak demand, or if they exhibit diversity leading to lower total peak demand. Generation behaves very differently, and PV within a local area mainly deliver their peak generation at the same time.
Figure 5. In an unloaded radial distribution feeder, adding generation of active power $P$ raises the transformer loading, here leading to congestion or overload at the dashed line (at transformer or line). The transformer and line loading rises practically regardless of the location of the generation. Consumption can be considered as negative generation.

If the transformer in Figure 5 is congested, the countermeasure is to reduce the flow of active or reactive power through the transformer. This can be done at other nodes, which requires communication of some sort between point of measurement and point(s) of control. Local control is not possible as is the case for voltage management.

If network losses are disregarded the transformer load is simply the sum of all consumption and generation connected to the secondary side feeders. This means that the contribution from the individual nodes does not depend on where on the feeder they are located. The same applies to where control actions are taken – this can be anywhere on the feeder. The line parameters $R$ and $X$ determine if the network losses can actually be disregarded.

If network losses cannot be neglected, location does matter. The nodes can then be ranked based on a sensitivity that is implicitly used in power flow calculations. The branch sensitivity or Power Transfer Distribution Factor $PTDF_{ij}$ relates the change in generation or consumption at node $i$ to the change in power flow through branch $j$:

$$PTDF_{ij} = \frac{\Delta S_{\text{branch-j}}}{\Delta S_{\text{node-i}}}$$

Calculation of the branch sensitivity requires all line parameters such as $R$ and $X$.

3.2 Control Strategies

A control strategy for congestion management cannot be local like for voltage management. Apart from that, the choice control strategy must consider the same aspects:

- Level of coordination and communication between controlled network resources,
- availability of real-time measurements or reliance on state estimation, and
- complexity of network integration and implementation.
Again the main trade-off is roughly speaking between optimality and simplicity, which in this case means easily deployable, scalable and adaptable to different networks. For congestion management, the core principles are three:

- Increasing grid utilisation through safe operation up to current limits.
- At any time, engage the flexibility resources that offer the most effectiveness at least cost. Typically use reactive power first if relevant, then increase active power consumption and finally curtail active generation.

### 3.3 ANM Algorithm for Congestion Management

The ANM congestion management algorithm is based on a PI controller, see Figure 6. It has two similarities with the ANM voltage limitation algorithm:

1. It assumes excessive generation on the feeder, and
2. it acts first when the monitored quantity has exceeded its maximum value.

**Figure 6. Block diagram of central control of active power consumption and generation for congestion management. Flexibility dispatch decides in which order flexible resources should be used.**

The PI controller has asymmetric output limits $-P_{\text{max}}$ and 0. When $I_{\text{meas}}$ exceeds $I_{\text{max}}$ the controller asks for either load increase or generation curtailment. The selected control action is determined by the flexibility dispatch. This can be seen as an ordered dispatch list, where the flexibility of each resource is used completely before the next is used. The list can be ordered in many ways, but three options are particularly relevant:

- Order dispatch list by monetary cost for certain volume such as 1 kWh, see [1]. If two resources have the same cost, they are used simultaneously.
- Order dispatch list by technical efficiency of the resources using branch sensitivities. Cost and efficiency can also be combined.
- Order dispatch list by a combination of monetary cost and technical efficiency, yielding monetary cost for certain technical impact.
As the PI controller raises the control effort, the flexibility dispatch thus allocates the flexibility resources that are most efficient – in terms of cost, impact or a combination. This is very similar to the price curve use for marginal pricing, which for any required volume allocates the generation that has the least cost.

### 3.4 ANM Algorithm for Reactive Power Management

Congestion management is a matter of limiting a flow. This limit can actually be zero, which is relevant for exchange or reactive power across a TSO/DSO interface. An ANM algorithm for such reactive power management results from changing active power to reactive power in the congestion management algorithm, see Figure 7.

![Figure 7. Block diagram of central control of converters for reactive power management. Flexibility dispatch decides in which order flexible resources should be used.](image)

The idea is that the reactive power capability of e.g. wind turbine generators replace installation of reactive power resources such as shunt capacitors or shunt reactors. The flexibility dispatch is carried out like for the congestion management case.

### 4 ALGORITHM SIMULATION AND TESTING

The developed algorithms are intended for use in distribution networks, regardless of voltage level or the rated power of flexibility resources. In this section, a medium voltage test network with wind power generation is used to demonstrate the functionality of the algorithms described in Sections 2 and 3. The developed methodology is equally valid in other configurations, such as for a low voltage network with PV units.

#### 4.1 Test System

The algorithms have been tested with the CIGRE benchmark MV network [2]. The 20 kV network consists of two feeders, each connected to an overlying 110 kV network through a 25 MVA transformer. There are 14 MV buses in total, with 13 of them being load buses. To demonstrate the performance of the ANM algorithms, the smaller benchmark feeder was modified to include distributed generation in form of two small wind power plants. The updated feeder is shown in Figure 8.
Figure 8. Modified feeder in CIGRE MV benchmark network with wind farms at buses 2 and 3.

The loads at buses 1-3 represent a combination of aggregated residential, commercial, and industrial loads. The load at bus 1 is close to 40 times greater than the combined loads of buses 2 and 3, as it represents aggregated loads from parallel feeders not explicitly modeled in the benchmark network. The benchmark daily load profiles have 15 min resolution and are shown in Figure 9. The corresponding daily generation profile for the wind farms is shown in Figure 10.

Figure 9. Daily load profiles. Residential load in blue, and industrial/commercial load in dotted red.

Figure 10. Daily wind generation profile.

The MV buses are connected through long overhead lines (OHLs), mimicking the characteristics of a rural network. The total rated generation capacity is 9 MW, and the ratio between generator rating and maximum load is roughly 75:1 at bus 2 and 10:1 at bus 3. This means the voltage profile is highly dependent on the wind generation pattern. The ANM algorithm performance was therefore specifically tested in simulations with the daily profile at midday, where the wind generation is close to 100 % of the rated active power, creating a need for control actions. It is assumed, based on European grid codes that the wind power converters can provide a power factor, \( \cos(\varphi) \leq 0.95 \) leading/lagging at full power production [6].
At 12:00, 3 MW of wind power is generated at bus 2, while at bus 3 the wind power plant injects 6 MW. This results in overvoltage and the end of the feeder, as well as overloading of the line between buses 1 and 2. In the following sections, the two problems will be treated separately, and the related reactive power management algorithm will then be discussed.

4.2 Simulation Environment

The modified CIGRE benchmark network was implemented in DigSILENT PowerFactory, while the ANM algorithms were stored in separate Python scripts. The algorithms were deployed for use in balanced three-phase networks. To accommodate time-series input data of different resolutions, a linear interpolation method was also implemented. The relative generation profile was then applied to the added wind power plants. All simulations were based on iterative power flow calculations with stepwise data exchange between the simulation software and the active ANM algorithm. Important parameters in this aspect are the sampling interval and the rate of change of active and reactive power output. They should be selected such that sufficient control performance can be achieved while a time-scale separation to inverter dynamics is maintained. The sampling interval in the following example was set to 10 seconds, and it was assumed that steady state is achieved after a set point change well within that time frame for all participating flexibility resources. The maximum rate of change in this case was set to +/- 10 % per 10 seconds time step.

4.3 ANM Voltage Limitation Algorithm Performance

Given the ratio between the present generation and demand in the benchmark feeder, it is natural to first look at controlling the wind power plants for voltage limitation purposes. The upper voltage limit was set to 1.05 p.u. and the ANM algorithms described in section 2.3 were used in simulations of a high-production mid-day scenario at 12:00. Two different constant power factors were used to visualise the interaction between changes in reactive power and curtailment. The resulting feeder voltage profiles are shown in Figure 11. It is evident that all algorithm variants can limit the voltage at the end of the feeder. The voltage at the beginning of the feeder is also lowered in all cases. Particularly when a generous power factor is used special attention must be paid to this issue to avoid undervoltage problems at parallel feeders without generation.
Figure 11. CIGRE MV feeder voltage profile at 12:00. Maximum allowed grid voltage is 1.05 p.u. (dotted black line)

Figure 12 shows the total generated power for the different cases. The output from the wind power plant at bus 2 is unaffected by any action by the ANM algorithms, as the steady state voltage at bus 2 is below the limit. The sequential Q+P algorithm is assumed to be used with inverters that provide a power factor 0.90 at rated active power, and the algorithm was allowed to freely change power factor to maximise the inverter reactive power capabilities when the active power output was lower than the rated power. As seen in Figure 12, neither the Q+P algorithm, nor the constant power factor algorithm, in the case when the power factor is set to 0.90, affect the active power injections at bus 3. When the constant power factor 0.95 is used, curtailment is needed to reduce the voltage. This results in a reduction of the power at bus with roughly a sixth of the potential output.

Figure 12. Generated power from wind turbine generators in the simulated benchmark system at 12:00.
From Figure 13 a major difference between the sequential ANM algorithm and the constant power factor algorithms can be distinguished. The Q+P algorithm allows for changes in reactive power only when the voltage limit is violated, which leads to a stronger reaction at bus 3. Eventually it leads to a steady state where reactive power is only absorbed at the end of the feeder. The resulting power factor is slightly smaller than 0.90 since the active power output is just below the rated power at midday in the studied scenario.

With a constant power factor reactive power is instead absorbed at both bus 2 and 3. Given a sufficiently generous power factor no curtailment is necessary, as seen when cos(\(\phi\)) = 0.90. However, with a smaller amount of reactive power available, curtailment is still needed to limit the voltage.

A significant amount of reactive power is absorbed when the power factor is 0.90. When compared to the sequential algorithm simulation, the difference in active power output is relatively small compared to the reactive power changes. This shows the impact of the X/R ratio on P and Q efficacy and the dependence of voltage change sensitivity on the location of change of P or Q. One can conclude that given large converter and power transfer capacity margins, an ANM algorithm relying on a constant power factor with gradual curtailment as a secondary control action, would provide means to allow a large share of distributed generation, while maintaining high network utilisation. However, increasing network complexity and stricter operational constraints would require a smaller and more efficient use of reactive power resources. Given that the sequential Q+P algorithm does not increase reactive power consumption during normal operation, and when a constraint violation occurs changes reactive power set points only at affected locations, it might then be preferrable to use.

![Figure 13. Absorbed reactive power from wind turbine generators in the simulated benchmark system at 12:00.](image)
To exemplify the dynamic behaviour of the ANM solution, resulting bus voltages from a simulation with the Q+P algorithm are shown in Figure 14. The appearance of a small voltage overshoot in the morning of the simulated day highlights the need for a closer inspection of the PI controller gain settings in the implementation phase so that the desired dynamical behaviour is attained even during fast changes in power output (in this case corresponding to a sharp increase in wind speed between 8:00 and 9:00, see Figure 10).

Figure 14. Simulated bus voltage changes from ANM Q+P control in the benchmark system.

Given the relatively small load demand at buses 2 and 3, the impact on voltage by an increase in the active power consumption, even a significant one, is negligible when the two wind power plants were present. To demonstrate the functionality of the ANM algorithm for flexible loads, the restrictions on the ANM algorithm increasing the load demand above the benchmark maximum were removed. Without the constraint present, it is possible to study the total demand needed to maintain the voltage within the network limits during the previously discussed mid-day conditions. One can also examine the interaction between the ANM load algorithm and the ANM wind power algorithms. The results from some simulated algorithms combinations are shown in Figure 15.
Figure 15 shows that local consumption would have to be increased tenfold at bus 3 to limit the voltage if no actions are taken by the wind power plant controllers. Again, the local nature of the algorithm favours control actions at the end of the feeder, meaning the small load at bus 2 will not increase. It is evident that the use of flexible loads to some extent can reduce the curtailment of wind power, as seen when a constant power factor algorithm is applied. However, the lack of coordination between the flexible load and generation resources prevents the operator from prioritising specific control actions. Here, it would be desirable to increase consumption before considering curtailment. If the proper communications infrastructure is in place, this problem can simply be solved through a flexibility dispatch, similar to the approach taken with the ANM congestion management algorithm.

While the relative rise in load demand seen in Figure 15 is significant, in absolute numbers the increase is not as extreme. In a low voltage feeder where the installed distributed generation capacity is lower, EV chargers or smaller battery systems can be suitable for use as flexible loads to create a sufficient increase in demand.

4.4 ANM Congestion Management Algorithm Performance

The large power production at noon does not only affect the network voltage, but it also poses a network capacity challenge. As seen in Figure 16, the loading of the line exceeds the rated current on two occasions during the day if no control actions are taken. The overloading of the line notably coincides with large wind generation (see Figure 10). Again, this makes using an ANM algorithm to control the wind power plants the natural choice, particularly if other flexibility resources are scarce.
Figure 16. Simulated loading of the overhead line between buses 1 and 2 in the benchmark system.

The ANM algorithm for congestion management activates resources via the flexibility dispatch, which allows for different prioritisation schemes. Two options that have been tested are using power transfer distribution factors (PTDF) and equal sharing of the control action. While dispatch based on PTDF minimizes the total control effort, it shifts the control actions to the same resources due to the network topology. If variations in PTDFs between different resources are small, a more evenly distributed control effort might be desired. The results from a simulated congestion management scenario without ANM and with ANM using two different flexibility dispatches are shown in Figure 17. Note that no attention is paid to overvoltage issues in this example. In the first ANM case, PTDFs show that the wind plant at bus 2 has greater impact on the congestion than the one at bus 3. The difference is however very little and in the second ANM case, the curtailment is shared equally among the two wind plants.

Figure 17. Simulation of benchmark system at 12:00 with ANM congestion management. Resulting line currents (left figure), with rated line current is 195 A, and corresponding active power injections (right figure).

Both alternatives can easily be modified. Instead of sharing the control effort equally in absolute numbers between the flexibility resources, equal relative changes in active powers can be used. For the simulated scenario, this would mean that both wind plants are instructed to curtail the same percentage from their output. The use of PTDF can be complemented by additional constraints to distribute the control
effort more evenly. The algorithm modified to limit the curtailment to maximum absolute number or be proportional to the output. It would force both wind power plants to contribute to the congestion management. In Figure 18 below, the dynamics of the PTDF-based ANM algorithm is exemplified.

Figure 18. Simulated line current change from ANM congestion management algorithm in the benchmark system. Flexibility dispatch is based on PTDF, which affects wind power generation only at Bus 2 so that the two curves for Bus 3 coincide.

Flexible loads can also be included in the congestion management algorithm, which provides an opportunity to reduce curtailment. It adds a second step to the control action prioritisation scheme, meaning control efforts would not only be distributed based on bus location but also on asset type.

4.5 ANM Reactive Power Management Algorithm Performance

As shown in section 3.4, the congestion management algorithm can be converted to manage reactive power flows by changing the controller input signals. In the example in Figure 19, the reactive exchange between the radial feeder and the overlying HV network is measured. At 08:00 in the simulated day the ANM algorithm is activated and quickly brings the reactive power flow from the HV network to zero from a starting point of significant magnitude. During normal operation, the feeder reactive power demand is driven by the large load at bus 1. In this example, the flow of reactive power is measured at the MV-side of the HV/MV transformer and for simplicity the control effort is divided equally between the wind plants.
Using a local reactive power dispatch reduces the loading of the transformer and aids the DSO in reducing costs associated with excessive reactive power exchange with the HV network if such limits exist. It is important to note that extensive use of the reactive power management algorithm might have a negative impact on voltage limitation and congestion management efforts. As it is essential from a safety and reliability perspective to successfully achieve the latter two objectives, they should be prioritised over reactive power management in case of conflicting actions.

5 FURTHER DEVELOPMENT OF ANM ALGORITHMS

Some additional topics related to the presented ANM solutions are briefly discussed in this section. The first is on data needed from algorithms to show the actions of participating resources. The data could be used by the DSO to evaluate the performance of ANM algorithms in operation, and for short- and long-term network planning purposes. The information about actions taken by flexible resources could also form the foundation for a financial reimbursement solution for participants in an actively managed network. The last aspect is not the focus of this report, but nevertheless an important factor in a real-world implementation, and closely linked to the structure of the algorithm in use.

The second topic is concerned with the interaction between different ANM algorithms. In the previous sections, voltage and current constraints have been treated separately, while in actual network planning and operations they must be considered simultaneously. In section 5.2 a first step of the algorithm merging process is exemplified in which control of active power output from PV units in a low voltage network is coordinated.
5.1 Algorithm Data Availability and Financial Solutions

Gaining access to flexibility resources, see [1], is vital for a functional ANM solution. Asset owners might be required to provide certain network services according to grid codes or a legal framework. An alternative is a market-based solution where flexibility can be traded [1], thus giving asset owners a financial incentive to actively participate in network management. In any case, it must be possible to extract information about how that the ANM algorithms actually utilise each resource. If flexibility is required by grid codes, this is compliance monitoring, while in the market case it is part of the financial settlement.

The ANM algorithms are designed to operate in near real-time and set points are updated at every sampling instance. The resolution of the data that can be used in a market-based system will depend on the ANM algorithm parameters. As the asset controllers always provide $\Delta P$ and/or $\Delta Q$, both the duration and magnitude of control actions can easily be recorded. If the time it takes to reach steady state after a set point change is negligible with respect to the sampling interval, the utilised energy from a flexible resource that is utilised by ANM can then be calculated as

$$E_{\text{EnergyFlex Resource}} = \sum_{i=1}^{n} |\Delta P_i| \cdot t_s,$$

where $n$ is the number of data samples, $|\Delta P_i|$ is the magnitude of the ANM control signal at sampling time instance $i$, and $t_s$ is the sampling time. A similar approach is possible when examining the injection or absorption of reactive power over time. If the dynamic behaviour is to be studied in closer detail, the product in the equation above can be replaced by a function modelling the dynamics between two samples $\Delta P_j$ and $\Delta P_{j+1}$.

Lastly, it is worth noticing the difference between a local ANM controller and centralised ANM control in terms of potential market solutions. Without coordination, the distribution of control actions is largely predetermined as the choice of algorithm and associated parameter settings play a large role. A centralised system on the other hand allows the operator to choose from multiple control actions, meaning several control objectives are available through manipulation of the flexibility dispatch list. Objectives include minimization of curtailment, power transfer losses, costs, or the environmental impact, and can be achieved through prioritization based on asset characteristics and location in relation to the network topology and specific grid constraints.

5.2 Combining ANM Algorithms

Network operation within both voltage and current limits is normally a requirement, with or without an ANM solution present. The algorithms described in previous sections have been developed to manage issues related to separate constraints, which does not necessarily mean they are able to run in parallel. If multiple constraints are occurring simultaneously and the responses from different ANM controllers are conflicting, there is a risk that the network will be exposed to unfavourable or even harmful operating conditions. To avoid such a scenario it is
necessary to, when combining the discussed ANM algorithms in operation, establish a protocol for constraint prioritisation.

By prioritising the strictest constraint, the ANM algorithms can simultaneously manage both voltage and congestion using the same active power flexibility resources. This is illustrated in the example below, where curtailing the generation that causes overvoltage and congestion works to solve both problems. Adding reactive power capabilities to the combined ANM algorithm increases the control complexity and will be considered in the continued work within the ANM4L project. Using reactive power to reduce voltage might counteract congestion management efforts, and lead to an increase in curtailment or flexible load demand. Similarly, managing the reactive power balance in a transformer using reactive power from wind turbine generators, may cause voltage issues at them.

The outcome of how these issues combine depends on the ANM algorithms but ultimately on the physical properties of the network with connected loads and generators. Considering line impedance, congestion is related mainly to the cross-sectional area of line conductors, while voltage issues depend on that too, but also on the length of the same conductors. Considering an increasing amount of local generation, a short feeder is therefore likely to exhibit congestion issues before voltage issues, while the opposite holds for a long feeder. When voltage problems occur on the short feeder, managing them with reactive power is not possible as congestion excludes increased currents.

A combined ANM algorithm for voltage limitation and congestion management using only generator curtailment is shown in Figure 20. The centralised congestion management algorithm has been superimposed with the curtailment part of the local sequential voltage limitation algorithm for renewable energy sources to create the combined algorithm. In this case curtailment can be used to mitigate overvoltage as well as overloading of network components. Each local controller has an additional control signal selection that prioritises the control action – required by voltage management and congestion management respectively – that gives the largest $\Delta P$. This corresponds to the strictest constraint, or in other words the minimal curtailment needed to both prevent overvoltage and give the required individual contribution to the coordinated congestion management.

Initial simulations of combined ANM algorithm have been performed on a low voltage test feeder, see Figure 21 [8]. The algorithm was deployed to simultaneously prevent overvoltage at the end of the feeder and overloading of the MV/LV transformer.
Figure 20. Combined voltage limitation and congestion management ANM algorithm block diagram. Note that there is one Local controller at each PV installation, but only one Central controller.

The test feeder consists of five households with identical 30 kW roof-top PV installations. A simplified daily generation profile with interpolated hourly values was used, and it was assumed that the load demand is negligible in comparison to the generated power during the time of study.

Figure 21. 5-bus LV test network. The five households have identical 30 kW roof-top PV installations.

The feeder model was implemented in SIMULINK with the SimScape Electrical toolbox. The MV Network was represented by a Thévenin equivalent circuit, and a dynamic ANM controller model was used for simulations. A flexibility dispatch where resources were given a random ranking was included for congestion management. The dispatch list, shown in Table 1, also include the maximum curtailment level that each unit is willing to provide.
Results from simulations of the LV test feeder, shown in Figure 22, shows the capability of ANM algorithm to limit the voltage at bus 5 to the maximum allowed 1.1 p.u. during the PV peak production hours at mid-day. The algorithm can simultaneously control the current through the MV/LV transformer, as seen in Figure 23.

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<th>Flexibility dispatch</th>
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<td>Ranking</td>
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Figure 22. Simulation of LV feeder bus voltages without ANM (left) and with combined ANM algorithm (right).

Figure 23. Simulation of LV feeder currents without ANM (left) and with combined ANM algorithm (right). The corners on e.g. the red curve in the left plot are associated with voltage limit at bus 5, transformer current limit, voltage limit at bus 4 later repeated in reverse order.
In this case, the voltage limitation part of the algorithm is activated first, as the voltage limit is reached before the current limit in the morning. As the local algorithm in this simple case cannot adjust reactive power it gradually curtails the PV unit at bus 5 where the voltage increase is most significant. The curtailment actions by the different PV units throughout the simulated day can be seen in Figure 24.

As the total generated power keeps rising, the congestion management part is also initialised. The PV unit at bus 3 is ranked highest, followed by the unit at bus 1. The curtailment limit for the PV unit at bus 3 is quickly reached, which initiates curtailment at bus 1. The added control actions temporarily halts the increase in curtailment for voltage limitation purposes at the end of the feeder, also seen in Figure 24. However, since the total generated power continues to increase up until noon, curtailment at bus 5 must be increased again to limit the voltage. This in turn positively impacts the loading situation which reduces the need for actions by congestion management part, which means no actions are needed from the PV units at buses 2 and 4. In the afternoon the reverse process takes place due to the symmetry of the generation profile.

The combined ANM algorithm example shows how congestion management and voltage limitation can simultaneously be achieved. For the radial LV feeder, local voltage control actions have been given priority and preventing overloading of the transformer becomes an operation mainly concerned with correcting offsets created by the voltage limitation part.
6 CONCLUSIONS

The main issues associated with large-scale integration of renewable energy sources presented in this report are overvoltage and overloading of network components. The purpose of the developed active network management algorithms is to mitigate these two issues to increase the renewable energy penetration while maintaining reliable network operation conditions. This is made possible through control of the active and reactive power output of flexibility resources, which include inverter-interfaced distributed generators, flexible loads, and battery energy storage systems.

The algorithms are intended to be easily deployable, scalable, and adaptable to different networks and therefore simplicity was favoured over optimality in the development process. The algorithms are derived from a basic structure, which includes a PI controller and an input signal that is computed from limit values rather than a reference value. This makes it possible to safely operate the network within voltage and current limits.

Overvoltage typically occurs at the end of radial distribution feeders in times of coinciding large power production and small load demand. Voltage issues tend to be most efficiently managed at the location of occurrence, which makes the problem local in nature. Consequently, a local voltage limitation ANM algorithm was developed. It uses both active and reactive power when available, either sequentially or with a constant power factor. A version was adapted to loads with only active power control.

While renewable energy sources can be spread out through the distribution network, bottlenecks are normally located close to or at the point of connection to the overlying transmission network. This makes a simple, purely local solution infeasible, and a central ANM congestion management algorithm was therefore developed. Through the algorithm, control actions are distributed via a flexibility dispatch to participating flexibility resources. A separate version of the congestion management algorithm was created to manage the flow of reactive power through an identified interface; typically in a transformer.

Finally, combined voltage limitation and congestion management was presented, and it was demonstrated how these can be used to simultaneously control voltage locally and manage a network bottleneck in a centralised configuration.
7 REFERENCES


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