Application of Resilience Enhancing Smart Grid Technologies to Obtain Differentiated Reliability

M. Nijhuis & M. Gibescu
Electrical Energy Systems
Eindhoven University of Technology
Eindhoven, The Netherlands
m.nijhuis@tue.nl

J.F.G. Cobben
Asset Management & Electrical Energy Systems
Alliander & Eindhoven University of Technology
Arnhem & Eindhoven, The Netherlands

***Abstract*—With the introduction of smart grid technologies in the distribution network the resilience of the network can be increased. The advantage of the use of these technologies is that they could be more effective than conventional technologies in creating a local increase in the resilience of the network. This approach would allow for differentiating the reliability per (groups of) customers. Different smart grid technologies are evaluated based on how cost-effectively they can increase the local reliability. The creation of microgrids in combination with local energy storage and the reconfiguration of the network by remote switching, are the two smart grid technologies which are investigated in this paper. The use of energy storage can increase the reliability of a single node without affecting the other nodes, however the costs of implementing energy storage are still similar to the cost of conventional network reinforcement methods to locally increase the reliability. The cost of using remotely-controlled switches to increase the reliability at a single node is much lower. With this method, the increase in reliability is however not only achieved at a single node, but at other nodes as well. This makes it difficult for the DNO to charge in a fair manner for this additional reliability.**

***Index Terms*—Power system reliability, distribution network analysis, distribution network market**

I. Introduction

One of the key requirements of the distribution grid is reliability. As society becomes more and more reliant on electric power the need for this power to be always available also increases. Th reliance on electrical power can however differ significantly between consumers. Whilst for a residential consumer a power outage in the middle of the day might not bear much cost, the same outage for many small and medium enterprises (SME) will incur a substantial economic loss. In the current set-up of the distribution network the distribution network operator (DNO) is only rewarded/penalised for the system-wide level of availability that it maintains. In recent years there have been calls to allow for differences in reliability levels between consumers based on either new markets or as an addition to the current tariff structure employed by the DNO [1] [2] [3] [4] [5]. The main tools the DNO currently has at its disposal for the increased reliability of the network is to increase its focus more on certain consumers during restoration and pre-emptive maintenance. When it comes to the prevention of outages the DNO has limited possibilities to alter the distribution network to achieve less outages. The increase of the resilience of the distribution network can be one of the ways in which the DNO can alter its reliability in the future. Smart grid technologies, like on-line failure diagnosis [6], remote switching [7], demand side management and the use of storage [8] and micro-grids [9] can increase the resilience of the distribution network and thus increase the reliability [10]. Most of these technologies can increase the resilience of the distribution network on a more local level than conventional grid reinforcements. This is the focus of this work. As the amount of money one wants to pay for a reduced outage can differ with a factor ten between SME's and residential consumers, the need for local differences in reliability is already present.

An evaluation on how much the different smart grid technologies can alter the availability of the distribution network on a local level versus the complete system and against what costs has not yet been performed. This analysis is required to determine whether with the introduction of smart grid technologies the DNO can introduce these technologies to clients which require augmented resilience against an resilience based surcharge. In the paper first a closer look is taken at why differentiating reliability for customers is beneficial from a social welfare point of view, secondly an investigation is made into how the different smart grid technologies can be applied in order to improve the resilience of the distribution network. Thereafter the different technologies are compared and assessed based on their ability to alter the resilience of distribution network locally and the cost associated with the induced availability increase. Based on these steps conclusions can be drawn about the applicability of smart grid technologies for the enabling of individual consumer differentiated availability within the distribution network.

II. Reliability differentiation

The reliability of the distribution network (the percentage of time the customers in the network are supplied with power) is determined by the resilience of the network (the ability of the network to keep supplying power) and the failure frequency.

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When looking at the current approach towards reliability in the distribution network three main problems occur. First of all for some customers the standard level of reliability is too low and the DNO has limited power to increase their reliability even though the customers are willing to pay for it. Secondly, for a part of the customers the level of reliability is too high, effectively paying more than they would like (forced riding), and there are people who are happy with the level of reliability, but would have paid more to receive it (free riding) [11]. This is conceptually illustrated in Fig. 1.

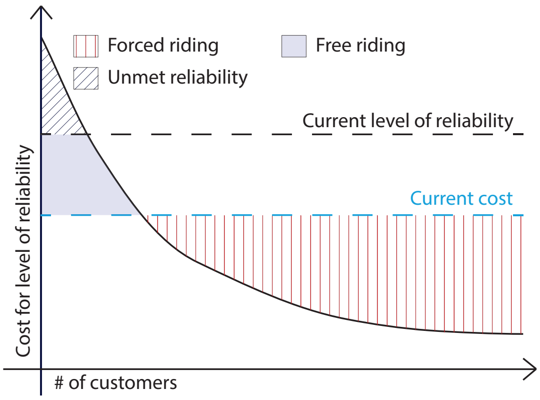

Fig. 1. Current situation with same level of reliability

The forced and the free riding of the customers can be considered economically unfair, as people are either paying too much compared to the level of service they require or they are not paying enough for the service they require. This can be solved by introducing multiple reliability levels within the distribution network, as depicted in Fig. 2.

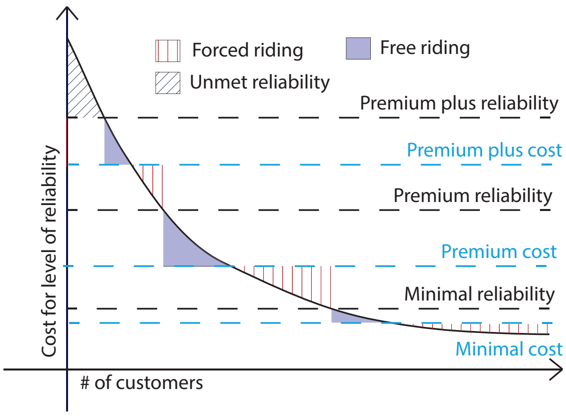

Fig. 2. Future situation with differentiated levels of reliability

As an example, the figure shows three levels of reliability. From the figure it becomes clear that due to the higher maximum availability level the amount of unmet reliability drops. The increase in available reliability levels also reduces the amount of free and forced riding, as can be seen from the smaller areas in Fig. 2 compared to Fig. 1. Moving to multiple levels of reliability which can vary locally will increase the amount of social welfare, even as on average the reliability of the system could drop [3]. The use of smart grid technologies offers new possibilities to increase the resilience of the network locally and achieve the multiple reliability options, as explained in the section IV.

III. Reliability in the Distribution Network

The technological advances in ICT and distributed energy storage make it feasible to increase the amount of sensors and actuators in the distribution network, allow for automated remote operation, and allow for safe islanding of a part of the system for a limited period of time. This gives rise to a number of different approaches to increase the resilience. To give an idea on the quantification of reliability, the well-known system average interruption duration index (SAIDI) has been altered for a nodal assessment. As the goal is to determine the difference in availability between different nodes in the network the nodal average interruption duration index (NAIDI) at node i is defined as follows:

$$NAIDI_i = \frac{\sum_{j=1}^{n_{f,i}} f_j \cdot r_j}{n_{c,i}} \tag{1}$$

where $n_{f,i}$ all the different failures which affect node i, f_j the yearly occurrence of failure j, $r_{j,i}$ the time to restore power to node i if failure j occurs and $n_{c,i}$ the number of customers connected to node i.

A real-life network of a Dutch DNO consisting of 73, 10kV buses and 381, 0.38kV buses is used to analyse the various approaches to increase reliability. The NAIDI of the 10kV part of the network and one 0.38kV feeder are graphically shown in Fig. 3.

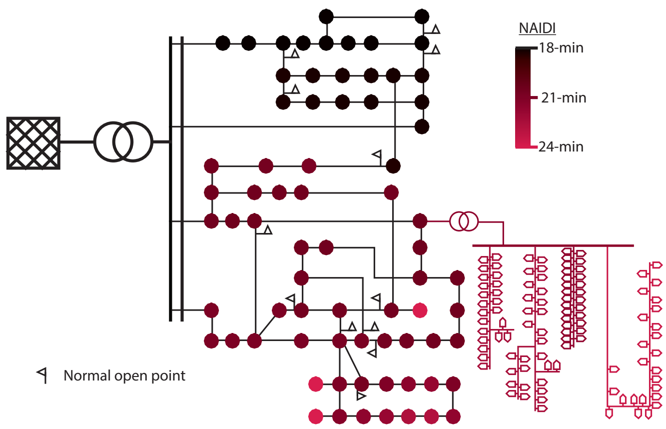

Fig. 3. Nodal average interruption duration index without the addition of smart grid technologies

The figure shows a resulting NAIDI of 18-24 minutes, which is average for $n-1$ underground cable networks [12]. One may note that the NAIDI already differs significantly throughout the network, as the DNO will choose to invest in increasing the resilience of the network based on the system-wide change in SAIDI, not to achieve an equal NAIDI for all customers. This is common practice because most regulators almost solely judge the DNO on the SAIDI. Within the network in Fig. 3 there are three nodes which have a single branch leading towards them. Any fault in these branches would lead to an outage at these nodes which cannot be restored by rerouting the network, so the customers have to wait for the branch to be directly repaired. These nodes are also the nodes with the largest NAIDI.

The NAIDI is calculated with the assumption of an uniform failure rate of both joints and of cables. The average failure rate is based on the failures over the past 5 years recorded with the Dutch grid operators used for the case study. For the restoration of the network it is assumed a mechanic needs to drive to the location of the fault (30 minutes) and manually perform the switching actions (30 minutes per switching action). If there is a single branch connecting the node to the rest of the network, the mechanics cannot restore the power by rerouting the network. The faulted section has to be repaired directly in order to restore power to the node, this will take up to 210 minutes. These times correspond to the average times for the Dutch DNO over the last years [13]. For the LV-network there are usually no switching options and direct reparation of the faulted component is always needed.

Failure rates and the repair times have been registered by the Dutch DNO. The resulting failure statistics have been combined to generate an overview of the causes of failures and the failure rates in the Dutch power system. An overview of the part of these statistics which are used in the study are shown in Table I. From the table it can be seen that the MV components fail less frequent than the LV components. This is caused by the lower average utilisation of the MV components. This lower utilisation is present as the MV-network is designed with a N-1 approach. The loads in the network are modelled through transformer measurements of the peak loading in combination with the household load model. The household loads are modelled with a bottom-up Markov Chain Monte Carlo approach [14].

TABLE I
FAILURE RATE AND OUTAGE DURATION OF MV- AND LV-NETWORK COMPONENTS [13]

Component	MTBF [year]	Repair time [min]
LV-cable	26.6 [\km]	190
LV-joint	2460 [\#]	150
Transformer	2660 [\#]	290
MV-cable	92 [\km]	210
MV-joint	1500 [\#]	170

IV. INCREASING RESILIENCE TROUGH GRID INVESTMENTS

The reliability of the network can be increased by either decreasing the outage duration, the number of affected customers, or by reducing the number of outages. To evaluate how much the reliability at a single node can be increased and for what cost, a number of different network interventions have been analysed. First, the conventional intervention of laying additional cables is evaluated, followed by a discussion on the use of remote switching and thirdly the cost of storage for safe islanding during grid outages.

A. Conventional measures

The first measure to increase the reliability of a node, is to decrease the outages the node experiences by laying additional cables. A direct connection from the substation to the node can be created. The node would only be affected by faults within this new cable. The node is no longer connected to the downstream network, as this is still connected through the cable which was already in place. In this way the node will no longer be affected by downstream faults in cables or joints. To analyse the increase in reliability, the original reliability is compared to the reliability which can be achieved with a new feeder consisting of a single cable to the node. The length of the cable is determined based on the shortest path over the roads, between the substation and the node. The cost of laying an additional meter of cable is assumed €75 in this analysis (cost level of a Dutch DNO). An overview of the maximum reliability for each node is given in Fig. 4, as well as the cost for the laying of additionally required cables.

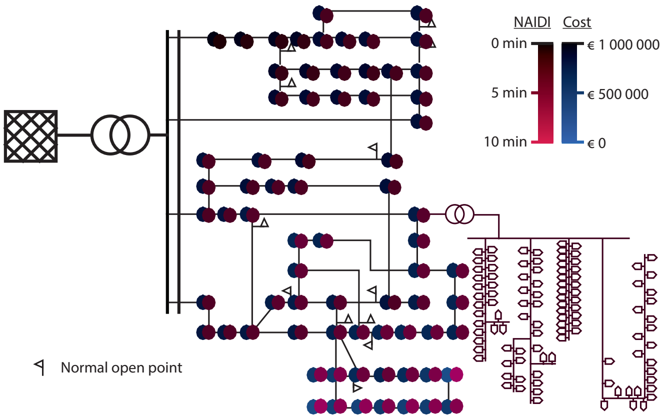

Fig. 4. Maximum change in NAIDI at each node and the associated costs for the conventional method of adding more MV-cables

From the figure it can be seen that the NAIDI for all the nodes can be significantly reduced, with none of the nodes having a NAIDI of more than 7 minutes. The decrease in NAIDI is attained through the decrease in the severity of outages. This is achieved through the smaller amount of components, i.e. the meter of cable, in the feeder which can fail and by the decrease in restoration time. The restoration time can be reduced due to the improved identification of the faulted section, as the amount of sections in the feeders is decreased, and the reduced amount of required switching actions. Depending on the geographical location of the node, the reduction of the NAIDI can differ significantly. The NAIDI of the most reliable node is 0.24 minutes, which is almost than 27 times less than the node with the largest NAIDI which is 6.48 minutes. The cost for the conventional solution is also highly dependent on the geographical location of the node. With the cost ranging between €26 400 and €709 000. These costs can be prohibitive, especially for users at nodes further away from the substation. The average cost of the conventional way of improving system reliability by laying of additional cables is €262 000.

B. Remote switching

Most switches in the distribution network require manual operation. The automation of these switches can increase the resilience of the network, especially if the faulted section in a network can be identified remotely as well. The time it takes for a technician to drive towards the faulted section and manually perform the necessary switching actions to reroute the supply, can be significantly reduced or even eliminated. The increase in network resilience depends on the network characteristics. The optimal placement of switches in the distribution network to optimise the SAIDI has already been extensively covered in research. To generate local changes in reliability and to see which effect this has on the system-wide reliability, a slightly different approach is required. The placement of the switches can be assessed through a particle swarm approach [15]. In this approach the switch placement is optimised based on the change in restoration time through (possibly remote) switching actions in the network. In this paper, the optimisation is changed to focus on reducing the NAIDI of a single node rather than the system-wide SAIDI. For the switching time it is assumed that the first switching action takes 5 minutes. This also accounts for the localisation of the fault. Any subsequent switching actions are assumed to take 1 minute. This is a significant reduction from the 30 minutes switching on average for the manual switching case.

For the network shown in Fig. 3 this optimisation has been performed for each node with a search space limited to the introduction of up to 10 remote switches within the network. The number of switches is limited to 10 as it is assumed that the largest change in NAIDI can be achieved with this amount of switches. With the introduction of more switches the SAIDI can be even further improved, but an improvement in the individual NAIDI is no longer possible. It is assumed that the cost of installing a remote switch amounts to €5 000 (cost level of a Dutch DNO). The resulting NAIDI and the cost of installing these switches is given in Fig. 5.

From the figure the change in NAIDI can be seen. With the introduction of the remote switches the NAIDI can be reduced at almost every node. There are three grey nodes within the network. In these nodes the NAIDI can only be slightly improved in comparison to the other nodes. This limited improvement in NAIDI is caused by the relative importance of the fault in the single branch leading towards the node. As the use of remote switches can only reroute the current if there are other branches connected to the node, this node will still have a long restoration time if the single supplying branch becomes faulted. The NAIDI in the other nodes can be decreased to lower than 6 minutes, with the absolute differences between the nodes decreasing.

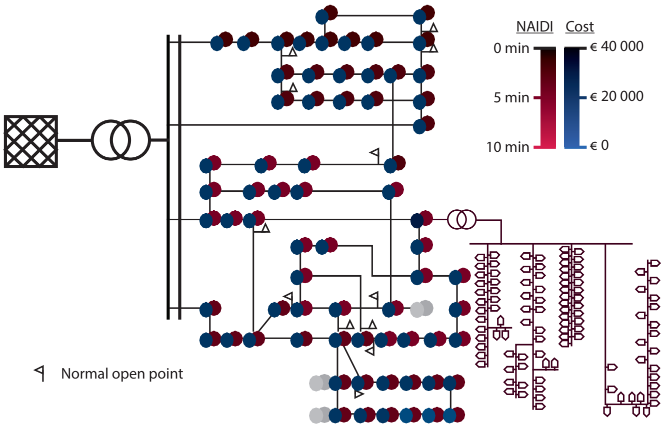

Fig. 5. Maximum change in NAIDI at each node and the associated costs for placing remote controllable switches

As remote switching capabilities are introduced in the network to improve the reliability of a certain node, the system-wide reliability will also improve. As the consumer connected to a single node will have to compensate the network operator for the improved reliability, other users which profit from this improved availability will do so free of charge. This free riding is defined as follows:

$$Fr_i = \frac{\sum_{j \in n} (C_j d_j) - C_i d_i - \sum_{j \in n} (C_j d_{j,a}) - C_{i,a} d_i}{\sum_{j \in n} C_j} \quad (2)$$

where Fr_i is the amount of free riding which is introduced if the availability of node i is maximised, C_j is the amount of customers connected to node j, d_j the yearly average outage duration at node j, $d_{j,a}$ the yearly average outage duration at node j with the remote switches implemented to achieve the lowest NAIDI at node i, and n the number of nodes in the system. The amount of free riding is calculated for each of the nodes and is plotted in Fig. 6.

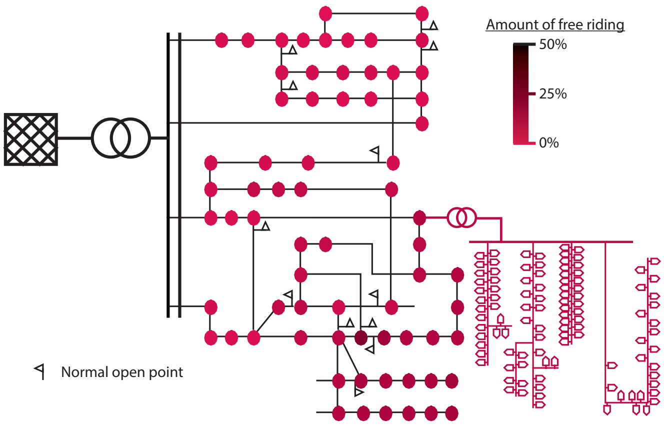

Fig. 6. Percentage of free riding due to the implementation of remotely-controlled switches

From the figure is can be seen that at every node there is an amount of free riding. When installing remote switches to improve the reliability at a single node, the average amount of free riding is about 9%, which means that the combined SAIDI of all nodes, excluding the node for which the remote switches are optimised, is reduced by 9%. For the node with the least amount of free riding this can be reduced to 3%, while the maximum amount of free riding is 27%. The minimum amount of free riding is found in the nodes closest to the substation. For these nodes, faults in large parts of the network can be isolated with a switch close to the node. In the rest of the network, no switches are necessary for this single node. For nodes in this part, the fault cannot be isolated by the remote switches and the mechanic still has to drive and manually isolate the fault. The nodes with the highest amount of free riding are the nodes which require many switching actions to properly isolate all the possible faults. Also nodes at places where the network has multiple branches generally have a higher amount of free riding. This free riding is caused by the capabilities of that node to efficiently isolate a part of the network. These nodes are also where DNO's currently would place additional circuit breakers or remote switches.

C. *Micro-grid & nano-grid*

The costs for electrical energy storage have been decreasing. This gives rise to the use of energy storage within the distribution network. One of the main advantages of utilising energy storage in the distribution network is the increase in reliability. By using energy storage a part of the network can be islanded during an outage. A micro-grid can be employed to keep single or multiple nodes within the MV network energised, while the same can be done for a single or a few households in the nano-grid concept. In this way the increased reliability which a micro-grid offers is usually restricted to the single node. Some other nodes might be effected by the micro-grid due to the decrease load at the micro-grid node. This can make switching actions possible which were not possible before due to the current carrying capacity or voltage limits of the network. In the examined network there are only two nodes for which this can make a difference and the resulting difference in the availability in those nodes is lower than 5% of the initial NAIDI. Therefore the change in NAIDI in these nodes is neglected in this research. To determine the feasibility of implementing a micro- or nano-grid to increase the reliability is determined by the loading of the nodes. Based on the available generation, the loads and network topology an reliability assessment for the micro-grid can be performed [16] [17]. In these assessments not only the chance of outages due to component failure is assessed, but also the chance of outages due to a lack of electricity generation capabilities within the micro-grid. From the reliability analysis the amount of energy storage required to minimise the risk of this generation inadequacy is determined. The resulting amounts of required energy storage are depicted in Fig. 7.

In the figure, the storage requirements for both the MV and the LV network are depicted. As there is a large difference in the required amount of energy storage, different colours are used for the MV and LV level. From the figure it can be

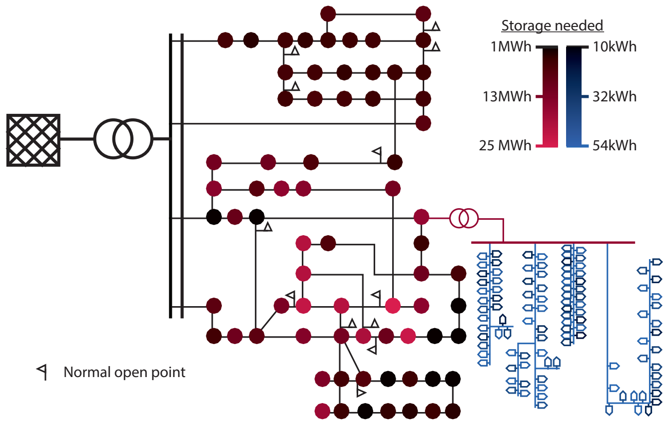

Fig. 7. Required storage need to mitigate the impact of outages on the MV and HV level

seen that there is a large difference in the required storage cost between the nodes. The amount of storage is mostly dependent on the loading of the nodes, therefore the probability distribution of the amount of required energy storage differs significantly from the distribution of the availability. The three nodes which have a single branch connecting them, are still amongst the nodes with the largest energy storage requirements. This is caused by the longer outage duration when the single branch connecting one of these nodes is faulted. To gain insight in the cost of the energy storage to generate a higher level of reliability a price of €400 per kWh has been assumed based on currently available Lithium-ion battery technology [18]. The resulting cost levels are comparable to the cost of laying an additional cable to improve the reliability. Only for the nodes close to the substation or highly loaded nodes, the cost of the energy storage is higher than that of the additional cable. However, the lifetime of an energy storage system ($\approx$ 20 years) is considerably less than that of a MV cable ($\approx$ 50 years). If this is taken into account, the energy storage options are more expensive for the MV nodes. For the LV, the use of energy storage is one of the only techniques available to improve the reliability for a single LV node. The cost of the reliability improvement would be in the range of €12 500 in the LV-network.

V. Conclusions

With the introduction of smart grid technologies the resilience of the distribution network can be improved. When looking at the conventional option to improve the reliability by the laying of additional cables, the investment costs are ranging from €26 400 to €709 000. If the cost the DNO incurs for increasing the reliability is directly passed on to the consumer, this large cost difference can be considered unfair. The consumers have no influence on the design of the network and the design of the network is not publicly available. Meaning the consumers cannot select their location based on the network design. The cost for generating an adequate amount of reliability of the distribution network would be thus hard to influence and to assess for the grid users.

With the introduction of energy storage or remote switching technologies, the amount of possibilities to target reliability improvements at a single node increases. Energy storage can increase the reliability to near perfect for a single node. The other nodes in the network have little to no increase in their reliability indicators. Therefore, the free riding when installing energy storage for a single node is limited. However, the cost of increasing the reliability with energy storage is comparable to the cost of the conventional solution. As an alternative, the introduction of remotely-controlled switches can reduce the outage duration to a couple of minutes. By contrast, the cost of remote switches are only a fraction of the cost of the energy storage or additional cables. Still, it must be noted that the use of remote switches will be beneficial to the whole network rather than just a single node, hence the introduction of remote switching will lead to a certain level of free riding. When installing the remote switches to minimise the NAIDI at a single node the rest of the network can have a decrease in SAIDI up to 21%. In some situations the NAIDI improvement for a single node can have a free riding effect of 100% in another node, meaning that the minimisation of the NAIDI at a certain node also inadvertently minimises the NAIDI at another nearby node. In these situations, a choice must be made between the free-riding, lower-cost solution, or the higher cost when employing alternative like installing energy storage. Where the placement of remote switches can only be performed by the DNO, the end-user can also chose to install an energy storage system without involving the DNO. Leaving this increase in reliability to other market parties rather than the usually government owned DNO.

Though in this paper only a case study is performed on a single network the identified trend should hold. As the cost for using conventional reliability improvements generally will prove to be much higher than the cost of more advanced methods, i.e. placing remotely operable switches. Though the amount of free riding will be different for other networks, the identified trend that many nodes in the network benefit from increased reliability through the placement of remote switches. Changing the reliability on a nodal basis for existing networks will remain difficult to be performed without large additional costs or considerable amounts of free riding.

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