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Technical Benefits of Distributed Storage and Load Management in Distribution Grids

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***Abstract*—On the one hand, several developments make the operation of the distribution grids more and more complex. On the other hand developments in energy storage and the availability of loads which are not time critical bring up possibilities to provide more flexibility in the grid and to use the available system more efficiently. In this paper, these and other advantages of as well distributed energy storage as load management of not time critical loads are discussed. An approach is described to analyse the available capacity in the grids, to investigate how this capacity can be used by applying storage or load management and to compare the benefits of storage and load management. This approach is illustrated using a real medium voltage network and measured data. It shows the part of the capacity in the distribution grids which is now unused, but can be made available by applying storage or load management of non-critical loads. The size of the storage and the non-critical loads which are needed to use this capacity are determined. The characteristics of future loads, the need to support integration of distributed generation and the desired level of reliability of supply are factors that determine the size of the storage and how storage or load management can be applied best.**

***Index Terms*—Energy storage, load management, power distribution.**

I. INTRODUCTION

NOW and in the future, a reliable electricity supply is of utmost importance for satisfying the needs of individuals and enabling the functioning of societies and economies. However, various developments lead to an increasing complexity of the design and operation of electricity grids. A consequence of the liberalisation of the energy market is that all consumers and producers must be given access to the grid.

This increases uncertainty with respect to the future demand for capacity with respect to volume as well as to location compared to the past where vertically integrated utilities controlled both the networks and the generators. This uncertainty is amplified by the development towards more distributed generation connected to the electricity distribution networks. Despite all these changes and uncertainties, network operators are obliged to provide their consumers with a reliable power supply. This challenge is further increased by the ageing of the existing infrastructure and the ever increasing demand for electricity.

All this puts the question in which way future demands can be met with the existing infrastructure prominently on the agenda. The consequences of these developments could be mitigated by enabling a more flexible operation and efficient use of the (existing) system, without compromising the reliability of supply. In this paper, a perspective on acquiring the desired flexibility is outlined. Traditionally, electricity networks are dimensioned on peak demand. This is inevitable due to the fact that storage of substantial amounts of electricity is technically and economically infeasible. As a result, a vast amount of currently unused network capacity is available. When this could be used, much more energy could be transported with the same network so that investments on network reinforcements could be postponed or omitted.

To this end, it must be possible to shift demand for electricity in time or, more precisely, to shift the transport of electricity in time. In principle, this can be done in two ways, namely:

- Incorporating (distributed) electricity storage in the networks.
- Allowing load management by connecting flexible loads which are not time critical.

Additional advantages of enabling electricity storage and/or load management would be that this supports the integration of decentralised renewable energy sources into the electrical power system and could improve the reliability of supply and thus counterbalance a reliability decline due to the ageing of the infrastructure.

In this paper, the benefits of distributed storage and load management for the operation of distribution networks are investigated. To this end, first, the working principles and benefits of distributed storage and load management are described in general. Then, the approach is presented to quantitatively analyse the available capacity in the grids, to investigate how this capacity can be used by applying storage or load management and to compare the benefits of storage

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and load management. Finally, this approach is illustrated using a real medium voltage network and measured data. It should be noted that an elaborated analysis of the commercial and regulatory aspects of distributed storage and load management is outside the scope of this paper and, therefore, these topics will only be touched upon.

II. DISTRIBUTED STORAGE

New technologies become available for energy storage and the developments on information and communication technology make an optimal use of these storage techniques possible. In literature many advantages that distributed energy storage offers are described [1]-[4]. From a distribution network operator's perspective, the main advantages that storage gives are the more efficient use of the grid (either for serving loads or connecting distributed generation) and the improved reliability of supply. To facilitate the integration of intermittent, distributed generation energy storage can store the energy produced by distributed generation when the source is abundant and demand is low, and release the power during peak periods. This supports high penetration of distributed renewable energy sources without requiring major grid reinforcements. From the broader perspective of the transmission system operator and/or commercial energy companies, an additional advantage of distributed storage would be that it supports maintaining the power balance within a control area or an energy portfolio. However, the fulfilment of this global, system wide requirement can as well be achieved by large scale storage technologies, such as pumped hydro accumulation storage or compressed air energy storage [5]-[7]. As this research focuses on the benefits of distributed storage for distribution grids, this topic will not be treated any further.

Besides the possibility to delay grid investments due to load growth or connection of distributed generation, energy storage generates value by charging the storage assets with cheap electricity in the off-peak periods and using this electricity during peak periods. It is, however, likely that the grid operator will not be allowed to exploit this benefit in a restructured energy sector although the technical and a commercial optimisation of the operation of storage facilities overlap each other.

The scope of this paper is restricted to the technical aspects of the incorporation of electricity storage in distribution grids and the commercial aspects will not be treated further.

A. Efficient Use of the Capacity of the Grid

In the past, the transmission systems faced many challenges because power plants became larger and larger and operation of interconnected networks became ever more complex. Meanwhile, the distribution systems 'only' delivered power from the transmission network to the consumers, so that the requirements on the network were quite obvious and uncertainty was limited. Further, due to the design and investment philosophy of most utilities, distribution networks tended to be overdimensioned.

However, times have changed and it has become very important and necessary (in order to maximise the rate of return on investments) to operate a distribution system closer to its maximum capacity. Using distributed storage, the effective load (load minus storage) can be flattened and the capacity of the grid can be used more efficiently. Electricity can be stored at off-peak load periods when the demand is low and used at peak load periods. In this way, the growing electricity demand can be sufficed without the need of large investments to expand the grid. This is in contrast with the design of the existing grid, which is based on the peak load. Load levelling brings the opportunity to transfer much more energy with the capacity of the existing grid. This principle can be seen in Fig. 1. A standardised day load profile of a household consumer in the Netherlands is shown. If energy is stored during the night when the demand is low and used in the evening when the demand is high, a system with a power capacity of the dotted line can be sufficient for normal operation.

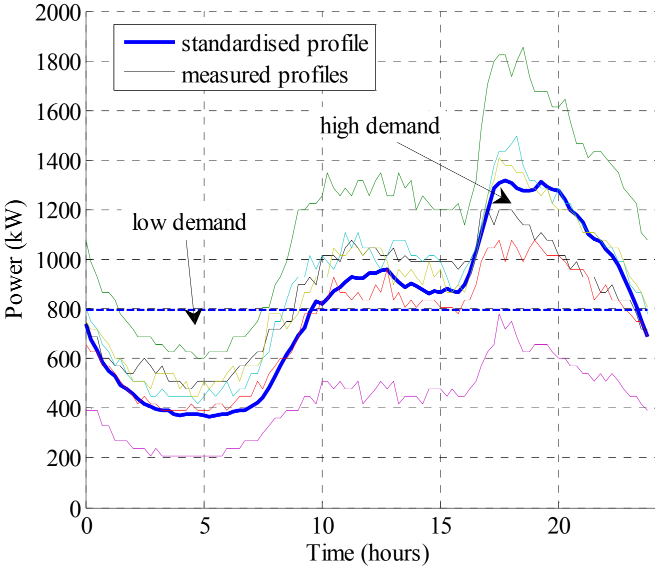

Fig. 1. A standardised day load profile of a household in the Netherlands, combined with 6 load profiles which are measured in the network of Enexis

B. Improving Reliability of Supply

Energy storage can be charged from the grid during normal conditions and can provide the necessary power to supply the network during interruptions. For a period of time, a part of the network can then function in island mode. An application of storage for reliability improvements is described in [8]. Storage can thus improve reliability of supply. Especially distributed storage – which is applied closer to the consumer – makes the system less dependent on the failure of network components and hence requires less redundancy of the system. This aspect becomes more important with the ageing of the infrastructure.

III. LOAD MANAGEMENT

Load management refers to the distribution network operator (DNO) being able to control (a part of) the load of consumers served by the distribution network. It can be used to increase demand by increasing loads which are not time critical, but it can be used to reduce demand only to the extent that these loads are decreased and loaded on an earlier or later moment in time. Hence the non-critical loads cannot reduce or level the demand of critical loads. For the same reason, they do not improve reliability of supply and facilitate network integration of distributed generators to a lesser extent than energy storage. The availability of non-critical loads can increase the demand when the source of the distributed generators is abundant, but when the supply by the generators is limited non-critical loads can not reduce or level the demand of critical loads like storage can.

Non-critical loads can be realised in two distinct ways, namely:

- Through processes and appliances of the consumers that are not time critical and have relatively long time constants. These are typically thermal processes, such as air conditioners, heating, cooling, etc.
- Through electricity storage ‘behind the meter’, being charged from the grid but for technical or institutional reasons unable to deliver energy to the grid. An important example of this would be the electric car, which cannot easily deliver energy back to the grid due to the administrative complexity of such a transaction, but forms a substantial not time critical load.

It can be argued that as long as load management by the DNO does not lead to any inconvenience for the consumer, no (financial) compensation for the consumer should be required. However, to put this in practice, in most cases regulation will have to be adapted because in most cases consumers are given an unconditional right on using network capacity.

Technically, it would also be possible to create flexibility by controlling distributed generators; their output can be reduced when network components are overloaded and their output might be increased if desired by the network operator. However, this will require compensation to the owner for the energy not delivered or produced extra. Both cost and complexity of management of distributed generators by the network operator are higher than that of inherently non-critical loads. Therefore, management of distributed generators by network operators is not treated further in this paper.

IV. APPROACH FOR ANALYSING GRID CAPACITY

The question addressed in this paper is how distributed storage and load management can be introduced to the network in such a way that it benefits the grid operator. As argued in the introduction, it is a relevant question how future demand can be met with the existing grids. Introducing storage and/or load management to the network can provide flexibility to use the network more efficiently and to transport more energy with the same capacity. The approach used to investigate this is the following. First, the available capacity is determined, then it is investigated how this capacity can be used by applying storage or load management and finally, the benefits of storage and load management are compared.

A. Determining the Available Capacity

An analysis of the used capacity of the distribution grids of Enexis showed that the medium voltage distribution networks have a great potential to transfer extra energy within the capacity of the existing grid [9]. This is due to the fact that electricity networks are dimensioned on peak demand. Furthermore, they are laid out for a foreseeable future loading and a reliability criterion is applied. To keep the reliability of the networks on a high level, this criterion says that if a fault occurs in one cable, the electricity should be supplied after a switch-over by another part of the network. Therefore, the cables are designed to be able to transport a double cable loading. Without losing reliability, this capacity can be used for non-critical loads if, in case of an interruption, the non-critical loads are disconnected and the capacity can be used to supply the critical loads.

The method applied in this paper, however, only examines the part of the capacity which is needed to supply the peak demand but which is only partially used because the demand fluctuates over time. The remaining capacity available from the peak to the actual maximum cable loading is not considered. The examined capacity can be made available by applying storage or load management of flexible loads. The grey area in Fig. 2 presents this part of the capacity. The size of this area is determined and it is investigated how this capacity can be used to maximise the transport of energy.

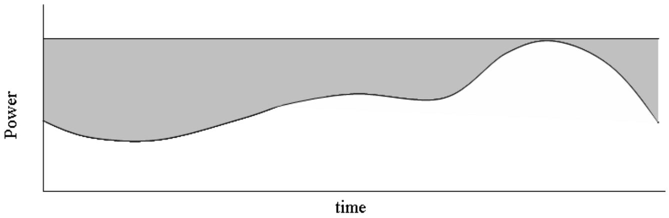

Fig. 2. A day load profile over time; the grey area shows the potential capacity to transfer extra energy

B. Use of the Capacity

Distributed storage as well as load management can be applied to make it possible to better use the spare capacity described in the previous section. Storage can be used to level the load and load management of not time critical loads can be applied to use the capacity for the non-critical loads when the demand of critical loads is low. If this is realised, the distribution system can operate closer to its maximum capacity without any loss of reliability. These two possibilities are investigated.

1) Applying Storage

Levelling the load by applying distributed storage makes it possible to support a higher demand, also during peak moments, with the capacity of the existing grid. To level the load completely, i.e. using storage to spread the load such that the power capacity of the dotted line in Fig. 3 is sufficient to supply the fluctuating, critical load, a certain power and capacity of storage are needed. It is supposed that the storage is located close to the consumers. The power $P_{storage,max}$ and energy capacity $E_{storage,max}$ of the storage are determined. The dotted line in Fig. 3 presents $P_{average}$. The formulas used to calculate theses values are

$$P_{average} = \frac{1}{T}\int_0^T P_{load}(t)dt \tag{1}$$

$$P_{storage,\max} = \max\left|(P_{average} - P_{load}(t))\right| \tag{2}$$

$$E_{storage,\max} = \max_{i=0,..,n}\left|\int_{t_i}^{t_{i+1}}\left(P_{average} - P_{load}(t)\right)dt\right| \tag{3}$$

where T is the total time, P_{load} the power of the load and n the number of times the P_{load} is equal to $P_{average}$.

Levelling the current critical load by using storage, makes that less capacity is needed and the amount of energy which is currently not used becomes available for other use, which can either be critical or non-critical loads. The available power for this extra load $P_{extra\ load}$ is constant over time when storage is applied in the way described here.

Besides determining the necessary power and capacity of the storage to level the load, it is explored how changing the power of the storage influences the amount of energy of the current load which can be supplied by the storage.

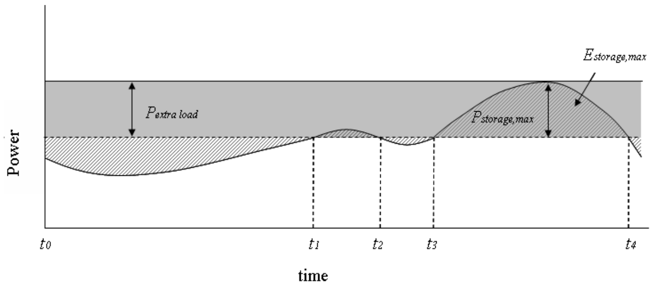

Fig. 3. Levelling the load with storage

2) *Applying Load Management*

As time varies, the amount of load which can be supplied by the distribution grids additional to the current load differs. At peak moments it might be that no extra load can be transported in contrast with off-peak moments when the capacity is not fully utilised. Therefore, additional, non-critical loads which can be supplied using the available capacity need to be managed over time. It is examined between which values the available power for these non-critical loads, $P_{extra\ load}$ in Fig. 4, varies. $P_{extra\ load}$ can be determined by

$$P_{extra\,load}(t) = P_{peak} - P_{load}(t) \tag{4}$$

where P_{peak} is the peak power over the total time investigated.

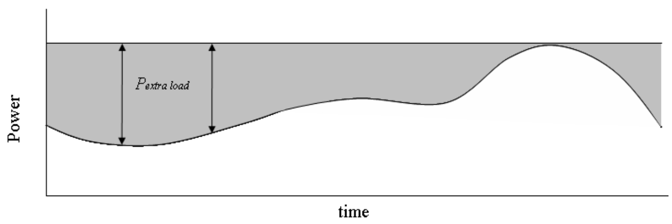

Fig. 4. Variable power for supplying flexible loads through load management

C. *Comparing Alternatives*

The two alternatives are compared and the advantages of both are discussed. The extra load which can be supported by the grid has different characteristics in both cases and both situations will support the penetration of intermittent, distributed generation to a different extent. Also, it is pointed out what applying storage and load management mean for the reliability of supply of the network.

V. TEST NETWORK AND MEASUREMENT DATA

The medium voltage distribution network which is presented in Fig. 5 is used for the analysis. This is a real network owned and operated by Enexis. In the network a ring-shape design is applied for most feeders. However, all cables which are laid out as rings are operated in two half rings by splitting two parts of the network by a net opening. When a fault occurs, the faulted cable section is isolated and all loads will again be supplied by reconfiguring the network by closing a network opening and connecting the two half rings.

The network analysed for this paper comprises six three core copper cables (cables 1 to 6 in Fig. 5) with a conductor cross-section of 70 mm^2 having a nominal loading of 195 A and they supply 50 MV/LV-transformers, which transform the voltage from the medium voltage level to the low voltage level and subsequently supply households.

The data used for the analysis is the load data of these six cables for one winter month (December 2007). The spread of the load for one the cables can be seen in Fig. 6; it shows the daily minimum, average and maximum cable loading.

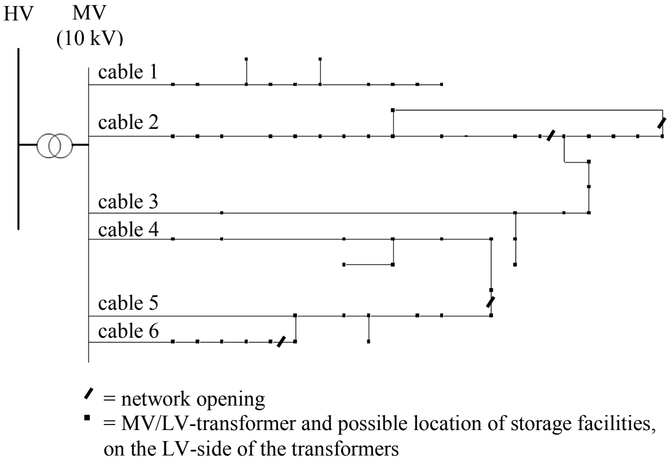

Fig. 5. An example of a 10 kV-distribution network operated by Enexis

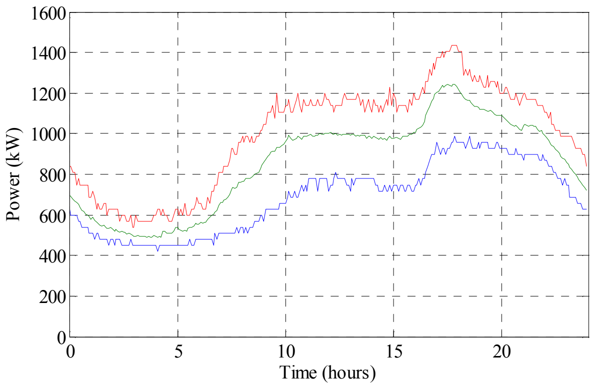

Fig. 6. The minimum, average and maximum day loading in December for cable 1

It is supposed that the storage will be located behind the MV/LV-transformers. In this way, the whole distribution network before the MV/LV-transformers profits from the load levelling by the storage.

VI. RESULTS

The approach discussed in the Section IV is applied to the medium voltage distribution network described in Section V. In this section the results are presented.

A. *Determining the Available Capacity*

First, the capacity which is available for transferring extra energy is visualised. The capacity of each cable needed for the peak demand is compared with the actual loading of the cable. In Fig. 7 it is depicted for the six feeders which percentage of the total energy that can be transported with these cables (if the power needed for the moment of peak demand is used for 24 hours a day) is used by the actual loading; this is presented for every day in the month December. It shows that the cable which is transporting the most energy on a certain day relative to its capacity (this is cable 2 on 20 December) uses maximally 68% of its available energy capacity; and thus leaving at least 32% of the capacity available for extra energy transport.

This percentage corresponds to an absolute value of 9909 kWh per day which can be transported through cable 2, additional to the current energy transport. The absolute values of the amount of the additional energy which can be transported with the capacity of the cables needed for peak demand are presented in Table I. The amount of additional energy that can be transported by these cables is also presented per MV/LV-transformer.

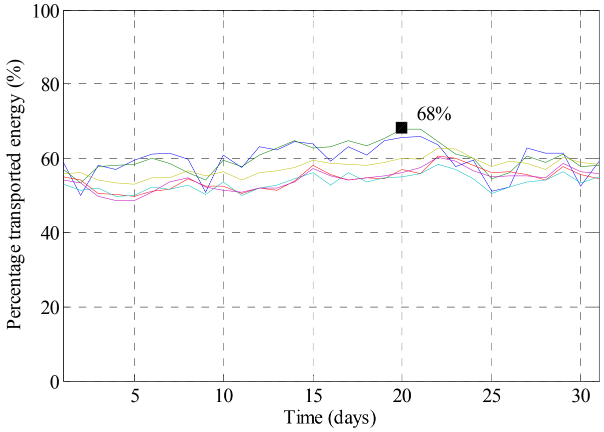

Fig. 7. The energy transported through the cable as percentage of the total energy capacity needed for peak demand

TABLE I
AVAILABLE CAPACITY TO TRANSPORT EXTRA ENERGY IN KWH PER CABLE AND PER TRANSFORMER

	Daily available energy per cable					
	cable 1	cable 2	cable 3	cable 4	cable 5	cable 6
$E_{available}$ (kWh)	11790	9909	15339	8061	15354	18437
# MV/LV-transformers	12	13	13	9	8	5
	Daily available energy per transformer					
$E_{available}$ (kWh)	983	762	1180	896	1919	3687

B. *Use of the Capacity*

Now, the possibilities of applying storage or load management to use this capacity are investigated.

1) *Applying Storage*

For every feeder it is determined what the energy capacity and maximum power of the total storage behind the feeder needs to be able to level the load completely. This was done for the month December, so in (1)-(3) the time T is 31 days, or 744 hours. Table II shows the total values for the storage facilities behind the feeder and the values for the storage behind every MV/LV-transformer, assuming that the load of every feeder is equally spread over the transformers

When the power of the storage is less than the values presented in Table II, the current load cannot be levelled completely and less energy will be transported by the storage. Fig. 8 shows the relationship between the power of the storage, if it is varied from 0 kW to the value of $P_{storage,max}$, and the amount of energy which in that case will be supplied by the storage. It is pointed out as a percentage of the total energy which is transported by the storage in case of 100% load levelling of the current load. It shows that with a power of 70% of the value of $P_{storage,max}$ almost the same amount of energy is supplied by the storage as with the maximum needed power for 100% load levelling. Based on this, it can be recommended that the power of the storage is chosen smaller than $P_{storage,max}$ and thus to not level the load completely if storage is applied.

TABLE II
STORAGE SIZE BEHIND EVERY FEEDER

	cable 1	cable 2	cable 3	cable 4	cable 5	cable 6
$P_{storage,max}$ (kW)	736	877	738	512	579	377
$E_{storage,max}$ (kWh)	4581	5704	4533	4266	4173	2188
# MV/LV-transformers	12	13	13	9	8	5
	Storage size per transformer					
$P_{storage,max}$ (kW)	61.4	67.5	56.8	56.9	72.4	75.3
$E_{storage,max}$ (kWh)	382	439	348	474	522	438

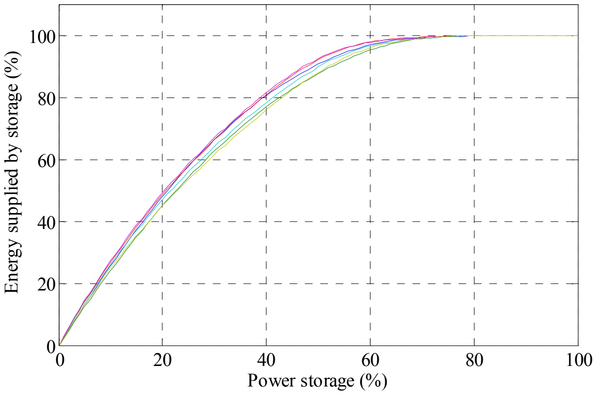

Fig. 8: The amount of energy supplied by the storage if the power of the storage is varied

2) *Applying Load Management*

Fig. 9 shows the load duration curves for the six cables, presenting the available power in every cable for all hours in the month December. This available power is the power of the cables needed for the peak demand minus the power which is actually used by the current load. It indicates the amount of energy available (presented by the area under graphs), but moreover it presents the size of the power available for extra, non-critical loads. These loads should be managed in such a way that the extra power absorbed fits under the curves of the varying, available power.

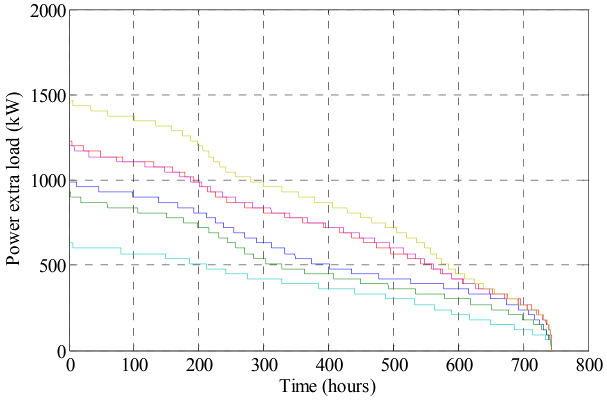

Fig. 9. The available power in the 6 cables in the month December

C. *Comparing Alternatives*

In this section the two alternatives are compared. First, the issue of efficient use of the grid is treated. The characteristics of the extra load which can be supplied by the available capacity through distributed storage or load management of non-critical loads as applied in this paper are discussed, and also how both alternatives support the increasing penetration of intermittent, distributed generation. Furthermore, the influence on the reliability of supply is discussed.

1) *Efficient Use of the Grid*

It was shown which power and which energy capacity of storage are needed to level the load. If the load is levelled it is easier to use the surplus capacity of the grid for energy transport. Less power capacity is needed for the current critical loads that are connected to the grid. The extra capacity which becomes available can therefore be used for as well an increase of critical loads as for non-critical loads. Connecting more storage to the networks makes it possible to add more critical loads to the grid.

When no storage is applied no critical loads can be added, because at certain moments of time the capacity is needed for the current, critical load, which is supposed to be not flexible at all. Applying load management makes it possible to use the available capacity for additional loads which are not time critical. However, to optimally use the capacity the power of these loads needs to be larger than the installed power of storage to reach the same goal. This can be seen in Fig. 10; the straight lines indicate the power of the extra load when storage as described in the previous section is applied, the curved lines indicate the power of the extra, non-critical loads in case of load management. Because this is pointed out for the six cables, the power and energy values are indicated in percentages. The power is given as a percentage of the maximal needed power for extra load to be able to use all the available energy capacity in case of load management and the extra transported energy is given as a percentage of the total amount of energy capacity available.

Table III shows the amount of energy per day which is currently not used by the grid and which is equal to the amount of the non-critical loads which can be supplied by this capacity. The table also expresses this amount of energy in a number of electric cars which can use the capacity if they are connected to the grid and managed as non-critical loads. These figures are based on the average distance a Dutch person drives per day, which is 55 km, and the estimation that an electric car can drive 5 km per kWh. Also the number of households supplied by the transformers is depicted in the table. The values show that quite some number of electric cars can be supplied with the existing grid if they are managed well. However, it should be noted that these numbers show the ideal situation in which 100% of the capacity is used.

How the available capacity can be used best depends on which kind of loads will be connected in the future. If future loads are mainly critical loads, the application of storage can be a solution to better use the capacity. If non-critical loads are added to the network, it might be possible that management of these loads results in a more efficient use of this capacity without the need for (extra) storage.

If the load profiles are less predictable and more fluctuating, which is the case when intermittent, distributed generation is also connected, more flexibility will be needed to use the capacity of the grid optimally. This flexibility can be supported by applying storage or load management of non-critical loads. Storage provides more flexibility to the grid and makes it possible to use the capacity of the grid to transport the energy supplied by distributed generation as well. Load management also supports this, but to a lesser extent. More flexible loads will be needed to obtain the same flexibility as storage in terms of integrating intermittent, distributed generation.

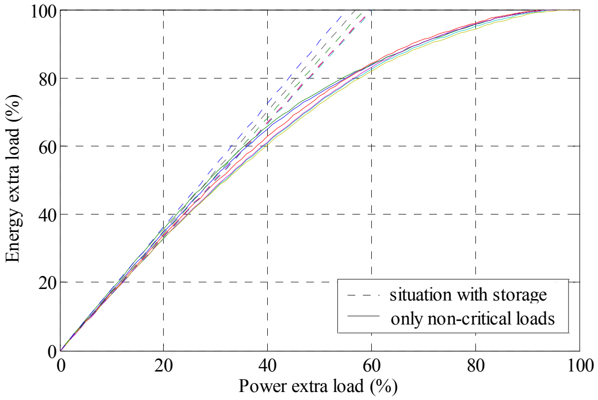

Fig. 10. Needed power of the extra load to optimally use the capacity for all 6 cables

TABLE III

DAILY AVAILABLE ENERGY PER TRANSFORMER EXPRESSED IN ELECTRIC CARS

	cable 1	cable 2	cable 3	cable 4	cable 5	cable 6
$E_{available}$ (kWh)	983	762	1180	896	1919	3687
# households behind transformer	200	171	191	133	310	660
# electric cars	197	152	236	179	384	737

2) *Reliability of Supply*

Applying storage or load management in the way as discussed in this paper will not affect the reliability of supply in a negative way. When a fault in the network occurs in principle the same capacity is available for rerouting the power. Above that, when a fault occurs, assuming the storage capacity is not fully used for other purposes, it can be used to supply consumers.

As a consequence fewer consumers will suffer from interruptions or consumers will suffer from an interruption for a shorter period of time. Adding non-critical loads to the network does not improve reliability of supply.

VII. CONCLUSIONS

In this paper, the issue of how the distribution grids can profit from energy storage and load management is addressed. An analysis of a part of the medium voltage distribution network of Enexis shows that there is a lot of unused capacity available. At least 32% of the capacity of the investigated cables which is needed to meet the peak demand, is now unused and can thus be used for extra energy transport. Using this capacity does not negatively impact the reliability of the network.

This capacity can be made available by applying distributed storage or load management. The size of the storage, in terms of power and energy capacity, which is needed in the ideal case of levelling the current load completely, is determined. Varying the power of the storage behind the feeders shows that storage needs 30% extra installed power to transport only the last few percent of energy to level the load completely. This is something to keep in mind when choosing the size of the storage for this goal. Besides applying storage, it is possible to use the capacity by load management of non-critical loads. The needed power of these non-critical loads is, however, much larger than the needed power for the storage to reach the same goal of using the capacity optimally.

The choice between storage or load management, or a combination of the two, depends on the future demand. Storage adds more flexibility to the network, which can be useful in case of adding more critical loads or integrating distributed generation. But if many non-critical loads are available these might add the desired flexibility without the need of storage. An advantage of storage above load management is that it adds reliability to the network. When distributed storage is applied in the network, this should be taken into account when determining the size and operation of the storage to optimally benefit from this advantage.

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IX. BIOGRAPHIES

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He is currently manager of the Innovation department of Enexis B.V., one of the largest Distribution Network Operators of the Netherlands. His spearheads are energy transition (including distributed generation and smart grids), asset condition assessment and increasing workforce productivity through new technologies. From 2003 to 2007 he was responsible for network planning and for the design of extension, maintenance and renewal policies for Enexis' regional transmission networks. He has authored and co-authored more than 100 papers, covering a broad range of aspects of the electricity supply.

Wil L. Kling (M’95) received the M.Sc. degree in electrical engineering from the Eindhoven University of Technology, the Netherlands, in 1978.

From 1978 to 1983 he worked with Kema, from 1983 to 1998 with Sep and since then up till the end of 2008 he was with TenneT, the Dutch Transmission System Operator, as senior engineer for network planning and network strategy. Since 1993 he is a part-time Professor at the Delft University of Technology and since 2000 also at the Eindhoven University of Technology, The Netherlands. From December 2008 he is appointed as a full Professor and chair of Electrical Power Systems group at the Eindhoven University of Technology. He is leading research programs on distributed generation, integration of wind power, network concepts and reliability issues.

Prof. Kling is involved in scientific organisations such as Cigré and IEEE. He is the Dutch Representative in Study Committee C6 *Distribution Systems and Dispersed Generation* and the *Administrative Council* of Cigré.