Benefits of an Energy Storage Device for a Wind Farm

Martin Aten, John Barton, and Richard Hair

Abstract—**Energy storage has been a long sought after concept that could give several benefits for an intermittent energy source like wind power. The primary objective of the study presented in this paper is to determine the role that energy storage can play in alleviating network constraints and avoid the need for network investment. Two case studies have been considered in which a new wind farm would cause an existing adjacent radial line to be thermally overloaded at times of high wind, unless the generated wind power is curtailed. Important parameters affecting the viability of using energy storage for the purpose of avoiding spillage without reinforcing the network are: line length, ratio of wind farm size to line rating, wind farm energy curtailment, network reinforcement costs, energy storage systems costs, electricity wholesale price, and losses in the store and power conversion.**

Index Terms—**Wind Energy, Energy Storage, Voltage Control**

I. Introduction

There is a fundamental limitation with wind generation as a tradable commodity in that the wind source makes it difficult to guarantee output power at certain points in time. Combining an Energy Storage (ES) facility with a wind farm can provide a wind farm with the following benefits:

- Balancing of power thereby providing standing and spinning reserve [1].
- Improve tradability (arbitrage) by time shifting energy captured from wind, and allowing frequency control.
- Overcoming network constraints such as thermal overloading, thereby allowing deferral of investment in congested overhead lines.
- Enhance power quality by voltage regulation improving transient stability, and mitigating flicker.

While energy storage is often still perceived to be costly, its true value is actually very difficult to assess as it depends on how all related benefits are factored into the evaluation [2]. The cost-effectiveness of energy storage is enhanced if several compatible functions are combined, for example arbitrage, enhanced power quality, overcoming network stability problems and network investment deferral [3].

In large grids, the location of newly proposed wind farms are often in sparsely populated places, where there is typically a shortage of network capacity, resulting in technical constraints. These may be overcome by costly investments in the network, however the higher rating of the upgraded network is only required during times of high wind power generation. If at peak power output of a wind farm there is excessive voltage variation, or thermal overloading in some of the power system components, then this could be alleviated by temporarily storing the energy and dispatching it at a time when there is less wind. This would allow deferral of investments in the network, and more wind energy to be captured, which would otherwise have been 'wasted' e.g. by using blade pitch control. At the same time, the power electronic controllers associated with an energy storage system can improve the power quality at the point of connection of the wind farm and facilitate compliance with some grid code requirements such as voltage control, fault ride through capability, and flicker mitigation [4].

In small isolated power grids, energy storage may be a justified alternative to using diesel generators, not only from an economic point of view due to savings in fuel cost but also when one takes into account the environmental benefit of reduced CO_2 emissions. In the long term, fuel prices are likely to increase, whereas the cost of energy storage technologies is likely to decrease by new developments and mass production.

This paper describes two case studies of wind farms where the use of energy storage is evaluated as an alternative to network investment in the case of a radial line connecting a wind farm to the remainder of the network.

II. Network Constraints for Distributed Generation

Most distribution networks were traditionally designed for the purpose of feeding loads but not for accommodating generator connections. The recent penetration of embedded generation, like wind farms, into the distribution networks can give a variety of technical challenges. These can be summarized as follows [5]:

- Thermal overloading of lines or cables
- Voltage variation exceeding statutory limits
- Increased fault levels that cause switchgear ratings to be exceeded
- Reversal of power through older distribution transformers that may have limited reversal capability due to the tap changer

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M. Aten and R. Hair are with EON UK Power Technology, Ratcliffe on Soar, Nottinghamshire, NG11 0EE, UK (e-mail: martin.aten@eon-uk.com, richard.hair@eon-uk.com).

J. Barton is with Bryte Energy Limited, Loughborough Innovation Centre, Epinal Way, Loughborough, Leicestershire, LE11 3EH, UK, (e-mail: jbarton@bryte-energy.com, rgammon@bryte-energy.com).

- Power Quality
- High losses
- Protection issues

From a performance and flexibility point of view, the most desirable way to overcome thermal overloading of a line would be to replace it with a higher rated line or add another line in parallel. This can however also be a rather costly and problematic solution. Re-conductoring the line with higher rated conductors is not always an option, as the highest rated conductors that the towers can carry, may have been installed when the line was first planned. In that case, the only way to increase the line rating would be to build a new transmission line. In the case of a required replacement, an existing line may be strategically so important that it cannot simply be taken out of usage, therefore a new line would have to be constructed in parallel, after which the older line could be dismantled. Although it may be somewhat easier to obtain planning permission for a new line in parallel with an existing one, planning permission is certainly not guaranteed, and in some cases there may be no space.

One interesting approach to get more power through an existing line is to utilize dynamic thermal rating, where conductor temperature and line sag may be derived by measuring ambient conditions [6]. This concept goes well with wind generation, because at times of high wind power the line conductor will also be cooled down by the wind.

In [7] energy storage was evaluated as a means to capture more wind power in the presence of voltage rise as the main network constraint. Note that if wind turbine generators and/or a Static Var Compensator (SVC or STATCOM) can apply voltage control then this may prevent excessive voltage rise by varying reactive power flow through the adjacent line. The resulting reactive power flow however contributes to the apparent power through the line and may add to a possible thermal overload problem. The main purpose of using an energy store in the scenarios presented here is to overcome thermal overloading problems of a radial line connecting the wind farm to the main grid.

III. Energy Storage Technologies

Different energy storage (ES) technologies are suitable for different applications. A storage time of less than one minute tends to be required for power quality improvement, and transmission grid stability. Note that storage time is defined as the discharge time at rated power. Contribution to spinning reserve and frequency and voltage regulation requires a storage time in the range of minutes, whereas load leveling, peak shaving and energy management may require hours to days worth of energy storage [8]. Table I lists the most common ES technologies considered for utility-scale, and their perceived feasible storage times.

It is envisaged that storage times of hours to days will be required in order to store energy as an alternative to reinforcing the local network to avoid spilling wind energy. Whereas pumped hydro may presently be most established for large and long term energy storage, it would only be applicable and economical for the scenario described here if there happens to be a nearby elevated water reservoir in a hill or mountain as well as a water reservoir at a low level. Moreover, this technology has limited scope for further development and cost reduction. Therefore, Compressed Air Energy Storage and flow batteries, or perhaps future Fuel Cell technology could be suitable ES technologies for the application described here.

TABLE I
Energy Storage Technologies

ES Technology	**Suitable range of storage times**
Pumped Hydro	Hours to many days
Compressed Air Energy Storage (CAES)	Hours to days
Flow Batteries	Hours to few days
Batteries	Minutes to hours
Flywheel	< few minutes
Superconducting Magnetic Energy Storage (SMES)	< few minutes
Supercapactior	< few minutes

IV. Case Study Scenarios

The case study scenarios considered here are meant to illustrate potential benefits of using energy storage in realistic scenarios, though they are not intended to reflect any specific wind farm project currently proposed in reality. Case study scenario 1 is illustrated in Fig. 1 where an offshore wind farm has a proposed capacity of 36MW and is located 8 km off the coast. The grid connection is via a 15km, 33kV line followed by a 32:132kV transformer connecting to the remainder of the grid. The local load at 33kV is assumed to be 1.5 MW at its minimum and 4.5MW at its maximum level. Table II shows the data of a 150mm^2 line that was built originally to feed the local load, which is constrained to transfer less than 23 MVA in summer and less than 29 MVA in winter. The Energy Store is placed onshore before the Point of Connection POC, and can thus be considered to be part of the wind farm output.

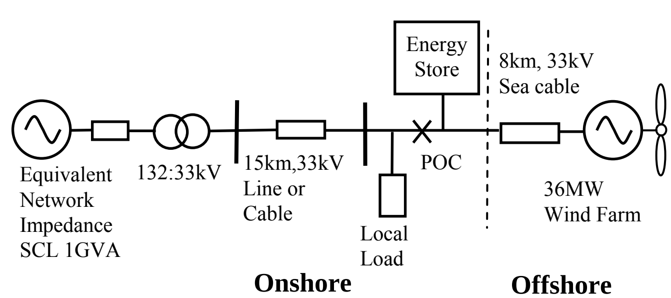

Fig. 1. Case study scenario 1: 36MW wind farm connecting to grid via a constrained 15km 33kV line. Assumed Local Load: 1.5 MW min, 4.5MW max.

TABLE II
ASSUMED 33kV LINE & CABLE DATA

Line / Cable	R Ω/km	X Ω/km	Winter MVA	Summer MVA
150mm^2 line	0.180	0.34	28.9	23.1
300mm^2 line	0.089	0.32	45.7	36.6
400mm^2 cable	0.062	0.11	38.8	35.7

Fig. 2 shows case study scenario 2 where an offshore wind farm has a proposed capacity of 180MW, again located 8km off the coast. The relatively short distance through sea allows the use of 33kV cables, allowing the use of an existing 33:132kV transformer onshore, which is significantly cheaper than if an offshore transformer were needed. The nearest possible grid connection is via a 60km, 132kV line. Table III gives the data of this 175mm^2 line that was built originally to feed the local load having a minimum value of 12MW and maximum of 36 MW. This line would be constrained to transfer less than 105 MVA in summer and less than 131MVA in winter.

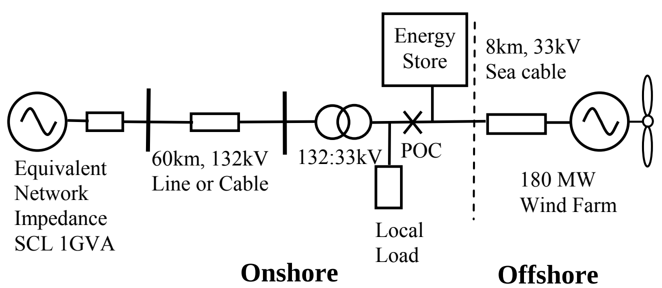

Fig. 2. Case study scenario 2: 180MW wind farm connecting to grid via a constrained 60km 132kV line. Assumed Local Load: 12 MW min, 36MW max.

TABLE III
ASSUMED 132 kV LINE & CABLE DATA

Line / Cable	R Ω/km	X Ω/km	Winter MVA	Summer MVA
175mm^2 Line	0.176	0.373	131	105
300mm^2 Line	0.108	0.376	238	185
630mm^2 Cable	0.038	0.127	202	186

The wind data used has an average wind speed of 8m/s and was measured in a coastal area of England over a period of ten years. The local load profile is derived from actual measurements, but has been scaled to the minimum and maximum values of the load assumed for each scenario. The load profile is adjusted for week or weekend/holiday days and for each month. In both cases the assumed losses in the 33kV sea cables are around 2% at full rated power. The purpose of this study is to evaluate how in both scenarios an energy store could capture more wind power as an alternative to upgrading the lines to a higher rated line or cable. It is assumed in the costing that network reinforcement is not required for any other purpose than dispatching the stated wind power generation in either scenario.

V. CALCULATION METHODOLOGY AND ASSUMPTIONS

The calculation method employed here uses a time stepping approach. The hourly average wind speed is used to calculate a wind power assuming a typical power curve of a 2.75MW wind turbine, scaled to the power rating of the wind farm. Losses in the sub-sea cable are subtracted, as is the power consumed in the local load to give the net power. The net power is compared with the power rating of the line for the season and any excess power is directed to the energy store, via a power electronic converter. If the store is full, then excess power is spilled. When some time later, the net power is smaller than the power rating of the line, the store exports its energy to the local load and the line. The store is assumed for simplicity to have a constant round trip efficiency of 85%, which means that the energy available on discharge is 85% of the energy that was put into it on charging.

The power electronic converter is rated for the maximum power surplus, which is the generated power minus line capacity, sub-sea cable losses and local load. This is also taken to be the maximum discharge power rating of the store. The power losses in the power electronic converter consist of a standing loss of 1% of its power rating plus a dynamic loss of up to 1% of rated power. The dynamic loss is proportional to the square of the power in or out of the store. The losses of the power electronics do not apply when the store is empty as it is assumed that the store and power electronics are turned off. The loss in the main distribution line is calculated using load-flow equations using the impedance values given in tables II and III.

For each scenario, many different sizes (energy capacities) of store were compared. As the size of store increases, the amount of spilled wind energy decreases, but the cost and losses associated with the store increase. Spilled wind power and losses in the store and power electronics were costed at 9.5p/kWh, including a value of 4p/kWh attributed to what is known in the UK as ROCs (Renewable Obligation Certificates). Line losses were costed at an assumed average wholesale electricity price of 5.5p/kWh and do not include the wind power premium because they occur beyond the Point of Connection (POC).

One of the motivations of this study was to get an idea of how low the cost of energy storage should become in order to make it viable in the scenarios described here. Therefore, low energy storage costs were assumed of £50/kWh and £100/kWh, which may approach the lower end of the cost ranges of CAES and flow batteries, according to the cost guide in [9]. The cost estimate for the power electronics DC/AC inverter needed to interface to the network is assumed to be £50/kW. The following network reinforcement costs are assumed:

- £30,000 per km to construct new 33kV OHL
- £230,000 per km to install new 33kV cable
- £350,000 per km to construct new 132kV OHL
- £1,000,000 per km to install new 132kV cable

Actual costs of installing new lines and cables can vary greatly according to numerous factors such as the landscape, landowner(s), obstructions, price of raw materials and local labour costs.

All assumed costs are highly indicative and were calculated over a 20-year lifetime of the wind farm and of the energy store. The net-present-value (NPV) of electricity flows were calculated as simply the annual totals multiplied by 20 years, as interest rate effects were assumed to be cancelled by future increases in the price of electricity.

VI. Case Study Results

The net benefits of energy storage illustrated in Figures 3 to 6 below show the optimum store size in each scenario, for energy storage costs of £50/kWh and £100/kWh. In each case the net benefit of the store is equal to the wind power saved, less the cost of the store and its power electronic converter and less any increase in losses in the store, power electronics and in the local line. Net benefit is evaluated with reference to the case of no store in which all excess wind power is spilled. The optimum store size is that where the net benefit of the store is a maximum. This also corresponds to the size of store that gives the wind farm project its maximum value. It can be seen that for storage at £100/kWh, the optimum store size in each scenario is lower than for storage at £50/kWh. This is because as the store cost increases, it is more cost effective to spill more wind power and reduce the size of the store. Even at £50/kWh, a considerable fraction of the wind power available is spilled during windy periods. The sizes of store that would be required to eliminate all wind power spillage would be much larger and prohibitively expensive: almost 700MWh in scenario 1 and almost 3000MWh in scenario 2.

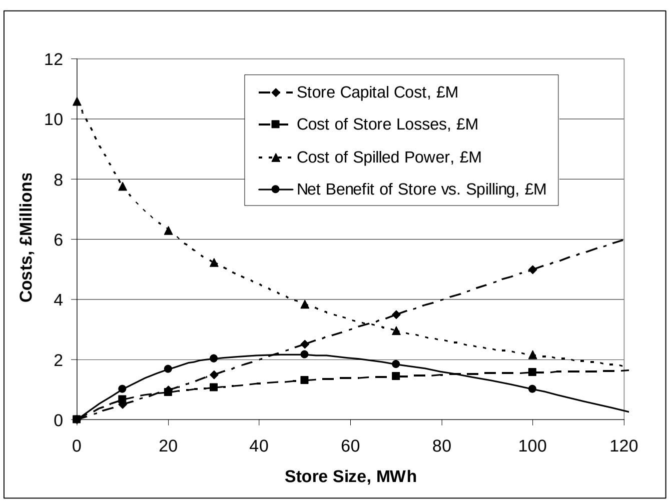

Fig. 3. Store size optimization for a 36 MW wind farm in scenario 1 with £50/kWh energy storage

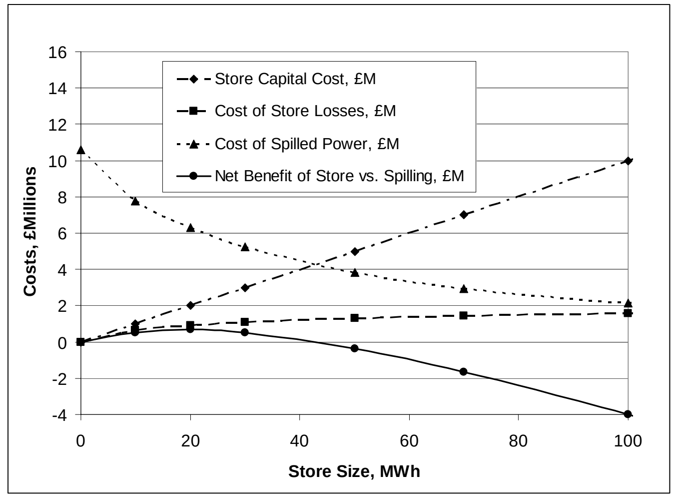

Fig. 4. Store size optimization for a 36 MW wind farm in scenario 1 with £100/kWh energy storage

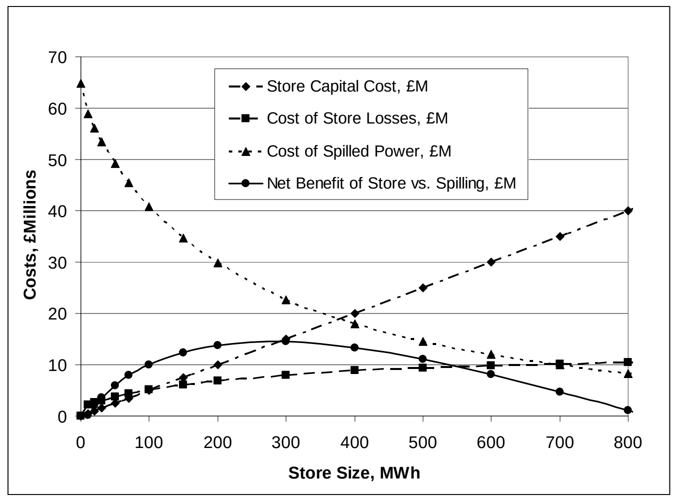

Fig. 5. Store size optimization for a 180 MW wind farm in scenario 2 with £50/kWh energy storage

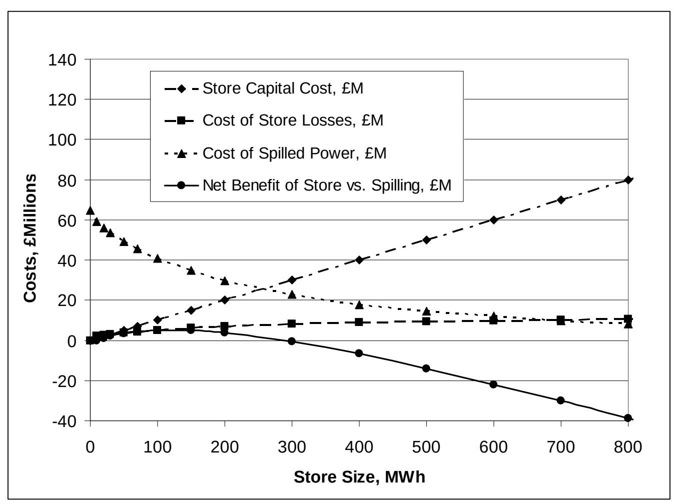

Fig. 6. Store size optimization for a 180 MW wind farm in scenario 2 with £100/kWh energy storage

For each scenario, the costs and benefits of different options are compared in tables IV and V respectively. These options include the above calculated store sizes in the energy storage options. The datum case for each scenario is the connection of the wind farm to the existing line with no energy storage.

The results show that it is not worth reducing the sizes of the wind farms to match the local line ratings. Even with some energy spillage, wind power is so valuable that it is worth building the entire wind farm capacity. It also appears that the most cost effective action is to build an additional overhead line of higher rating. However, planning permission may not always permit this course of action.

If storage costs £100/kWh, then an additional underground cable could be a better option than an energy store in both scenarios. However, if storage costs only £50/kWh, then in scenario 2, a 300MWh energy store would be comparable with a new underground cable, provided its maintenance costs and losses are relatively low, and its life time is at least 20 years. Note also that network reinforcement would add much more transmission capacity allowing the dispatch of more power in case of a future expansion in generation if applicable.

TABLE IV
COST AND BENEFIT ANALYSIS OF OPTIONS FOR SCENARIO 1, A 36 MW WIND FARM, 33 kV CONNECTION

Option:	Spill Excess Power	Reduced Wind Farm, 25MW	New OHL 300mm^2	New Cable 400mm^2	Energy Store at £50/kWh	Energy Store at £100/kWh
Wind Farm Cost, £M	56.1	39.2	56.1	56.1	56.1	56.1
Value of Wind Power, £M	232.8	161.7	232.8	232.8	232.8	232.8
Cost of Loss in Sub-Sea Cable	3.2	2.2	3.2	3.2	3.2	3.2
Cost of Loss in Local Line, £M	6.9	4.4	6.4	5.4	7.2	7.1
Cost of Spilled Wind Power, £M	10.6	0	0	0	3.8	6.3
Power Rating of Store, MW	0	0	0	0	10.7	10.7
Energy Rating of Store, MWh	0	0	0	0	50	20
Cost of Store Losses, £M	0	0	0	0	1.3	0.9
Cost of Store, £M	0	0	0	0	2.5	2
Cost Power Electronics, £M	0	0	0	0	0.5	0.5
Cost of Line Replacement, £M	0	0	0.5	3.5	0	0
Net Value of Project, £M	156.0	115.9	166.7	164.7	158.2	156.7
Benefit Relative to Spilling, £M	Datum	-40.1	+10.7	+8.7	+2.2	+0.7

TABLE V
COST AND BENEFIT ANALYSIS OF OPTIONS FOR SCENARIO 2, A 180 MW WIND FARM, 132 kV CONNECTION

Option:	Spill Excess Power	Reduced Wind Farm, 118MW	New OHL 300mm^2	New Cable 400mm^2	Energy Store at £50/kWh	Energy Store at £100/kWh
Wind Farm Cost, £M	277	182	277	277	277	277
Value of Wind Power, £M	1164	763	1164	1164	1164	1164
Cost of Loss in Sub-Sea Cable	16	11	16	16	16	16
Cost of Loss in Local Line, £M	34	20	33	25	36	35
Cost of Spilled Wind Power, £M	65	0	0	0	23	41
Power Rating of Store, MW	0	0	0	0	60	60
Energy Rating of Store, MWh	0	0	0	0	300	100
Cost of Store Losses, £M	0	0	0	0	8	5
Cost of Store, £M	0	0	0	0	15	10
Cost Power Electronics, £M	0	0	0	0	3	3
Cost of Line Replacement, £M	0	0	21	60	0	0
Net Value of Project, £M	772	551	817	787	787	777
Benefit Relative to Spilling, £M	Datum	-221	+45	+14	+14	+5

VII. DISCUSSION

The scenarios with assumptions chosen above illustrate cases when energy storage is closest to becoming economic in a role of minimizing wind power spillage. If a wind farm is smaller in relation to the line rating, then the store would be under-utilised. It would not be cost effective to build an energy store for the few occasions when the wind power exceeded the sum of the export capability of the line and the local electricity demand. If by contrast, the wind farm is much larger in relation to the line rating, then the benefits of a new overhead line or even a new underground cable tends to be much more economical depending on the nature of the network and line distance involved. For a small surplus of wind power, the advantage of energy storage compared to line replacement is that, since the cost of ES is assumed to be proportional to the energy capacity, the ES cost is decreased with less required energy capacity. A new line or cable would be under-utilised in case of a small surplus of wind power due to a 'step increase' in power rating of the line with a fixed cost increase. On the other hand, the cost of a line is approximately proportional to its length, therefore an energy store becomes relatively more cost effective if the line to be installed is excessively long.

Note that the losses of the adjacent line are different after the Point of Connection for the different connection methods. Whereas energy storage has the effect of higher utilisation of an existing line and smoothing out the maximum currents, construction of a new line has the beneficial effect of reducing the losses by a reduced impedance. This skews the economics in favour of line and cable installation and away from energy storage. Note however that in the liberalised UK electricity market, the revenue of the generated wind power is presently determined by the power measured at the point of connection (POC), therefore the losses incurred after the POC make no difference to the revenue for the wind farm owner.

VIII. Conclusions

Energy storage can provide several benefits for a wind farm, which have to be combined in order to make it more economically viable. The work in this paper focuses on using energy storage as an alternative to network reinforcement, in the presence of a thermal loading constraint in an adjacent line. The main disadvantage of using energy storage for this purpose is that the storage capacity would have to be excessively large and expensive to minimise wind power spillage effectively: the more wind power spillage is avoided the higher and more costly the energy capacity needed, whereas the more savings are made on the energy storage, the more revenue is lost by having to spill wind power. On the other hand, avoiding wind power spillage can be achieved relatively economically by constructing a new and appropriately rated line subject to its length. For energy storage to become more attractive in future there is a need for reduced capital costs, higher efficiency of conversion, lower space take and increased life time.

IX. Acknowledgment

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XI. Biographies

Martin Aten obtained his MSc degree (Electrical Engineering) at Delft University of Technology, Delft, the Netherlands in 1995 and his PhD degree (Electrical and Electronics) at UMIST, UK in 2003. He was employed by ALSTOM T&D Power Electronic Systems in Stafford, UK from 1995. From 2003 he was employed by Smiths Aerospace in Wolverhampton, UK and from 2004 he was employed as a Technology Consultant at AREVA T&D Technology Centre in Stafford, UK. Since January 2006, he is employed as an Electrical Systems Engineer with EON UK Power Technology in Ratcliffe-on-Soar, UK carrying out network studies and research in electrical transmission and distribution systems and energy storage. Martin Aten is registered as a Chartered Engineer with the IET (the Institution of Engineering & Technology) and is a member of the IEEE.

John P. Barton was born in Nottingham, England on 20th September 1966, He received the B.A. and M.A. degrees in Mechanical Engineering from Cambridge University in 1989 and 1993. He worked on the design of gas turbine compressors and fans at Rolls-Royce plc. before receiving the MSc. In Renewable Energy Systems Technology from Loughborough in 2001. He has now completed a PhD at Loughborough University and is working as a research associate at Loughborough University while also working as a director of Bryte Energy Ltd. His area of interest is the use of energy storage with renewable energy sources in electricity networks.

Richard Hair holds a B. Eng (hons) Electrical and Eletronic Engineering degree. From 1982 he worked as an Electrification Engineer with the British Railways Board. From 1988 he was responsible for 132kV system design as an engineer with East Midlands Electricity. From 1994 to 1999 he was a project manager with East Midlands Electricity plc, and from 1999 he worked as an Electrical Engineer with Powergen Power Technology, Since 2000 he is Head of the Electrical Systems Group at EON UK Power Technology, responsible for a team providing computer modelling of network loadflow, fault level, and transient stability of transmission and distribution systems. Richard Hair is a Chartered Engineer and is a member of the Institution of Engineering & Technology (IET).