# A New Control Scheme in a Battery Energy Storage System for Wind Turbine Generators

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*Abstract*--**This paper introduces a new control strategy for battery energy storage systems used in wind generation. It is specifically targeted to large wind installations, specifically offshore wind applications. This control strategy maximizes the life of the battery and increases the efficiency of the energy storage system while still balancing the power fluctuations of a large wind turbine system. The depth of discharge and remaining battery life are the key parameters considered in this approach. The proposed control scheme is applied to the battery package such that each battery cell is controlled individually. Individual cell depth of discharge is controlled and cell life is calculated periodically so that all cells within the package reach the end of life at the same. Total storage capacity and individual battery cell size are calculated based on the characteristics of the wind turbine. To verify the presented method, a case is studied in PSCAD and corresponding results are provided.**

***Index Terms*-- Wind power, off-shore wind, Battery Energy Storage, Battery life, Variable Speed Wind Turbine, Control processor unit, depth of discharge.**

## I. NOMENCLATURE

| | |
|---|---|
| $R_{internal}$ | -Internal resistance of battery [ohm], |
| $C_{batt}$ | - Capacity of battery [joule], |
| i(t) | - Charge/discharge current of ESS [A], |
| $E_{ex}$ | - Stored/released energy [joule], |
| P (t) | - Charge/discharge power [watt], |
| t | - Charge/discharge time [sec], |
| τ | - Duration from the beginning to the present time [sec], |
| $P_{gen}$ | - Generated active electrical power of generator [MW], |
| $P_{ref}$ | - Reference power (output electrical power) [MW], |
| P(t) | - Difference between $P_{gen}$ and $P_{ref}$ [MW]. |

## II. INTRODUCTION

THERE is a growing consensus between scientists, policy makers, and the general public: we need to diversify our energy portfolio away from fossil fuels. There are many reasons why energy diversity is desirable, but they fall into three main categories: finite nature of fossil fuel resources, security of energy supplies, and climate change. Wind and solar energy systems have the potential to provide a large percentage of the world's power needs. In the United States, wind is the fastest growing renewable energy source averaging an annual increase in consumption of about 71% [1]. This is one reason why wind energy has been the focus of so much recent research. In order to understand the impact of wind energy on the grid, the wind turbine system must be comprehensively studied [2]. Due to natural characteristics of the wind, wind speed tends to fluctuate, causing the generated electrical power to fluctuate as well. This fluctuating power output imposes an upper limit on the percentage of the total electrical power (penetration) that can come from wind. The grid needs to be reliable and stable. If wind penetration is below around 20%, then the generated power fluctuations can be mitigated by natural gas plants or other conventional plants. If wind penetration is to be higher, then the electrical power it dispatches the grid must be smooth and stable. Energy storage systems (ESS) can provide power when the electricity generated from wind is less than the expected output, and can consume power when the generated electricity is higher than expected. The net effect is a smooth stable power supply. Of all the ESS available, battery energy storage systems (BESS) have been the ESS of choice when it comes to wind power. Therefore this paper examines the application of BESS to wind turbine systems. BESS have also been deployed in a myriad of applications including electric vehicles and solar power systems. Many different kinds of ESS have been studied [1, 2, 3 and 4]. Of these, batteries show high promise due to their high energy capacity, the maturity of the technology, and their high capacity per dollar ratio [2]. Of the available ESS, BESS does not have the highest energy capacity. For example, super-capacitive energy storage schemes have a higher potential capacity than battery systems. However, the technology employed in supercapacitors is in the early stages of development. Other promising ESS technologies are currently too expensive to be deployed commercially. For these reasons, BESS is the superior ESS available.

This paper is relevant because a large majority of wind ESS in use today utilize battery technology, and battery technology will likely be the dominate storage system for the foreseeable future.

The paper is outlined thus: In parts *A* and *B* of section III, modeling of a wind turbine and battery storage system are described. Following this (part *C*), equivalent circuits and available battery technologies are described. The algorithm for calculating the remaining life of a battery is described in part *D* of section III. Following this, a depiction of battery-sizing methods is relayed. A detailed explanation of the new control scheme is provided in part *E* and the model used for

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verification is described in part *F*. Results and conclusions are provided.

The design outlined in this paper aims to increase the battery life and efficiency of the BESS in a wind turbine system. To find the proper size of the BESS some technical notes and equations are presented. We present a method to estimate remaining battery life and finally, the control criteria and a detailed explanation of the factors battery life is dependent upon. Possibly damaging practices to BESS such as deep depth of discharges, or efficiency-marring practices such as energy-wasting cycling currents are also discussed, as well as the techniques employed by this control scheme in order to avoid these practices. Two case studies are also presented to exhibit the performance of the new design.

## III. WIND TURBINE GENERATION SYSTEM

In this paper, we modeled a type D (type 4) wind turbines with full scale converter which can produce 25 percent more energy than other types. The Type D turbine also has the best protection of all options for wind energy generation [2]. In other words, a fault from grid side cannot damage the generator and a fault within the generator-side does not pass to the grid side due to the use of applied power electronics in the wind turbine. In our model, we also used a permanent magnet synchronous generator (PMSG) based wind turbine, which is assumed to be the dominant generator in future. The detailed configuration of wind turbine system including BESS is shown in Fig. 1.

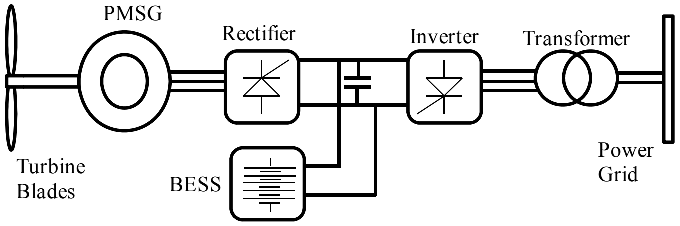

Fig. 1. Variable speed wind turbine configuration with battery energy storage system, Type D

All needed components of the wind turbine system are modeled in PSCAD including: the wind simulator, turbine and generator, full-scale converter, battery and some controllers.

### *A. Wind Simulator, Wind Turbine, PMSG and Converters*

The dispatch time is usually between 15 minutes to 120 minutes (all simulations for this paper were for 90 or 60 minute dispatches). The wind speed profile data originates from the measured data available from a wind turbine station in Audubon, United States [5] which is simulated using the wind simulator block in PSCAD [6]. Using available model blocks in PSCAD we modeled the wind turbine, PMSG, rectifier [4] and inverter [7].

### *B. Battery and Sizing of Battery*

Batteries are characterized in many terms including: power density, energy density and life cycle. Life of a battery is dependent on many variables. When the battery reaches the end of its useful service life, it is informally called a “dead” battery. The number of life cycles and the depth of discharge are the most important factors to consider when determining the battery life. The equivalent circuit model of the battery used in this paper is a combination of two resistors, one capacitor and one voltage source, as shown in Fig. 2 [8].

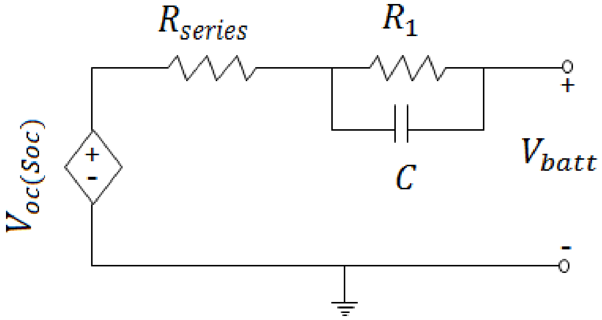

Fig. 2. Battery equivalent circuit

Different batteries have different characteristics, but lithium-ion batteries generally need to be replaced after 200 to 1000 charge-discharge cycles. This may take up to 4 or 5 years. It is a common misconception that the voltage of a battery will remain constant over the life of a battery. In reality the voltage is highly dependent on the depth of discharge of the battery, as shown in Fig. 3 [8].

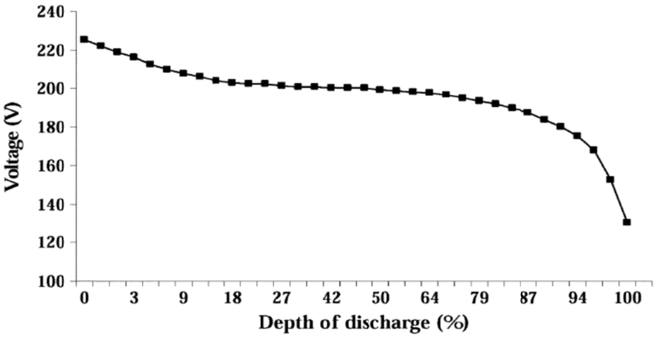

Fig. 3. Voltage of lithium battery versus its depth of discharge

The voltage of battery is also dependant on the freshness of the battery (batteries lose their efficiency, capacity and voltage levels when they are close to death). If more advanced Lithium-ion phosphate batteries are used, they may last up to10 years with 7000+ charge/discharge cycles [9].

### *C. Internal Connection of BESS*

Commercial battery cells are limited to a specific voltage, energy capacity and power. In choosing the proper BESS, we have to consider all these factors. The voltage has to large enough for the converter to match it with the DC-link voltage. The energy capacity of BESS has to be calculated so that the BESS is able to release and store the needed energy such that it does not become completely drained or filled at any point during the life of the turbine. If the capacity of the BESS is too small, it may become filled which will prevent it from storing any extra energy the wind turbine may produce, which could result in the output power being higher than the rated power of the turbine. Similarly, if the BESS capacity is too small the battery cannot release energy to compensate for brief or sustained lulls in wind speed. However we must make sure that the BESS capacity is not overly large. If the capacity is higher than is needed, it is a waste of money. Additionally, the BESS must have a large enough energy storage capacity (in terms of MJ) and be able to discharge power at a high enough rate (in terms of KW or MJ per second) to charge and discharge the DC-link. If the rate capacity is too small then the BESS cannot suitably charge or discharge the DC-link. One criteria of the DC-link is that it must provide a high output voltage. This is accomplished by coupling a number of battery cells in series (called a battery branch). If the battery branch's voltage is close to the DC-link voltage, the buck-boost converter works properly. The acceptable difference between BESS voltage and DC-link voltage is dependent on the ability of the converter which is provided by the manufacture. On the other hand, the power densities of commercially available batteries are limited. In order to achieve an acceptable power density for the BESS, we have to connect some battery branches in parallel. For example, if the battery can release/store 1 MJ energy per minute and the maximum needed energy is 4 MJ per minute, we have to connect 4 battery branches in parallel. Many studies have focused on utilizing a single branch of batteries to provide an ESS for wind turbines. Other researchers have proposed that we use several battery branches in parallel. We propose to use the branches in parallel method, as shown in Fig. 4. What is unique about this paper is that we propose a control strategy for a multi-branch system that fits the requirements of wind turbines.

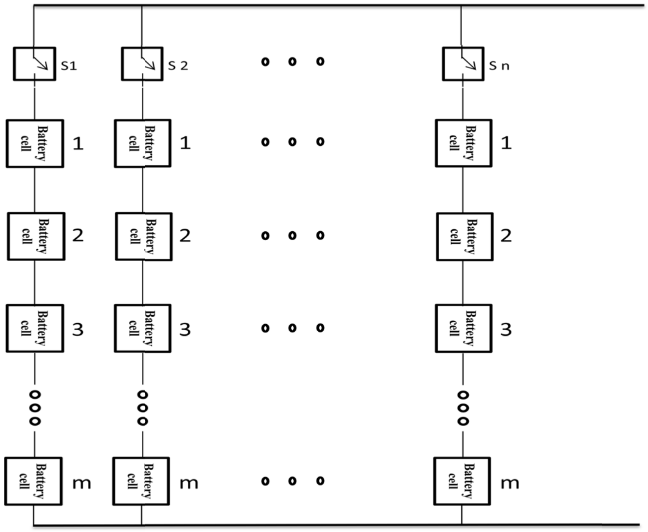

Fig. 4. Battery energy storage configuration

If the energy capacity of the BESS is calculated in advance, we can choose the energy capacity of each battery cell. In order to control the operation of the battery cells, switches are connected in series with the individual battery branches. These switches connect or disconnect the battery branches from the converter based on the difference between the generated electrical power and electrical reference power. For example, if each battery branch's power is 1 MW, and the difference between the generated power and the reference power is 2 MW, then 2 battery branches are connected to the converter and all other branches are left disconnected.

### *D. Remaining Life Estimation Method*

In this paper, we present some equations to find the proper model for estimating the remaining battery life. The most important terms in building the model are Depth of Discharge (DOD), temperature and the number of charge/discharge cycles. If we consider these terms the battery life estimation is approximately equal to the actual battery life [9, 10 and 11].

- Cycles of charge and discharge: after this number of charge and discharge cycles the battery loses its capability to provide power (its life is over). For the available lead-acid in our previous work the life cycle is between 200 to 1000 cycles.
- Depth of Discharge (DOD): the range of life cycle is wide. To calculate the exact battery life, we have to find the right life cycle. The battery life cycle is at its minimum range when the battery operates at high DOD and the battery life cycle is at its maximum range when it works at low DOD.
- Temperature: due to internal resistances some energy will be lost as heat during charge/discharge cycles. These internal resistances are temperature dependent, and become larger as the battery gets hotter. Consequently, the losses in a hot battery are higher than in a similar cooler battery.
- Rate of discharge: If the battery is charged or discharged at a higher rate than it is rated for, the life of the battery is significantly reduced. That is, if the battery operates at or below its rated values, it lasts significantly longer than a battery that is operated at above its rated values. One common way of determining the charge/discharge power is by monitoring the current passing through the battery.

Life of battery is highly dependent on the operation of battery at a specific DOD as shown in Fig. 5.

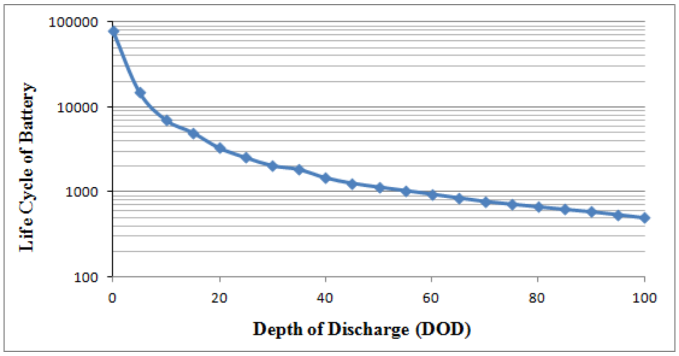

Fig. 5. Battery life is dependent on battery's operation in different DOD

For Example: Consider a battery supplying a DC-link. In this example, the DC-link needs 1 KW in 10 seconds. To provide this, a lossless battery will provide 10 KJ of energy. However, all batteries have losses that must be considered. If the discharge rate of the example battery is higher than its rated value then the losses will be greater than if the discharge rate was lower than the rated values. Thus, the battery must release more of its stored energy in order to supply the DC link (perhaps 10.5 KJ instead of 10 KJ). This equates to a decreased battery life time. Thus, if we control the rate of charge and discharge we can improve the overall efficiency of the ESS. To express the remaining battery life quantitatively, consider the following.

L is the maximum exchanged energy between the battery and the DC-link during one battery life in the best conditions, $E_{cap}$is the battery capacity in term of energy and N is number of life cycles (at specific DOD).

The maximum life cycle is different when battery operates at different DODs. In this case study, we suppose that the battery energy capacity is 2KJ. If the battery exchanges 2 KJ energy at 10% DOD, the life cycle is 7000. On the other hand, if the battery exchanges 2 KJ at 100% DOD, the life cycle is 500. The maximum amount of energy that the battery can exchange over its life ($L_{final}$) is found by multiplying the capacity of the battery by the number cycles the battery can achieve over its entire life at a specific DOD (life cycles), as shown in (1).

$$L_{final} = E_{cap} * N \tag{1}$$

where $N$ is the life cycles and $E_{cap}$ is the capacity of the battery.

The amount of exchanged energy is found by (2).

$$E_{ex} = \int_0^\tau P(t).\ dt \tag{2}$$

P(t) is the absolute value of the difference between the instantaneous power and the reference power, as in (3).

$$P(t) = |P_{gen}(t) - P_{ref}| \tag{3}$$

The generated power can be calculated by the wind speed and other characteristics of the wind turbine. The difference between the reference power and the generated power is the power that must be discharged from or consumed by the battery.

By saying that the battery operates at a specific DOD, we mean that the changes in the DOD are negligible, that is, if the battery release and stores an amount of energy that is only a small percentage of its total capacity, we can say that the DOD remains the same. For example, if we have a 2 KJ battery that exchanges 10 or 20 joules with the DC-link, then we consider the battery's DOD to remain the same. When the total amount of energy that has been exchanged between the battery and the DC-link (both charged and discharged) becomes equivalent to the capacity of the battery, we say one cycle has been completed.

For example, suppose the battery's capacity is 2 KJ and maximum life cycle is 90,000. The battery would last longest if the operating DOD was small. So, if the battery operated at a 1% DOD over the course of its life, then the battery would reach the end of its life after it has exchanged 180 MJ. If the battery operated at a 10% DOD over the course of its life, then it would have a life cycle of 7,000 (from fig. 5) and would reach the end of its life after it exchanged 14 MJ. Comparing the amount of energy exchanged during the 1% DOD lifetime and the 10% DOD lifetime we see that 13 times more energy was exchanged during the 1% DOD cycles. Therefore we say that operation at 10% DOD is 13 times worse than operation at 1% DOD. We can call this ratio between the life cycles of operating at a higher DOD to the life cycles of operating at 1% DOD the downgrading factor, or $K_{DOD}$. We can find $K_{DOD}$ by dividing the life cycles at the ideal case by the life cycles of the present operating case as shown in (4).

$$K_{DOD} = \frac{\text{life cycles at ideal case}}{\text{life cycles at present case}} \tag{4}$$

To consider the effects of using different DODs throughout the life of the battery, we apply $K_{DOD}$ to (3). The following equations show the effects of operating at different DODs. We can find the total energy exchanged between the BESS and the DC-link by taking into account the operating DOD at each time step. That is, we multiply $P(t)$, by the downgrading factor ($K_{DOD}$) of operating at that specific DOD for that specific time step. We then integrate this over all time steps, as shown in (5).

$$E_{ex} = \int_0^\tau P(t).K_{DOD}.\ dt \tag{5}$$

We must also take into account the internal losses of the battery. This is a simple matter of multiplying the internal resistance of the battery by the square of the current passing through the battery, as in (6). Note that the internal resistance will increase as the temperature of the battery increases

$$P_{loss} = R_{internal} * I(t)^2 \tag{6}$$

Due to these losses, the battery must release more of its stored energy than is required by the DC-link. The extra energy is wasted as heat. If the battery gets hotter, the amount of energy wasted gets higher was well, lowering the efficiency of the battery cell and shortening the life of the battery.

When the battery exchanges 180 MJ with the DC-link, the battery reaches the end of its serviceable life and the ratio of the exchanged energy divided by final L shows the consumed life of the battery, as in (7).

$$(L_{past}) * 100\,\% = \frac{\int_0^\tau (P(t).K_{DOD}.\ + R * I(t)^2)dt}{L_{final}} \tag{7}$$

We also must be able to calculate the life of the battery. The maximum life of the battery is achieved when the battery works at the lowest DOD and also without loss. In this case, the total exchanged energy will be 180 MJ, and the average rate of life consumption is calculated by dividing the exchanged energy (considering effect of DOD) and power losses by the total time that has passed ($\tau$), as shown in (8).

$$R_{ave} = \frac{\int_0^\tau (P(t).K_{DOD}.\ + R * I(t)^2)dt}{\tau} \tag{8}$$

The remaining battery life (RBL) can be calculated by subtracting the amount of energy that has already been exchanged between the battery and DC-link and the power losses from the total amount of energy that the battery can consume, then dividing this by the average rate of life consumption, as in (9).This equation assumes that the rate energy consumption will continue at the current rate. If the rate of consumption is changed, then the remaining battery life needs to be re-calculated.

$$RBL = \frac{\left(L_{final} - \int_0^\tau (P(t).K_{DOD}.\ + R * I(t)^2).dt\right)}{R_{ave}} \tag{9}$$

### *E. Detailed Explanation of BESS*

In the proposed new design we considered the following criteria:

- *Past Life of each branch*
- *DOD*
- *Resting mode (self-discharge & Temperature)*

- *Cycling current*
- *All battery branches have to die at the same time*
- *Discharge/charge rate*

If all of the above criteria are considered, a long-lasting BESS will result. As mentioned above in section C, we have some battery branches connected in parallel, where each branch is a number of battery cells connected in series. The BESS's control unit operates the switches of each battery branch so as to maximize the life time of the battery cells.

*Past Life of each branch:* in the proposed control design, the past life of each battery branch is an input for the control algorithm. The algorithm considers the life of each battery branch when deciding which branches to connect to the DC-link to meet a certain power demand. Branches with higher remaining lives will be connected before branches with lower remaining lives. The life of the batteries is calculated using the introduced model in section D (if the battery is fresh, the past life equals zero).

*DOD:* Operating the battery between 10% DOD and 20% DOD yields the longest life for the battery while still providing enough power to the DC-link and maintaining enough capacity to store energy.

*Resting mode (self-discharge & Temperature):* The manufacture of each battery provides a table of suggested temperature ranges for battery operation. If the battery operates at temperatures outside this range, it does not work efficiently and the battery gets damaged. In our design, we control the operation of all branches such that after a certain amount of work they go to the resting mode. The resting mode allows the batteries to cool down. In other words, during charge/discharge when the current passes through the battery, the internal resistance produces some heat causing the battery to become warm. If the battery becomes too warm, the efficiency will be lowered.

Another factor which has a great effect on the efficiency of the battery is self-discharge. When the battery is always connected to the system (even when it is not charging/discharging), the battery undergoes self-discharge. Over short time periods, the effects of self-discharge are negligible, but in long term the effects can be large (when battery is not connected to the system, the self-discharge of battery is considerably less).

*Cycling current:* Cycling current is the current that flows from one battery branch into another battery branch that is connected in parallel. Cycling current occurs due to voltage difference between battery branches. As shown in fig 3, the cell voltage is dependent upon DOD. Our control system maintains equivalent DODs across all battery branches so that there is a minimal voltage difference between different branches. This keeps cycling current to a minimum.

*All battery branches have to die at the same time:* All batteries of the same classification do not last for the same amount of time. Even if the batteries are produced at the same factory with the same materials and processes, small imperfections cause some batteries to die before others. Taking this into consideration, we monitor and control the work each battery branch performs. If one battery branch has done less work than another branch, it will be more likely to be connected to the DC-link. It is necessary to ensure that all branches die at the same time because if one branch were to die before the others, the whole system could lose its maximum power. For example, if 4 battery branches are connected in parallel with each branch rated at 1MW (4MW total) and one branch died before the others, the combination could only achieve a maximum power of 3 MW and could supply 4 MW if it was required..

*Discharge/charge rate:* If the rated power of each branch of battery is 1 MW, and if the DC-link needs 1 MW, just one battery branch's switch is "On" and the other batteries are not connected to the DC link. Similarly, if the needed power is *n* MW, then *n* switches are "On" and the remaining switches are "Off". The number of batteries connected to the DC-link is dependent on the difference between generated power and reference power, as shown in Fig. 6 and Fig. 7.

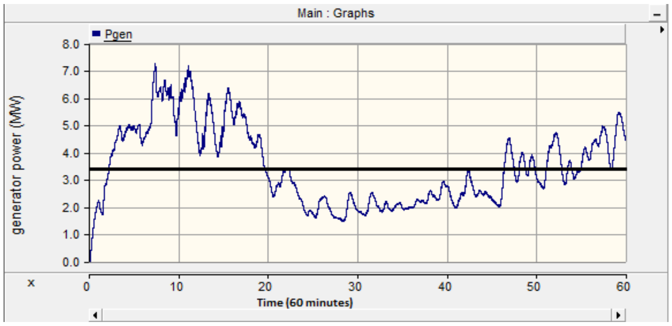

Fig. 6. Electrical generated power and reference power in 60 minutes

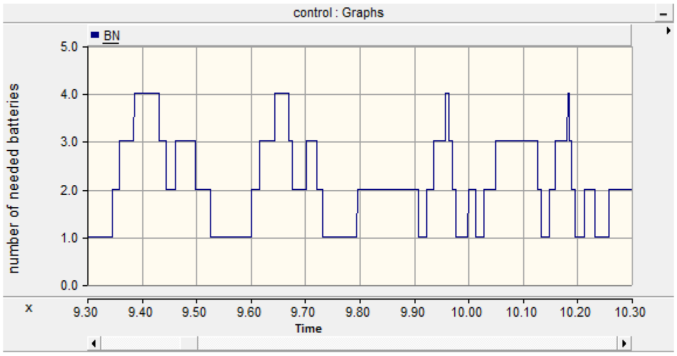

Fig. 7. Number of connected batteries in 1 minute

The difference between generated power and reference power is the amount of power that the BESS must provide. In one case study, over the course of one week the difference between the generated and reference powers never exceeded 4MW. The generated power varied from 0 to 7 MW while the reference power was 3.5 MW.

The control unit utilizes information about the batteries, such as remaining life and DOD of each branch, as well as information from the system, such as reference power, in order to determine which batteries to connect to the DC-DC converter. The most important factors are depth of discharge, rate of discharge, temperature and past life of the batteries. DOD and past life of battery are the primary factors for the control block to consider when determining which branches to connect. The other terms are also considered in order to have accurate control of the system.

The control algorithm sorts the batteries in terms of DOD and remaining life. The battery will best perform if its DOD is around 15%. At this depth of discharge it will operate within the ratings specified by the manufacturer and have considerably long life cycles. Thus, batteries that have a DOD close to 15% will receive priority when determining which branches to connect to the DC-DC converter.

### *F. Simulation and Results*

*Case study 1:*

In this case study, 3 fresh batteries with the same consumed life and the same initial DOD are connected in parallel. The above described control considerations are applied to the wind system and the following results are provided. The SOC of battery A is shown in Fig. 8 (Other SOCs are almost the same).

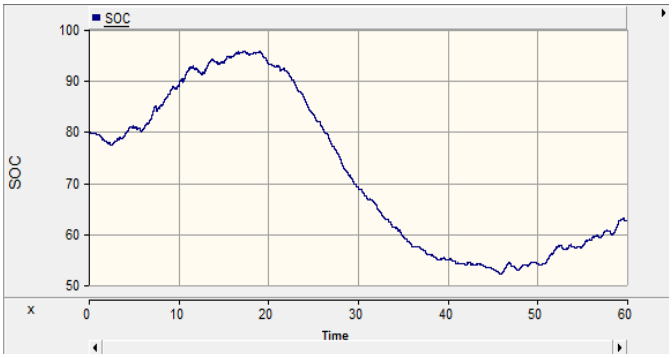

Fig. 8. SOC of battery A in 60 minutes

The remaining battery lives (initial and final lives) are shown in table 1.

TABLE 1
VALUE OF BATTERY LIVES (INITIAL AND FINAL)

| Battery | Initial life (percent) | Final life (percent) |
|---|---|---|
| A | 80 | 79.638 |
| B | 80 | 79.645 |
| C | 80 | 79.623 |

Using (8) we can find the rate of life consumption. The rate of life consumption is very high after 35 minutes. This increase in rate of life consumption is due to the large DOD of the battery. At such a DOD, the life of the battery is decreased significantly.

*Case study 2:*

In this case study, we set differing initial conditions for the battery branches to see if they can work properly or not. Such a situation might arise if one of the batteries gets damaged, has a lower quality, etc. The initial conditions of three battery branches are shown in table 2.

TABLE 2
VALUE OF BATTERY LIVES (INITIAL AND FINAL)

| Battery | Initial SOC | Initial life | Final SOC | Final life | Consumed life unit |
|---|---|---|---|---|---|
| A | 80 | 70 | 52.5 | 69.3865 | 409 |
| B | 70 | 75 | 53.230 | 74.454 | 460.5 |
| C | 75 | 85 | 58 | 84.345 | 493 |

As has been discussed, the control unit will ensure that individual battery branches to not operate outside their rated specifications. Note that the final SOC of all battery packages is almost the same which avoids current cycling. At any point in time there are either only one or two branches connected to the system, which also eliminates current cycling. As expected, the simulated control unit used the battery with the largest initial life the most. The remaining battery lives are not equal at the end of the simulation; however, because the control unit also ensured that the DOD never became too large and also allowed each branch to have sufficient rest time. In this simulation, the BESS worked in with one-branch-connected for 11.45 minutes, with two-branches-connected for 22 minutes and three-branches-connected for 26.5 minutes over the 60 minute test period. In terms of each battery operation time, battery A is connected to the system for 27.8 minutes, battery B is connected to the system for 32.25 minutes and battery C is connected to the system for 34.06 minutes. The results are shown in table 3.

TABLE 3
OPERATION TIME OF DIFFERENT BESS MODEs AND BATTERIES

| Battery | Operation time | # Battery connected | Operation time (min) |
|---|---|---|---|
| A | 27.8 | One battery | 11.45 minutes |
| B | 32.25 | Two batteries | 22 minutes |
| C | 34.06 | Three batteries | 26 minutes |

Wind turbines' parameters are given in table 4.

TABLE 4
VALUE OF PARAMETERS USED IN WIND TORBINE MODEL

| Air density | Power coefficient | Wind rated speed | Blade diameter | Wind turbine rated power |
|---|---|---|---|---|
| 1.229 | 0.42 | 11 m/s | 57 m$^3$ | 7 MW |

## V. DISCUSSION AND CONCLUSION

The proposed control design address three goals: increasing the life of the battery, increasing the efficiency of the system, and utilizing an ESS that matches the characteristics and requirements of large wind turbines. The proposed parallel configuration BESS matches the high voltage requirements of a wind turbine's DC-link. The proposed configuration coupled with the proposed control strategy has several advantages over other ESS:

- The size and capacity of the BESS can be designed to the requirements of a specific application.
- Batteries operating under the proposed control scheme operate at or just below their rated values, vastly improving efficiency. They experience low individual charge/discharge rates, which extends the life of the battery and lowers the operating temperature, improving efficiency.
- The control scheme ensures that there are negligible cycling currents and that the batteries remain in resting mode long enough to preserve their operating lives.
- The control scheme ensures that all batteries will reach the end of their serviceable life at the same time by taking into consideration the calculated remaining life of individual batteries as well as other factors, such as DOD, etc. It accomplishes this by connecting and

disconnecting battery branches depending on the above criteria. This decreases the required maintenance and ensures the usefulness of the battery pack over its predicted life.

- Battery branches can be isolated and replaced individually so that the BESS need not be taken offline during maintenance, which improves reliability of the battery pack.
- The state of charge and exchanged energy are continuously calculated due to the nature of the control scheme so that the amount of time the battery pack can continue supplying power can be reliably estimated.
- The initial cost of this BESS is lower than other ESS. This is because the proposed BESS relies on proven technologies. Battery storage technologies are currently significantly less expensive than other ESS of comparable power.

Compared to other ESS schemes, this system has a lower initial investment cost. Additionally, the advantages of the BESS translate into economic savings over the life of the wind turbine due to lowered operation and maintenance costs coupled with the extended lifetime of the BESS.

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