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Power Fluctuations Smoothing and Regulations in Wind Turbine Generator Systems

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POWER FLUCTUATIONS SMOOTHING AND

REGULATIONS IN WIND TURBINE GENERATOR

SYSTEMS

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In Partial Fulfillment

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Doctor of Philosophy

_____

by

Hamed Babazadehrokni

November 2013

Advisor: Wenzhong Gao

Author: Hamed Babazadehrokni
Title: Power fluctuations smoothing and regulations in wind turbine generator systems
Advisor: Wenzhong Gao
Degree Date: November 2013

Abstract

Wind is one of the most popular renewable energy sources and it has the potential to become the biggest energy source in future. Since the wind does not always blow constantly, the output wind power is not constant which may make some problem for the power grid. According to the grid code which is set by independent system operator, ISO, wind turbine generator systems need to follow some standards such as the predetermined acceptable power fluctuations.

In order to smooth the output powers, the energy storage system and some power electronics modules are employed. The utilized power electronics modules in the wind turbine system can pursue many different goals, such as maintaining the voltage stability, frequency stability, providing the available and predetermined output active and reactive power. On the other side, the energy storage system can help achieving some of these goals but its main job is to store the extra energy when not needed and release the stored energy when needed. The energy storage system can be designed in different sizes, material and also combination of different energy storage systems (hybrid designs). Combination of power electronics devises and also energy storage system helps the wind turbine systems to smooth the output power according to the

provided standards. In addition prediction of wind speed may improve the performance of wind turbine generator systems.

In this research study all these three topics are studied and the obtained results are written in 10 papers which 7 of them are published and three of them are under process.

Acknowledgment

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1. Chapter One: Introduction

Electricity is one of the essential necessities for people nowadays and when the power is off many people get into trouble. Therefore the power generation becomes a very important issue which has to be studied carefully. The stability of the system is another important issue as well as the frequency and voltage of electrical power. There are many sources to generate the needed electrical power. The majority of the power plants use fossil fuels, but due to some problems caused by the fossil fuel consumption, the demand of power generation by renewable sources has increased recently [1]. The major problems associated with the fossil fuel use are the air pollution, increasing price of oil and the depletion of fossil fuel resources. Renewable energies are mostly clean and their sources last for a very long time, but they are relatively expensive at the moment. In the United States, solar and wind technologies are the most rapidly increasing systems among all renewable resources. It is worth mentioning that the hydro power generation's capacity is also very large but due to geographical limitation and lack of water in many areas, there is no more significant capacity increase for hydro-power generation. Wind energy is not only one of the biggest renewable energy sources but also in some regions; it is one of the most reliable sources as well. Due to the growing importance of wind energy in the power system, researchers dedicate careful studies on this field. The

environmental characteristics of wind are different for different regions which are studied [2].

The number of wind turbines connected to the power grid and the capacity of wind power generation increase significantly. The ratio of renewable energy generation to the total generated power in many countries is considerable. For example, the ratio of renewable energy to the total energy in the United States is around 10% while it is planned to be 20% in 2020 [3].

Wind energy compared with the solar energy is more reliable because on cloudy, rainy days and even nights wind power generation is considerable but solar power generation is almost nothing. In some regions, the wind energy compared with the hydro energy is more reliable because in the summer time, the water is reserved for agricultural purposes. However, wind energy has its own problems. Wind never blows constantly, and the wind speed fluctuates which consequently causes the generated wind power to fluctuate.

Due to the variation in the wind speed and the cubic relationship between wind speed and wind power, the generated electrical power fluctuates relatively more than wind speed [2]. The main focus of this study is large wind turbines. The studied large wind turbines are as big as 500 KW wind turbines to 10 MW wind turbines. Considering to gird's operator standards, the output power of wind turbine has to be regulated and then dispatched to the power grid. There are many methods to regulate the wind power before dispatching the power to the power grid. Most regulations are realized by having wind speed prediction, applying power electronics and energy storage systems (ESS) to

the wind turbines which are studied in detail in this paper. The remaining chapters of this report are as follows: theoretical background of wind power generation (section 2), wind power in the power system (section 3), generators and power electronics for wind turbines (section 4), energy storage systems (section 5), and prediction and impact of prediction in wind power generation (section 6).

My contribution:

In my research, a design for hybrid energy storage system is proposed which also has an option to cooperate with the prediction of wind speed. The hybrid energy storage system is combination of a supercapacitor and a battery. In this design the life of battery is significantly increased. The other proposed designs are for battery energy storage system, one for constant charging rate and the other one is for variable charging rate. The constant charging rate means that the controller unit does not have the access to the amount of charges/discharge of battery and it can only control the connection and charging period. This design is proposed due to some limitation in industry which is not able to have variable charging rate, but the second battery energy storage design is fully able to control the batteries at any rate and time. In order to implement this idea we need an accurate life estimation method for the battery life and we proposed the throughput life estimation method which is another contribution of my research. The designs are also followed by proposed methods for sizing the hybrid energy storage system and battery energy storage system.

Finally, two prediction methods, Kalman filter and pattern recognition method are proposed by two supporting example.

2. Chapter Two: Theoretical Background

Wind power has been employed by humankind for long time, but the improvement in wind power technology was not significant for many years. Mostly the wind turbines were used to grind grains such as wheat or pump water to villages. By discovering electricity, humankind started to generate the electricity using wind turbines. Table 1 shows the capacity of power generation of wind turbine over the time.

Table 1 – size of wind turbine and its capacity over the time [4]

Year	Capacity (KW)	Rotor Diameter (m)
1985	50	15
1989	300	30
1992	500	37
1994	600	46
1998	1500	70
2003	3000 - 3600	90-104
2004	4500-5000	112- 128

In recent years, with the help of power electronics devices, the wind power generation highly increased and became a great source of renewable energy which has a potential to generate around 20% of total generation by 2020inUSA [5]. Couples of wind turbine

models are proposed which the biggest portion of wind power generation is by the doubly fed induction generator, DFIG, [2], but many researchers believe that the permanent magnet synchronous generators (PMSG) with the full-scale converters will be the dominant model soon [2]. The PMSG configuration does not need the gearbox, which is the main reason of failure in most wind turbines. Due to the employed full scale converter in the wind power system this configuration is very flexible in term of having different output voltage and frequency.

The major problem with the wind is that the wind speed is not constant. Variable wind speed results in the fluctuating output power which may make the power grid unstable if the ratio of renewable generation to total generation is considerable. In many developed countries such as Denmark and Germany, the installed capacity for renewable energy is around 40% of total generation. In reality the wind turbine can generate a considerable amount of power but they may pose a major risk for the stability of the grid due to power fluctuation. Some researchers believe that the wind turbines may makes the power grid unstable now but they have the potential to help the stability of the bus they are connected to and consequently the power system [6]. The wind turbines are categorized as offshore and onshore wind turbines. Onshore wind turbines are small wind turbines which are usually installed close to the consumers and in urban area. On the other side, the offshore wind turbines are usually large wind turbines and able to generate large amount of power, as big as mega-watts; but they are installed far away from consumers [7].

The installed capacity and the historical data for all regions such as offshore and onshore is provided by the Iowa State University website and other online sources such as the national laboratories website [3,8].

2.1   Mechanical power generation

The output power of the wind turbine is calculated as shown by (1) to (3). By having the wind speed, power coefficient, air pressure and wind turbine's blade area, the output power can be calculated [2].

$$P_{wt} = 0.5 \, \rho c_p A v^3 \tag{1}$$

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_1} - C_3 \, \beta - C_4 \right) e^{\frac{-C_5}{\lambda_1}} + C_6 \tag{2}$$

$$\frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$

ρ is the air density, A is the area of wind turbine blade, c_p is the power coefficient of wind turbine C_1 to C_6 are specific coefficients given by manufacturer of the wind turbines which are not same for all turbines and β is the pitch angle of wind turbine. The power coefficient which is a nonlinear function of turbines pitch angle versus tip speed ratio for different pitch angles of wind turbine can be calculated using equations (2) and (3). As it is shown in tip speed ratio, TRS,'s plot (figure 1), the maximum value of power coefficient (when pitch angle $\beta = 0$) - is almost 0.43, in this model. It is worth mentioning that depending on the manufacturer the power coefficient changes slightly.

The pitch angle controller is a mechanical controller which prevents the wind turbines blade from runaway. If the velocity of rotor exceeds an upper speed limitation, the pitch angle increases and consequently the effective wind power reduces. The relationship of

the TSR versus power coefficient in the power aerodynamic equation is shown in figure 1.
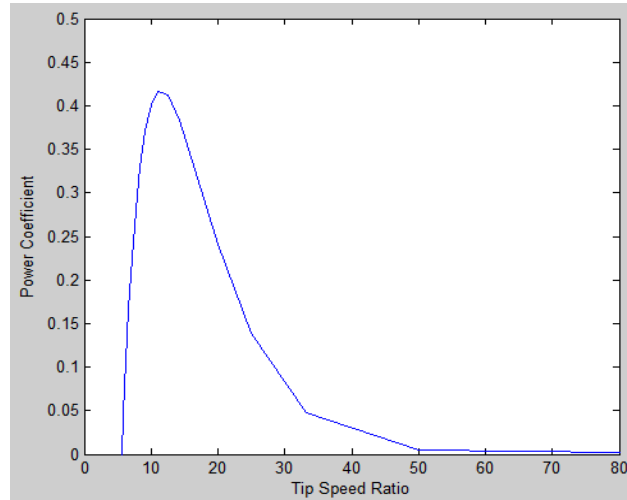
Figure 1- Power coefficient versus tip speed ratio at $\beta = 0$, [9]

2.2   Electrical power generation

Wind energy is converted to mechanical energy by the help of the wind turbine's blade, and by employing the generator which is coupled with the turbine's shaft, the mechanical power is converted to the electrical power. The electrical power at the terminal of the generator is sinusoidal AC electricity and the generated power varies with the wind speed. In the wind turbine generator system (type D), a full scale converter which consists of a rectifier and an inverter is employed between the generator and the power grid. There may be a transformer between wind turbine terminals and the power grid in order to increase the output voltage. The other component usually applied to the

wind turbine generator system is the Energy Storage System (ESS) that we study in this research study.

The type D (type 4) wind turbine generator uses the full scale converter which result in a good protection due to the existence of the power electronics elements [2]. In other words, a fault from the grid side cannot damage the generator and a fault on the generator-side does not go through the power electronics to the grid side. In this paper, we mostly use a permanent magnet synchronous generator (PMSG) which is assumed to be the dominant generator for the wind turbines in future. The detailed configuration of wind turbine system including battery energy storage system, BESS is shown in figure 2.
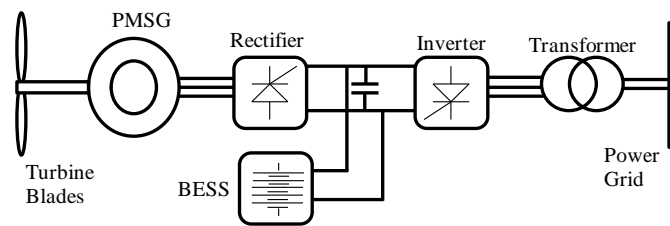
Figure 2- Variable speed wind turbine configuration, Type D [10]

The synchronous generator (PMSG): PMSG is coupled with the wind turbine without a gearbox. In simulation package PSCAD, there are different blocks to build and model the PMSG [11]. Power electronics play an important role in the configuration type D and a control design for the full scale converter is presented by S. K. Kim [12]. The wind turbine generator system includes the wind turbine blade, generator, DC-link, power electronics, transformer and load. In wind power plant or wind farm, the output power of many wind turbines are accumulated and then connected to the grid. In our case study,

power grid is modeled as an IEEE 14-bus test system. The 14-bus system is applied to the model in order to study the effects of utilizing ESS throughout the grid and to check the quality of the power delivered by the wind turbines. In this generation system, the power generated by the wind turbine is 10% of the total dispatched power. This power grid includes 7 generators and 13 loads (both active and reactive), as shown in Figure 3.
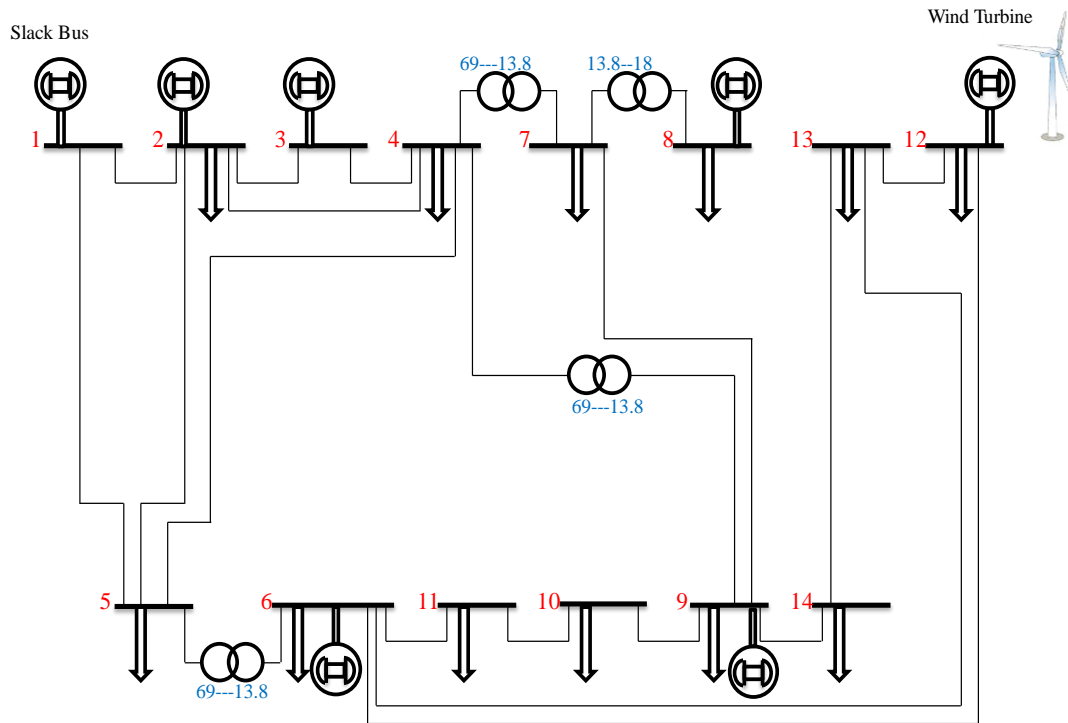
Figure 3- Connection of the wind turbine in the14-bus configuration

3.   Chapter Three: Wind Power in Power Systems

The wind power generation systems can be investigated in three levels: wind turbine level, wind farm level, and power system level. In the first level, a single wind turbine is used to generate power. For example, a single wind turbine which is couple with a water pump needs to pump water to uphill be considered as the first level of wind power generation system. The second level is wind farm level. The wind farm level is usually bigger than a single wind turbine and it can be used in remote areas or for a micro-grid system. The largest level in which a wind power generator system can assist is the power system level. At this level of generation, due to synchronization requirement of the system, more controls are needed. At this level usually a transmission line is needed to transmit the generation to the load area.

The first transmission system and power system were installed by Edison in 1880. The loss was high, the generation was very low, and also the transmission line was very short. By developing the design of the transformer many improvements were done afterwards in the power system level. Over the years, each part of the power system, including generation, transmission and distribution improved step by step and finally we can use the current power system which has spread worldwide and in the scale of thousands of Gia-watts.

The wind power technologies are improved considerably recently, but it is still very hard to generate all the needed energy by renewable sources. In some countries such as Denmark and Germany, the renewable generation is significant and in some other countries such as the United States and China, the amount of renewable generation by the wind is considerable but less than traditional sources, and finally in developing countries the average value of renewable energies, especially by wind power is less than 5 % of total generation. Top 10 countries in term of wind power generation are shown in table 2, [4].

Table 2: top ten countries in term of wind power capacity, 2012

Country	Wind power	% world total	Wind power production	% world total
China	62,733	26.3	88.6	19.3
USA	46,919	19.7	120.5	26.2
Germany	29,060	12.2	48.9	10.6
Spain	21,674	9.1	42.4	9.2
India	16,084	6.7	NA	NA
France	6,800	2.8	12.2	2.7
Italy	6,747	2.8	9.9	2.1
UK	6,540	2.7	15.5	3.4
Canada	5,265	2.2	19.7	4.3
Portugal	4,083	1.7	NA	NA
Rest of world	32,446	13.8	67.7	14.7

World total	238,351 MW	100%	459.9 TWh	100%

Worldwide total installed capacity with a total nameplate capacity is 238,351 MW as of end 2011. The European Union's generation exceeds 100,000 MW (in September 2012), while the United States passed 50,000 MW (in August 2012) [13].

3.1 Generators in Wind Turbines

There are four types of wind turbine systems. The most common types are type C and D which employ the doubly fed induction generator, DFIG or permanent magnet system generator, PMSG. The DFIG is the most installed type but the PMSG is going to be the dominant one in future [2]. In this study, type D wind power system is employed which has a rectifier, inverter and DC-DC converter. The control systems including the stability control, output power control, frequency control and other control systems can be applied to type D easier than other types. All these advantages are due to the existence of power electronics.

3.2 Full scale converter

In converting the AC power to DC power, a three phase rectifier is employed, as shown in figure 4. This rectifier consists of six switches mostly IGBTs. The applied switches not only convert the AC power to DC power, but a maximum power point tracking controller can be applied to these switches as well. The MPPT can be applied to

the rectifier in order to convert the maximum available wind power to electrical power as shown in figure 4.
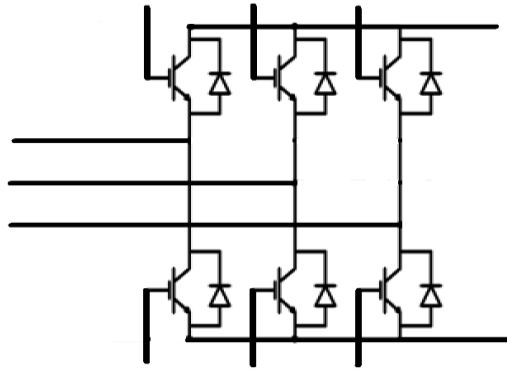
Figure 1- Generator side rectifier, [9]

The other employed power electronics device is the inverter. The inverter converts the DC power to AC power. The employed inverter is the voltage source inverter, VSI. This inverter also has 6 switches as shown in figure 5. The LC filter can be employed after the inverter to remove the harmonics and some fluctuations.
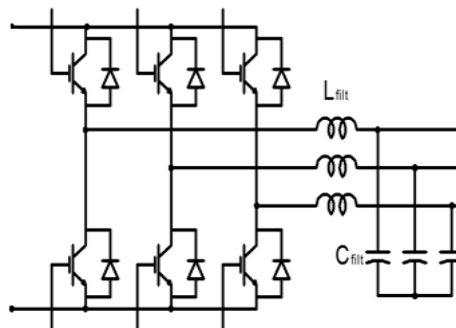
Figure 5- Grid side inverter, [9]

3.2.1 Voltage source inverter

The three phase inverter used in our model is VSI. Equations (4) to (7) are the basis of VSI modeling. The VSI uses the dq reference frame in order to calculate the firing times of the IGBT switches.

$$S = P + jQ \tag{4}$$

$$P = \frac{3}{2}\left(V_d \cdot I_d + V_q \cdot I_q\right) \tag{5}$$

$$Q = \frac{3}{2}\left(V_d \cdot I_q - V_q \cdot I_d\right) \tag{6}$$

V_d, I_d, V_q and I_q are the voltage and current in d axis , the voltage and current in q axis. P is the active power and Q is the reactive power. Considering V_d is zero in rotating dq coordinate, (6) is rewritten as follows, [12]

$$Q = \frac{3}{2}\left(-V_q \cdot I_d\right) \tag{7}$$

According to Figure 6, current references can be created using dq transformation. P_{ref} which is the reference power in rectifier is computed by dividing the instantaneous power by the rated power magnitude and the angle can be computed from PLL (phase lock loop). In order to synchronize the generation with the power system, we need to use the PLL which finds the initial AC phase. The calculated reference currents $I_q{}^{ref}$ and $I_d{}^{ref}$ are calculated based on the control strategy; P_{ref} and Q_{ref} are set depending on the control design. According to the VSI's control scheme, the DC-link voltage is kept balanced, and the control configuration is shown in figure 6.

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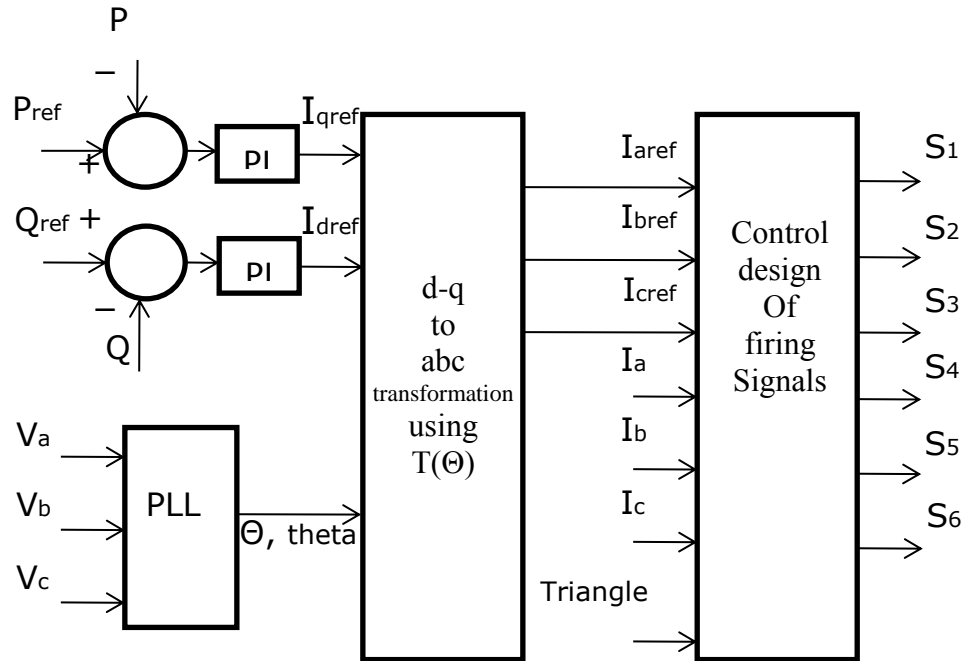
Figure 6- Block diagram of the controller (grid side), [9]

3.2.2 Maximum power point tracking

To make the best use of the investment in a wind power system, the wind turbines have to convert the most available wind energy to electrical energy. The rectifier's controller of the wind turbine by putting the right amount of load on the rectifier and consequently on the generator is able to convert the maximum available amount of the mechanical energy to the electrical energy. This control method is called MPPT. Generally MPPT can be categorized to two major methods, and each of them is divided into two parts [14,15]. The first method uses the load adjusting and by applying the wind turbine parameters, the wind turbine is able to provide an optimal look up table. By having the optimal look-up table, the amount of available mechanical power is calculated, and then by firing the IGBTs of the rectifier, the MPPT can be achieved. In the other

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method, the wind turbine characteristics have to be known in advance by the manufacturer. An example of maximum power point for different torque, power and rotor speed is shown in figure 7, [16].
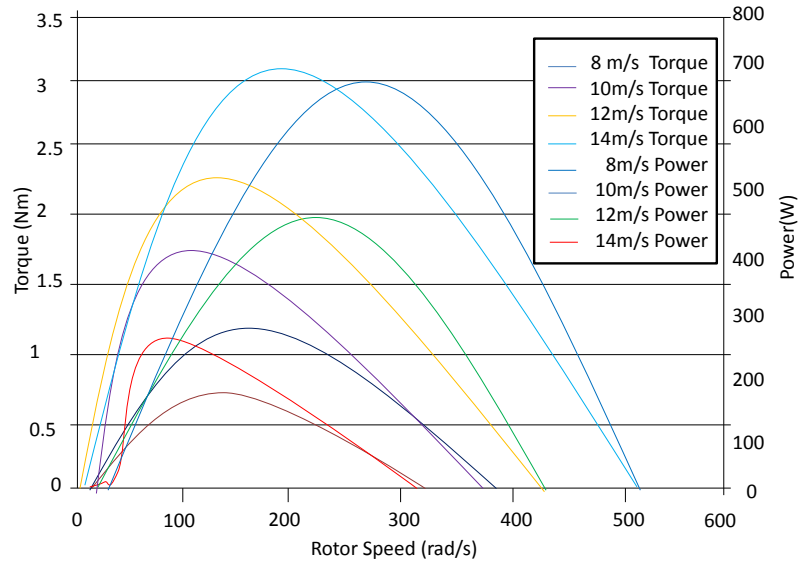
Figure 7- Unique MMPT point for each specific wind speed

There are different MPPT methods: constant Step control, variable Step control, anemometer and calculated equation control method. In the first method, the controller gradually changes the duty cycle of the active rectifier in order to find the maximum amount of power generation. The generated power at each sampling time is compared with the next sampling time's output power. The greater output power shows that the MPPT controller is on the right track. If by increasing the duty cycle the output power reduces, then the duty cycle has to be decreased. This algorithm finds the correct duty cycle and the correct amount of load can be applied to the generator, as shown in figure 8.
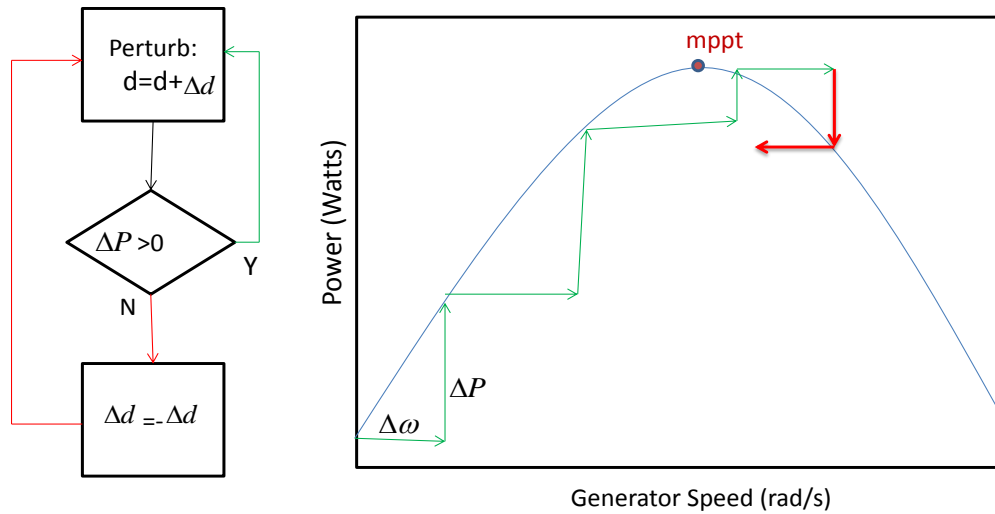
Figure 8- The step control method to track maximum power point, [16]

The Variable step control is the other method of MPPT, but the difference of this method from the step control method is the length of changes in the duty cycle. In this method, by finding the right direction in decreasing/increasing the duty cycle, the next changes in the duty cycle are bigger than the previous ones and if the changes in the duty cycle are not in the right track, the next changes in the duty cycle are smaller than the previous one. Using this method, finding the MPPT is faster than the step control method.

In the Anemometer control method, the wind speed is measured by anemometer and then, using a look-up table, the required load is calculated to fire the converter's switches. For example, we have to know for wind speed at 8m/s the available output power from generator, as shown in figure 9.

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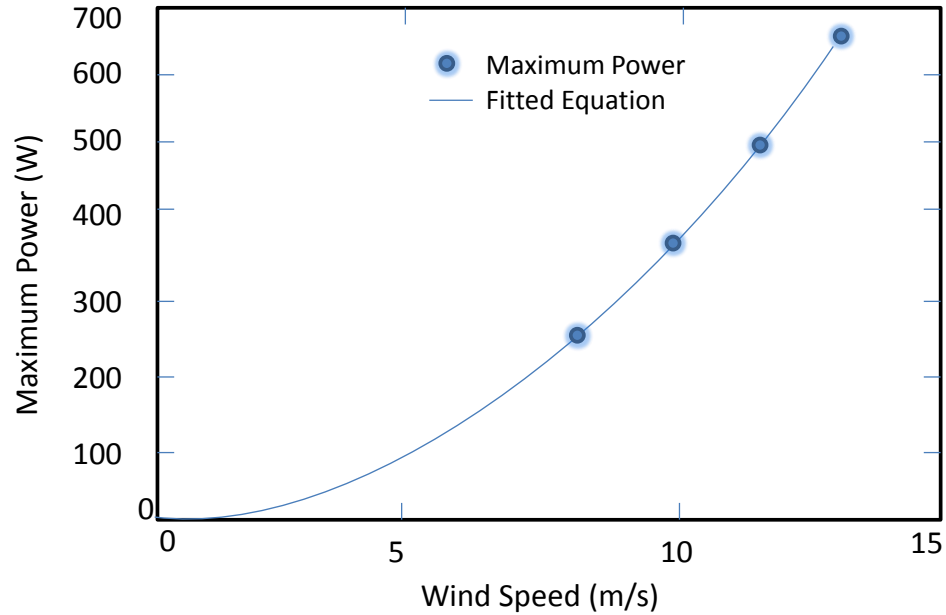
Figure 9- The step control method to track maximum power point [2]

In the Calculated equation control method, the right amount of generated power is calculated using the aerodynamic equations of the wind turbine [2] and the rest is the same as the anemometer control method. It is worth mentioning that many terms may have negative impact on this control method such as the effect of inertia on the instantaneous output power and also effect of LC filter. The step control method is also known as P & O control (perturb and observe) and also hill climbing as shown in figure 10. This method is very applicable method but not the most accurate. This method does not always find the MPPT and usually oscillates around the desired point. In addition, during the change in the wind speed, the settlement time is longer than other methods. The characteristic curve changes when the wind speed changes, as shown in figure 10, [15].

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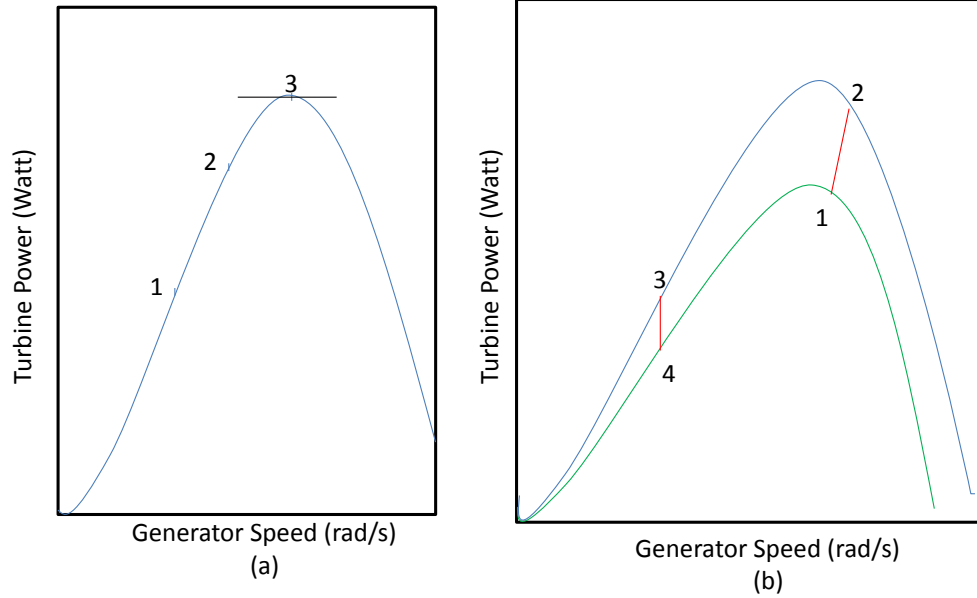
Figure 10- Characteristics curve in P & O method changes by wind speed change

All methods have some advantages and disadvantages. If we suppose that the accurate wind speed measuring technology is available, the most accurate method can be the calculated equation control. The step control's problem is its slow response time and the other methods have problem by measuring the exact wind speed.

4.   Chapter Four: Energy Storage Systems

Energy storage system can be applied to the wind turbine generation system to absorb the extra energy and release them when needed. The Energy storage system contributes in regulating the electrical output power. The ESS is either directly or indirectly (using a DC-DC converter) connected to the wind turbine system. In the type D configuration, the ESS is connected to the output terminal of wind turbine or to the DC-link of wind turbine. The ESS is usually connected via DC-DC bidirectional power converter. There are different materials or compositions for ESS [17, 18]. The new generation of ESS is hybrid energy storage system which is combination of different materials [9]. Each ESS by a single material has some shortcomings and in order to solve the problem of ESS, designers combine different ESSs with different materials. For example, the battery energy storage system has high energy density and low power density. On the other hand, the supercapacitor energy storage system has high power density and low energy density. Therefore by designing a HESS which is combination of supercapacitor and battery, a hybrid ESS is built with high power and energy density. Characteristics of different ESS materials can be found in [19]. In the design of ESS, some other factors (other than power and energy density) have to be considered such as life span and cost of ESS.

4.1   Hybrid energy storage systems

In this paper we propose a design for HESS which can help increase life of the employed battery in HESS. This HESS is a combination of supercapacitor and battery cells. The main goal of this design is to increase battery life in order to reduce the maintenance cost of wind turbine system. The batteries which are applied to the wind turbine usually last between 2 to 10 years depending to the material used in batteries. The life of wind turbine itself is more than 15 years which means that after a couple of years the battery cells in the ESS have to be replaced. Due to high price of supercapacitor the initial cost of wind turbine system with HESS is slightly more than the wind turbine system with BESS but over the life of wind turbine, the wind turbine with HESS is more economic than the wind turbine with the BESS. In order to find how to increase the battery life, first we have to identify the factors that decrease the life of battery. These are as follows:

- Heat

- High discharge current

- Continuous operation

- Operation at low SOC

- Battery wear

Heat: During battery operation, the current passes through the internal resistors of the battery and makes the battery hot which results in power loss and decreasing battery efficiency. When the battery gets hot, not only the efficiency decreases but also the heat damage the battery and reduces the life of battery. In order to avoid the heat, the battery

should operate with the current around or less than its rated value. The other advantage of this design is the rest mode is considered in it. If the battery has a period of time to cool down (rest period), the heat does not damage the battery considerably.

High discharge current: Overcharge/discharge rate may reduce the battery life to 10% of its average life span.

Continuous operation: if the battery continuously works, the life of battery decreases and by having resting mode in the battery's operation we may increase the life of battery. In other words, the resting mode results in the battery's self-recovery.

Operation at low SOC: the most important factor in increasing the battery life is the operation of battery at high SOC (state of charge) or low DOD (depth of discharge). Operation at high depth of discharge (DOD) highly damages the battery. According to the manual provided by the manufacturer, each battery has specific number of life cycle and operation at low SOC significantly decreases this value. For example, a battery lasts for 90,000 life cycles at low DOD, but if it works at high DOD, the life time of the battery gets shortened (e.g. 600 life cycles), as shown in figure 11.
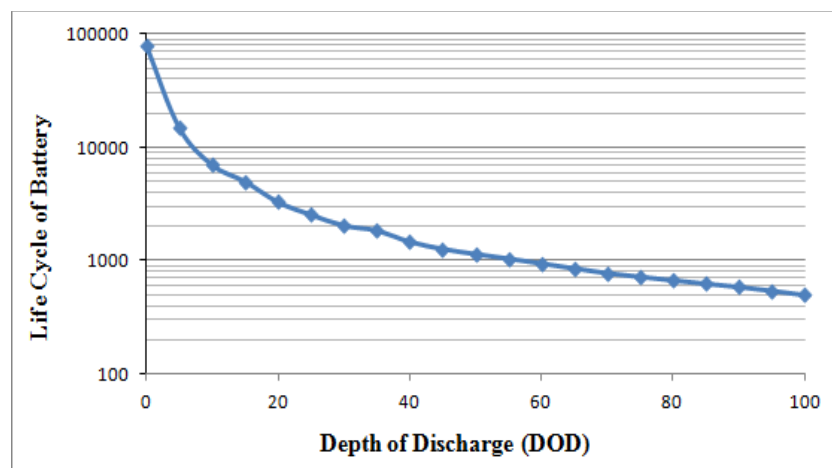
Figure 11- Life cycle of battery versus depth of discharge (DOD), [10]

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Design: in our design we consider all the damaging factors for the battery life in our design of the controller which controls the connection and disconnection of the HESS to the Dc-link via DC-DC converter. In the typical DC-DC power converter, the available generated power at the DC-bus is compared with the reference value of power and then the duty cycle is calculated. The calculated duty cycle is applied to the switches of DC-DC converter in order to regulate the output power. In the proposed design, the SOC of battery and SOC of the supercapacitor are measured and sent to the controller of HESS. The HESS controller considering the SOCs and other inputs fires the IGBT switches of the converter. The rest mode allows the battery to recover itself and also have time to cool down. In a simple word, in the charging mode, the supercapacitor's SOC is measured and then the measured value is compared with the predetermined upper bound. If the supercapacitor's SOC is greater than predetermined upper bound and also the wind power generation is more than the output power of wind turbine (which means the ESS has to store the extra energy) then the controller charges the battery.

Figure 12 shows the supercapacitor's SOC condition. If the SOC is greater than the upper bound, the output is one. Otherwise the signal is zero. In figure 13 the PWM signals are shown which fire the IGBT switches of converter, [9, 20].
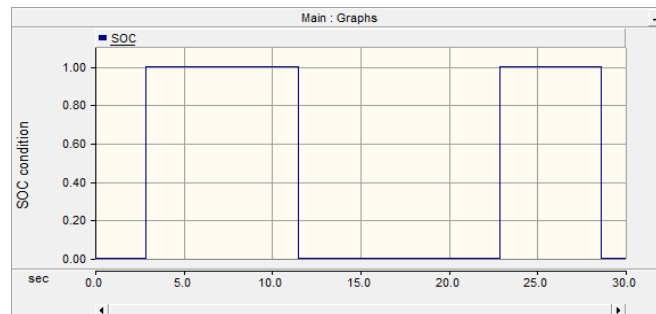
Figure 12- Supercapacitor's SOC exceeds the predetermined upper bound level

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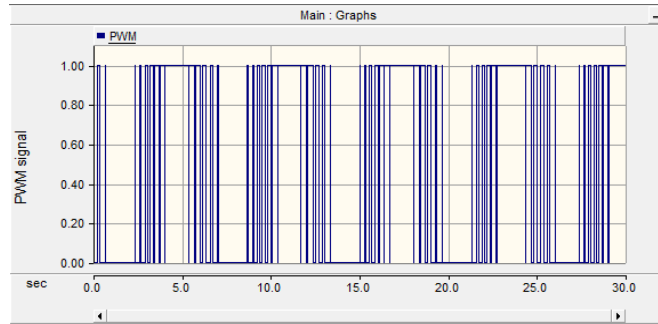
Figure 13- PWM signal provided by comparing the generated power and reference power

In the regular DC-DC converter, converter's IGBTs switch as shown in figure 13, while in our design the IGBTs switch as shown in figure 14.
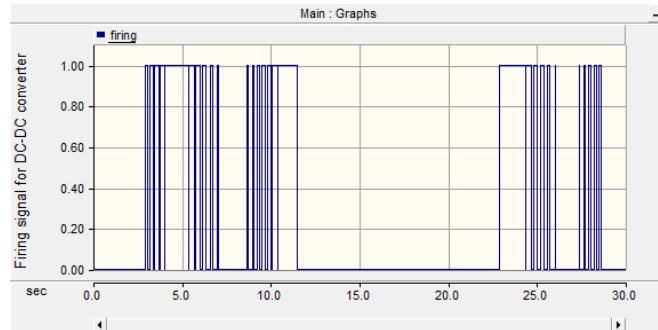
Figure 14- Firing signals that drives the DC-DC converter of battery

On the other hand in the discharging mode, first the supercapacitor's SOC is measured and then the measured value is compared with the predetermined lower bound. If the SOC of supercapacitor is less than predetermined lower bound and also the wind power generation is less than the output power of wind turbine (which means the ESS has to release the needed energy) then the controller discharges the battery. The intelligent controller of wind turbine for HESS also considers many terms other than SOC of supercapacitor. These values are the SOC of the battery, the power generation by the wind turbine, and the wind speed forecast. For example, if the battery's SOC is very low,

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the controller shifts the lower and upper supercapacitor SOC bounds to avoid deeply discharging the battery. The intelligent control design follows the flowchart as shown in figure 15.
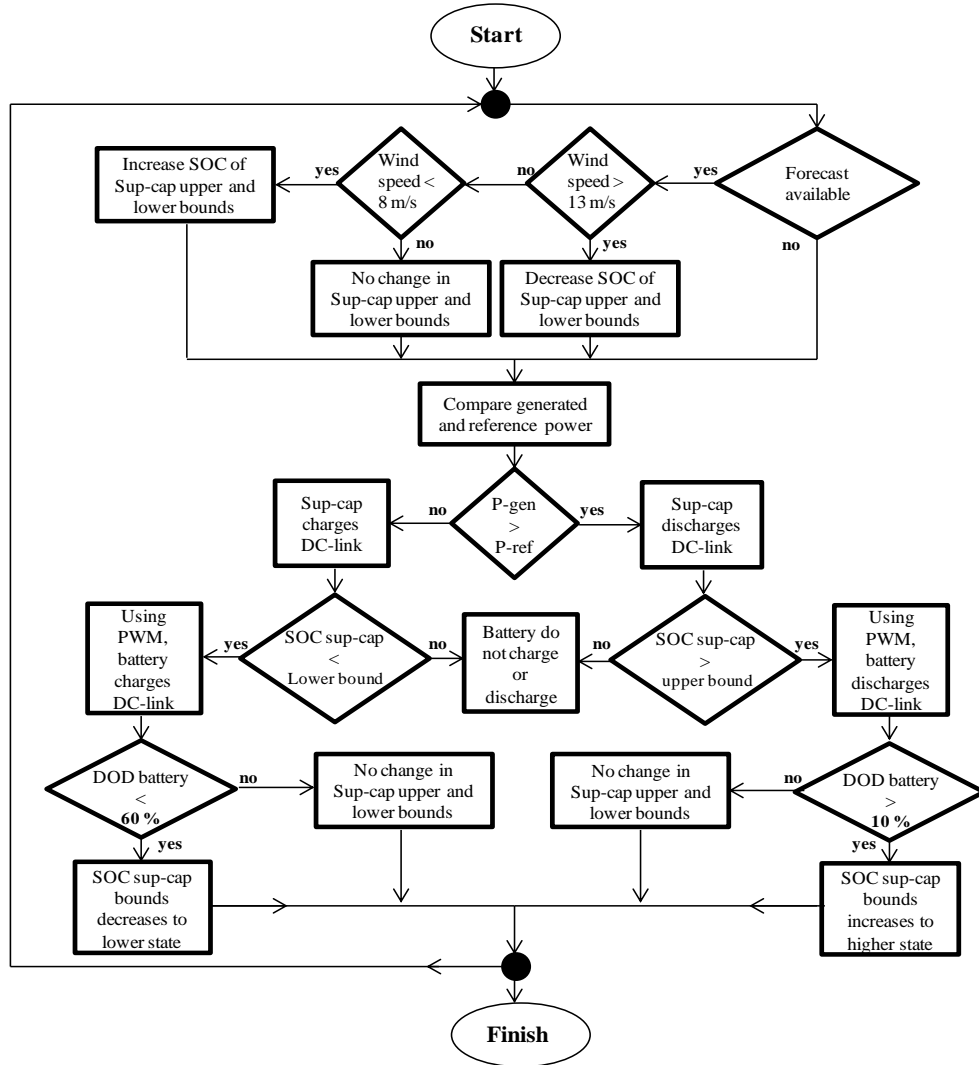
Figure 15- Control scheme of the HESS's flow chart

4.2   Battery Energy Storage System

One of the most popular energy storage systems is battery energy storage system. Due to relatively advanced technology in battery, high energy density and also cheap price of battery, the battery energy storage system is widely used in the industry.

4.2.1   Multi batteries in battery energy storage system

The available battery cells have specific voltage ranges, energy and power capacity. Considering the specific ranges of voltage and capacity, a single battery cell is not a proper ESS for a large wind turbine. Therefore, a specific number of battery cells have to be connected in order to make a proper ESS in term of size for large wind turbines. In other words, we have to connect many battery cells in series and in parallel to make a battery ESS with large capacity and then use it as BESS. The number of battery cells connected in series depends on the voltage of DC-link. The voltage of BESS has to be at least 25% of voltage of DC-link, otherwise the efficiency of employed DC-DC converter significantly decreases. The number of battery cells connected in parallel depends on the needed power by the wind turbine system. The energy capacity of BESS needs to be big enough to store or release the needed energy and avoid the unserved energy. Unserved energy is the energy which is generated by the generator but due to limitation it cannot be delivered to the power grid. In this study, a BESS design is proposed, as shown in figure 16, [10].
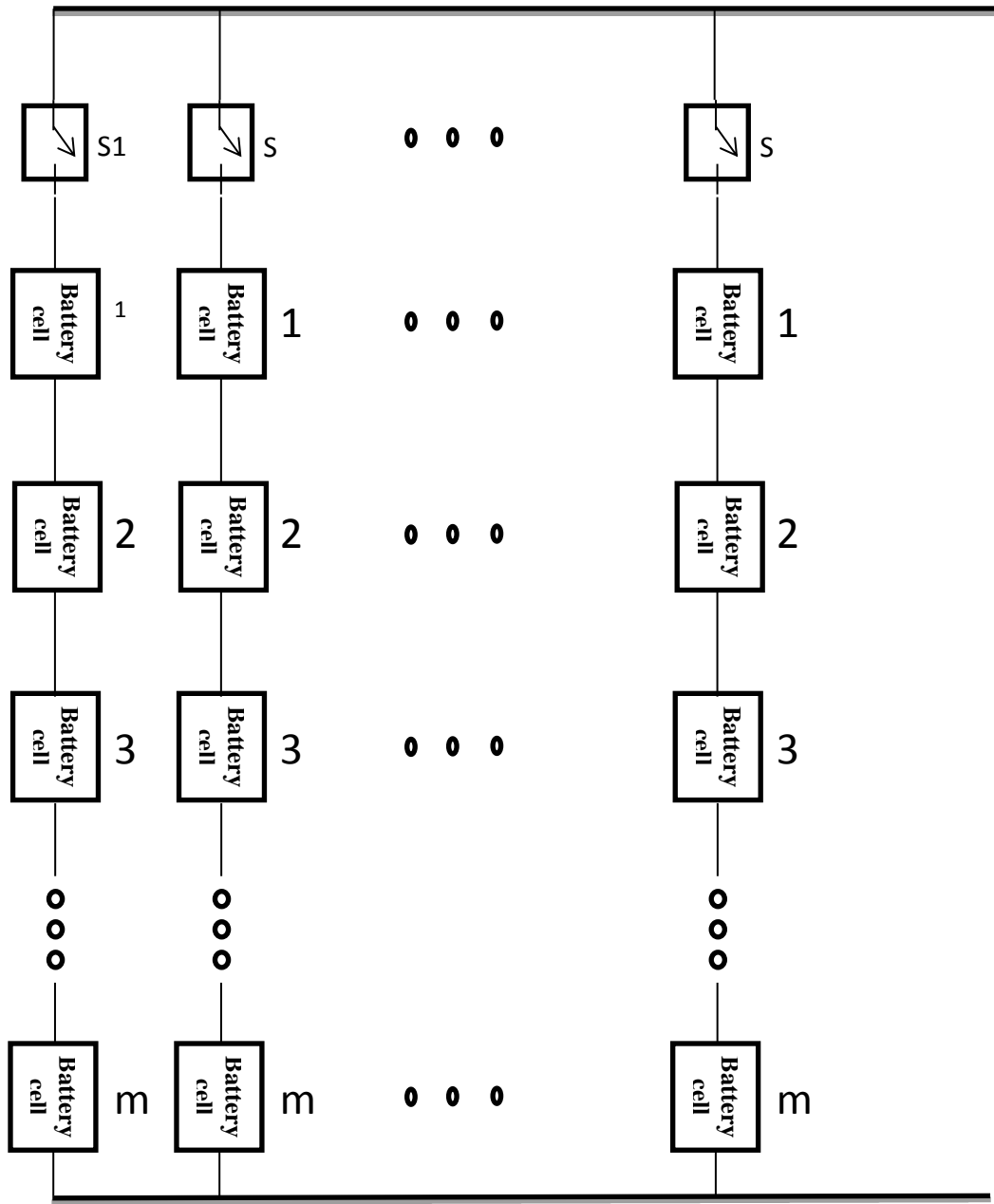
Figure 16- Battery energy storage configuration

To control the operation of the battery cells, switches on top of each battery cells branch are used which connect or disconnect the battery branches from the converter. The switches get on or off based on the difference between the generated electrical power and reference electrical power. For example, if each battery branch's power is A MW, and the

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needed power is 2A MW, then 2 battery branches get connected to the converter and all other branches are left disconnected. This design avoids the overcharge and over-discharge. Considerable rest mode is available, which helps cool down the battery cells and self-recovery. We also proposed a method to calculate the life of battery and associated new control method of BESS.

One of the main goals of this method is to ensure that all battery cells reach end of life at the same time. In case if some of battery cells get used more frequently and others remain fresh, the BESS loses some of its battery cells which consequently results in reduced BESS capacity. If the BESS does not have enough power, the whole package of battery cells becomes useless. Therefore all battery branches have to die at the same time. The life calculation of battery is proposed in [10] and based on this calculation and also SOC of battery cells, different battery branches get connected and the burden would be on the fresher battery cells.In an hour the wind power generation is not constant. For example an hour case is studied and the power generation is shown in figure 17. The black line shows the level of desired output power.
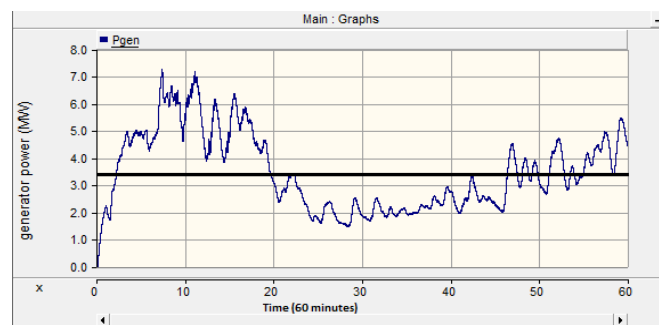
Figure 17- Electrical generated power and reference power in 60 minutes

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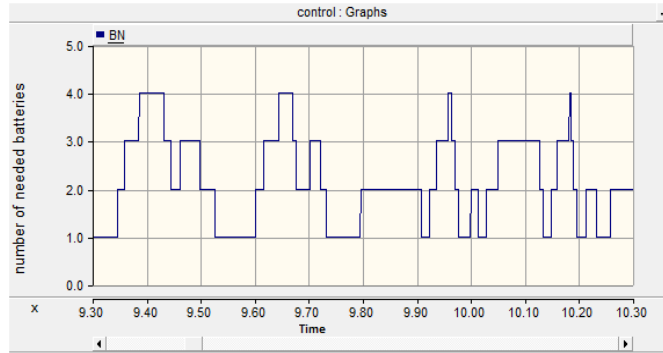
Figure 18- Number of connected battery branches in 1 minute

Figure 18 shows the number of battery branches which operate based on instantaneous power. In this case, different initial conditions and different passed life for the battery branches are assumed and then the case is run to check the result.

The initial conditions of three battery branches are shown in table 3.

Table 3: Value of battery lives (initial and final), [10]

Battery branch	Initial SOC	Initial life	Final SOC	Final life	Consumed life cycle
A	80	70	52.5	69.386	409
B	70	75	53.230	74.454	460.5
C	75	85	58	84.345	493

As the table shows, the BESS design ensures that individual battery branches do not operate with the overcharging/discharging current. It is worth mentioning that the final SOC of all battery packages become the same which prevent current cycling among branches.

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4.2.1.1 Sizing the energy storage systems

Energy storage system (ESS) can play a very important part in wind turbine generation system and consequently in the power grid. ESS is applied in electric vehicles, wind power systems, solar power systems and other generation systems. ESSs are different in term of material, configuration and size. The sizing of ESS highly depends on the designs and configurations. Therefore in this study, we find the proper size of ESS based on the proposed design and also on the environmental parameters of specific regions.

The first proposed design in this study is a HESS and the second one is the BESS. Proper sizes of ESS in term of energy and power for both designs are found [20, 21]. The size of ESS is usually based on the power rating of the wind turbine, the DC-link voltage and several other factors. The proposed method for HESS also considers the wind profile and the historical wind speed fluctuations in order to size the battery and the supercapacitor.

$$P(t) = V(t).i(t) \qquad (8)$$

P, V and I are the instantaneous power, voltage and current. According to (8) and since the voltage of supercapacitor and DC link are constant, the only variable is the input and output current of supercapacitor which has to be proportional to the needed or extra power that has to be compensated with the supercapacitor. Equation (9) shows the relation between current and the supercapacitor's capacity. The maximum current depends on the needed capacity of supercapacitor.

$$i(t) = C_{sc} \frac{dV(t)}{dt} \qquad (9)$$

C_{sc} is the capacity of supercapacitor. In order to find the proper size of battery in the ESS, we need to consider the turbine's power rating, the DC-link's voltage, the average SOC of the supercapacitor based on a wind profile as shown in (10).

$$C_{batt} \propto \frac{P_{wt} \cdot t \cdot V_{dc-link} \cdot SOC_{ave}}{C_{sc}} \tag{10}$$

C_{batt} is the capacity ofbattery, P_{wt} is the generated power by the wind turbine and V_{dc_link} is the DC link voltage. In order to calculate the ESS's size, we have to consider the following terms: power rating of wind turbine, the DC-link voltage, wind speed profile, duration of analysis, changes in wind speed which result in changes in wind power generation, power density of the battery, and the terminal voltage of the supercapacitor. In a short term connection cases of wind turbine to the power grid, in order to find the sizes of the supercapacitor and battery, the total energy capacity of HESS has to be calculated, as shown in (11).

$$E_{HESS} = P_{rated, \ turb} * t * 10\% \tag{11}$$

E_{HESS} is the energy capacity of HESS. "A" percent of the HESS is assigned to the supercapacitor and the rest is assigned to the battery, as shown in (12).

$$E_{SC} = E_{HESS} * A\% \tag{12}$$

E_{SC} is the energy capacity of the supercapacitor.Since we calculated the size of supercapacitor in term of energy, the capacity of supercapacitor can be calculated using (13).

$$C = \frac{2E_{sc}}{V^2} \tag{13}$$

A case is studied and the result is provided for better understanding of the design for short term connection sizing of HESS. The case is built in PSCAD and the results are

provided to validate the idea of design. The actual data (AUDUBON station, Feb, 2008) [8] is driven from the Iowa state university website is applied to the PSCAD model. The wind profile as shown in figure 19 is the actual data and the White Gaussian noise is added to the actual data, in order to create larger wind fluctuations and check the robustness of the design.
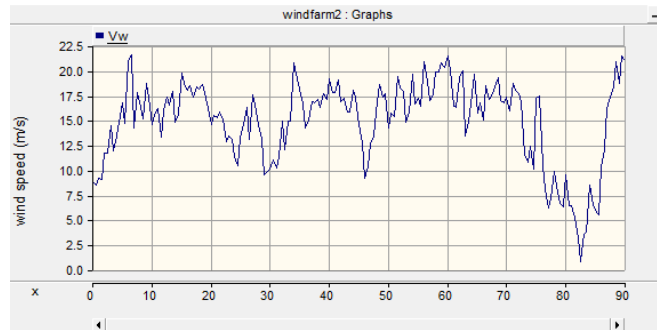
Figure 19- Wind speed (normal fluctuation) in 90 minutes, [20]

Considering the aerodynamic equation of wind turbines, the wind speed fluctuation causes a highly fluctuating wind power. To calculate the proper size of the battery and the supercapacitor, first the percentage of power fluctuations which the battery cannot accommodate has to be calculated. For example, the applied battery in this case is able to release 1 mega-joule energy per minute. Therefore the power changes bigger than 1 MW-min has to be accommodated by the supercapacitor. The power generation, the changes in generated power and the percentages of power changes bigger than 1MW-min are shown in figures 20, 21 and 22, respectively.
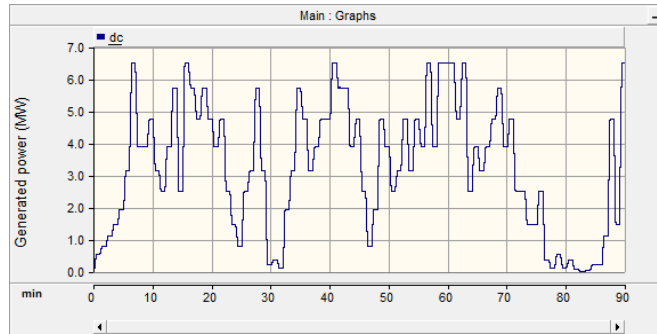
Figure 20- Generated power for a 90 minute dispatch, [20]
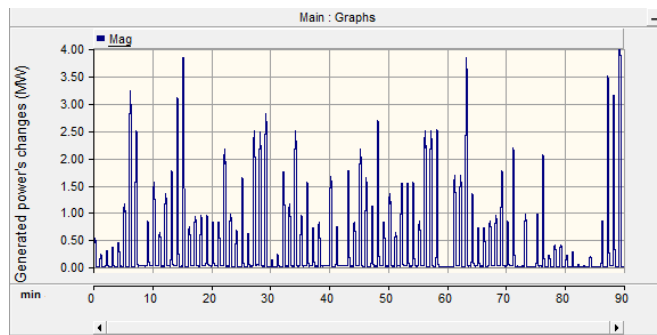
Figure 21- Changes in generated power in 90 minute, [20]
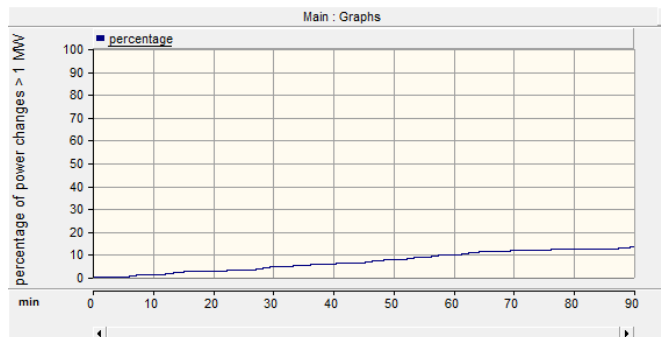
Figure 22- Percentage of changes in generated power greater than 1MW in 90 minutes with the

resolution of 50 μ-sec, [20]

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The coefficient *A*, used to calculate the size of the supercapacitor, in this case is 13.2%. Calculating *A* leads us to calculation of the HESS size for the specific geographical regions that the average power fluctuation of those regions are as large as the power fluctuation. Using the calculated coefficient "*A*" and (8) to (10), the size of the supercapacitor can be calculated for each specific a wind station. In order to find the proper size of battery we can use the mentioned equation which results in 31 Mega Joules (8.2 kW-hr) and the supercapacitor size is 0.78 F (safety factor is considered which is 1.1 times the calculated capacity). The calculated sizes of the HESS (battery and supercapacitor) are applied to the PSCAD model of the wind turbine generation system. The dynamic condition of supercapacitors' SOC is shown in Figure 23.
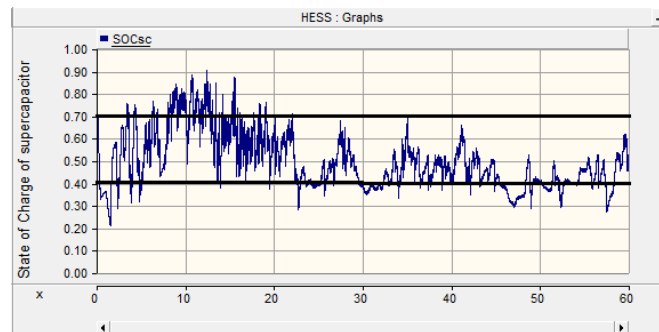
Figure 23- Upper and lower bounds and SOC of supercapacitor in 60 minutes, [20]

The battery does not perform any work for the majority of the case study which is the rest mode of the battery and consequently the battery's life considerably increases. The battery's exchanged energy is 2.987 MJ while for the regular HESS the battery's exchanged energy is 5.243 MJ. Battery's operating time in the design is 17 minutes out of

first 60 minutes which is 28.33% of the total time which in the regular design of HESS the battery always works, as shown in figure 24.
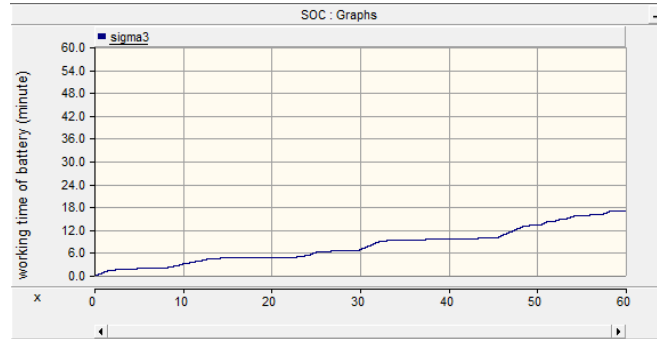
Figure 24- Working time of battery is just 28.33% of total time, [20]

To find the proper size for the BESS, we have to find the proper power and proper energy for the BESS. The design considers the amount of unserved energy and also the cost for the sizing of BESS. If the sizing is done properly, the amount of unserved energy is not very considerable. In addition, the capital cost has to be considered to make the design a cost effective design.

To find the proper size of BESS in term of power, we may choose the power of ESS from zero to the power rating of wind turbine, as shown in (14).

$$P_{ESS} = P_{WT} \tag{14}$$

In other words, the P_{ESS} equals the one per unit value of the wind power plant. In this case the ESS is powerful enough to compensate any power fluctuation but this design leads to not economical design. When a design is done and the ESS is installed in the wind turbine, it last to the end of wind turbine life. Therefore a very long data is provided

to find the proper size of BESS i.e. between four to five years for the battery energy storage system. We study a case of five year wind power provided by Global Energy Forecasting Competition2012, GEF-com 2012 [22]. The reason that the historical data of 5 years is studied is that the generated wind power will be different from the historical data of generated power but the uncertainty for specific regions is almost the same. For this wind power generation, we need an ESS with the power capacity considering figure 25.
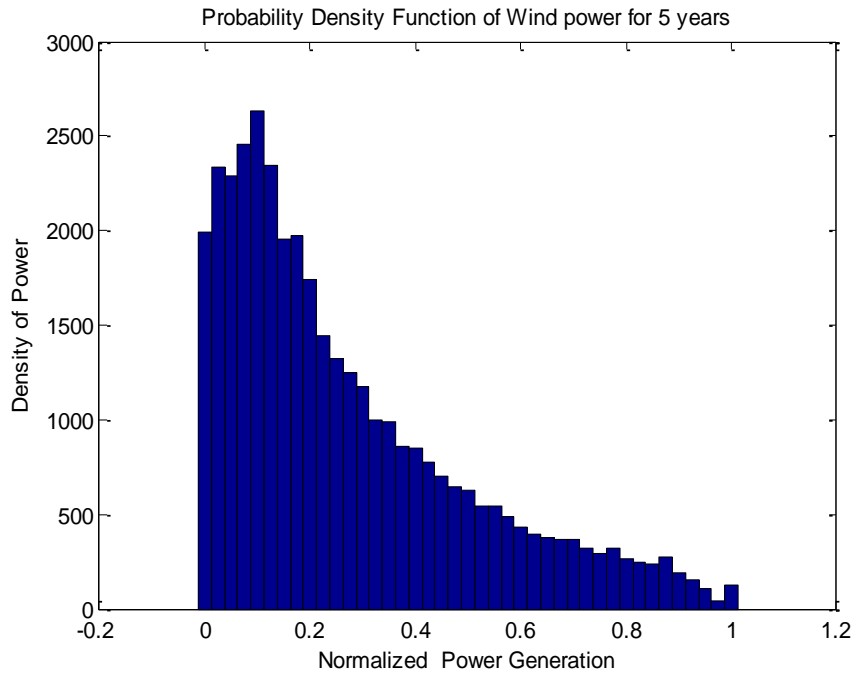
Figure 25- The normalized probability density function of generated wind power for almost 5 years

data
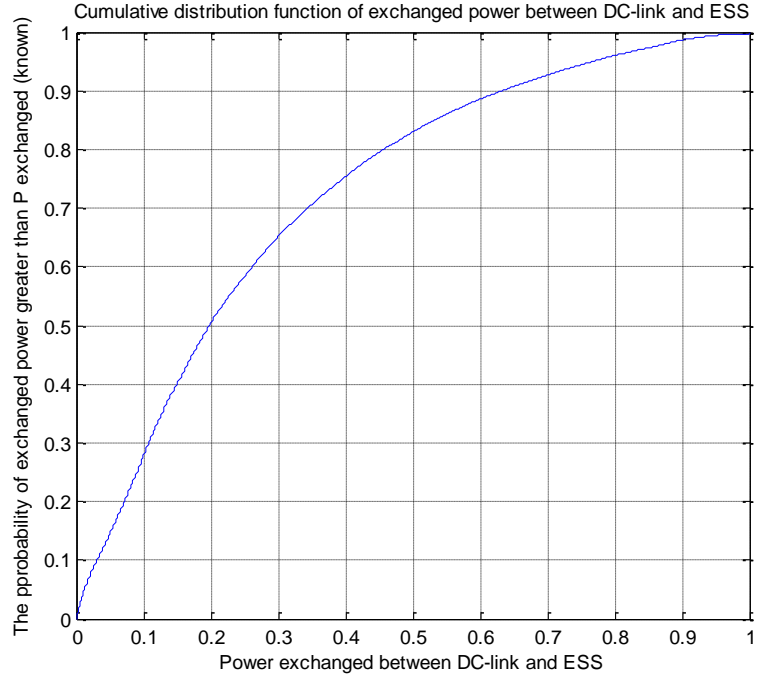
Figure 26- The cumulative density function of wind power generation

According to figure 26, the wind generated powers which are larger than 0.9 of P_{WT} does not happen frequently. Even if the ESS's size is chosen just 0.70 of P_{WT}, it can compensate more than 94% of total time. These numbers show that the power of ESS can be far less than power rating of wind turbine. In order to calculate the power rating of ESS, we choose a size which considering the cost of ESS and unserved energy, the design leads us to the most profitable design.

Equation (15) shows the amount of generation which is unserved, G_{us}.

$$G_{us} = \int_{\eta_{power}* P_{ESS}}^{1\, per\, unit} CDF\, dp \tag{15}$$

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This unserved energy is due to not choosing the power rating of ESS as big as power rating of wind turbine. Equation (16) shows the amount of unserved energy during a year by reducing the size of ESS in terms of power.

$$E_{WT} = \int_0^{K*365*24} P_{WT}. dt \tag{16}$$

Equation (17) calculates the amount of revenue which could be obtained from generated energy by the wind turbine which is multiplied with the energy price.

$$R_{us} = G_{us} * E_{WT} * \Phi \tag{17}$$

This study uses five years of historical data. If it is assumed that the geographical conditions of a specific region does not change considerably. Therefore, the average fluctuation and standard deviation remains almost constant for long time studies which make this method of sizing very practical.

Energy storage sizing in terms of energy is harder to calculate than the power sizing, because sizing in term of energy is involved with the time and SOC of the ESS. The key factor in the ESS sizing in energy aspect is that the ESS should never get fully charged or discharged unless it is not economic.

For better understanding of this method an example is provided. If the wind turbine's rating power is 1 MW, by application of power electronics we set the output power rating equal to 300KW. Due to the annual capacity factor, ACF, which is usually around 30% of total possible generation, the output power is set at this value [16].

The generation which is greater than half of the wind turbine rating power is an important factor. Considering figure (8), this number is just 13% of total generation. The wind speed is high at early morning and late nights and wind speed during day is low.

Therefore we approximately assume the wind is kind of periodic function with the period length of 24 hour. Then for a one-day operation time, the size of ESS with the lowest degree of risk can be calculated as shown in (18).

$$C_{ESS} = 13\% * P_{grid} * 24 \ (hour) \tag{18}$$

The calculated value is around 3 MW-h. Then the actual data is applied to the calculated size of BESS and the result is provided. Although the reduction in size of the ESS remains some unserved energy, by reducing the size of ESS the design becomes more economical. In order to check the sizing of this design, we applied 5 years of wind speed data to the calculated size. Table 4 shows the characteristics of the design and studied case.

Table 4- The statistics of the provided example, [21]

Rated power of wind turbine	1 MW
Size of ESS in term of energy	3 MW-h
Size of ESS in term of power	90 KW
Average generation in five years	269.97 KW
Standard deviation of power generation	233 KW
Length of connection time of wind turbine to the power grid	1560 days or 52 months

Considering the electricity and ESS price, the benefit curve is provided, as shown in figure 27.
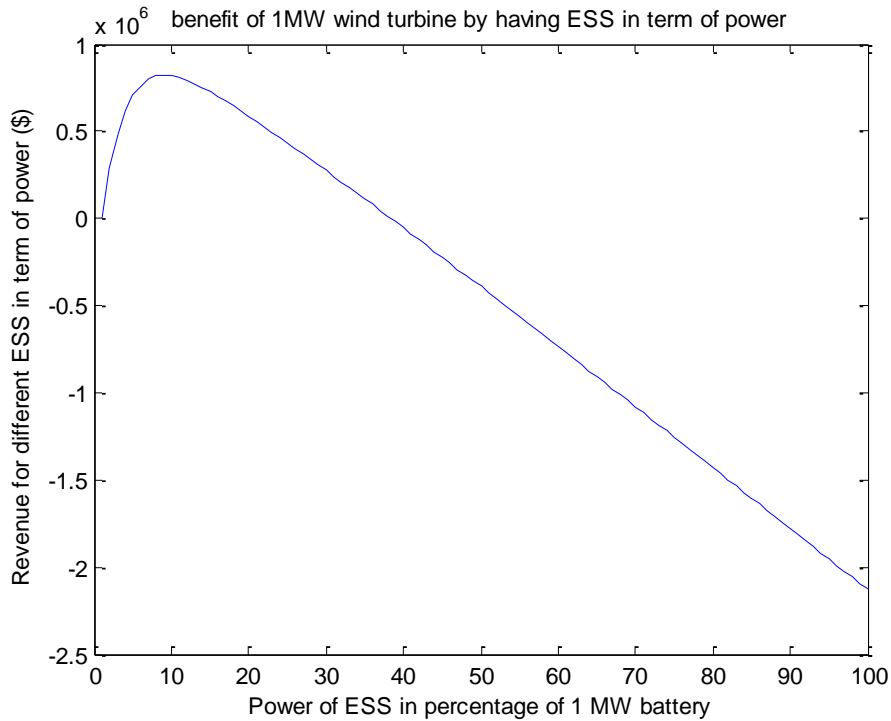
Figure 27- Revenue versus the size of ESS in term of power, [21]

The maximum revenue is around 822,310\$ and happens when the power of ESS equals to 90KW. The calculation is based on cost of BESS which is 350 \$/KW and the electricity rate is 10 Cents/KW-hour. The case studied for 4.2 years shows that if the wind turbine system has no ESS, the maximum amount of generated energy is 7014 MW-h. On the other hand the total generation of the wind turbine system in this period is around 10108 MW-h. Therefore the maximum unserved energy (when we do not have ESS) is 3094 MW-h. Using the provided statistics, we can find the optimal size of ESS then compare it with the sizing of different methods. Based on the price of energy storage system and price of electricity, a benefic curve is provided as shown in figure 28, which approves that the 3MW-h ESS is close to our sizing.

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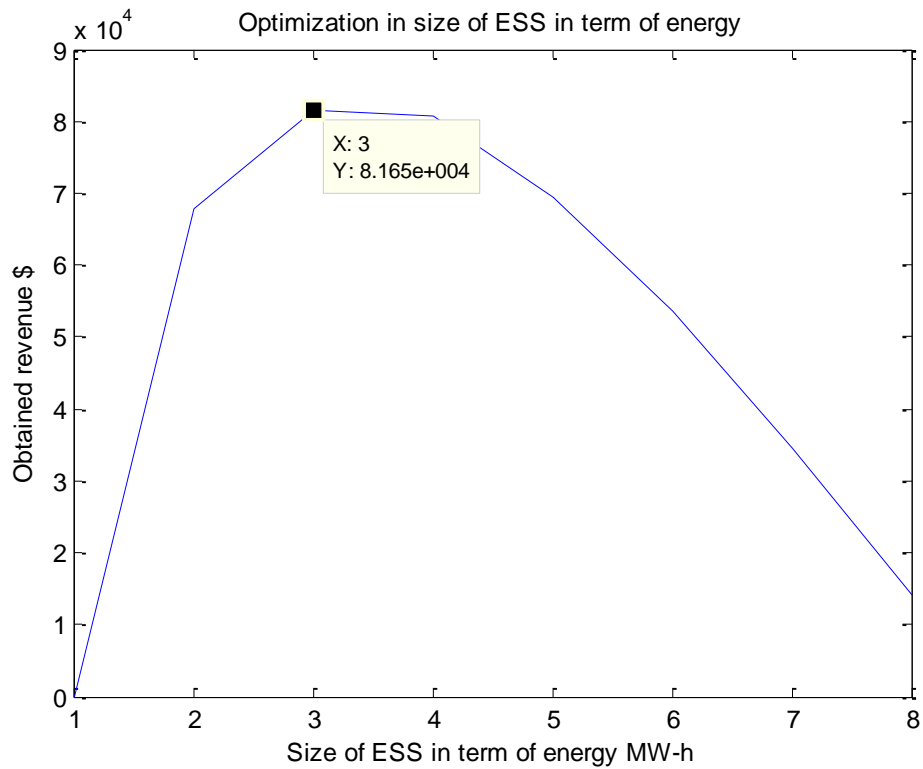
Figure 28- The optimized size of ESS in term of energy, [21]

The other battery management system happens when we have a battery as BESS and want to add one more battery to that. This energy storage system can be applied to wind turbines microgrids or any power generators which needs energy storage system.

Batteries because of their high capital cost, most batteries are equipped with a management system. The battery management system (BMS) aims to first protect the battery by keeping the battery cells inside their safe operating area and prolonging the battery life, then increasing the reliability of the overall system and finally making the system optimal in terms of efficiency and cost. The BMS at lower level manages all single battery cells by monitoring the condition of battery, reporting the data and

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protecting the battery cells by balancing and regulating their voltages [2]. Batteries as BESS are usually sized based on available capacity of on-site generation, average profile of demand, and economic parameters such as capital and operational costs to ensure a reliable and economic power supply [3]. However, over time larger batteries might be needed as wind turbines or loads are connected in the microgrid. In order to have a bigger energy storage system, one can either remove the old battery and install a new bigger battery or add a new battery to the existing system. Obviously, the second method is more cost effective as it will need less capital investment.

Due to the availability of different batteries such as Lead acid, Lithium-ions, and Nickel metal hydride [4] in the market, the new energy storage system could be a combination of different battery technologies with different characteristics. It is worth mentioning that the existing batteries have lost some portion of their capacities over time and they may also have different cycle lives at equal depth of discharges (DODs). Therefore a smart management system for multiple battery units should be capable of adjusting charge and discharge powers of used and new batteries based on their operating conditions.

Proposed methods for managing multiple batteries in a microgrid are based on considering depth of discharge, rate of discharge and other parameters related to the battery life [23]; However operating cost optimization and real-time dispatch strategy are not discussed in details. Multi-cell battery management algorithms are studied in [24] but these algorithms cannot be applied directly at battery package's level if batteries have

different characteristics. Multi-battery energy storage management systems without considering battery life and real time dispatch are discussed in [25].

This paper presents a novel control scheme for multi-battery management systems, MBMS, in expanding microgrids which the wind turbine is a power generator of this microgrid based on operating cost of different batteries. By considering the impact of DOD and discharge rate on the battery life, the proposed management system accurately and optimally dispatches all batteries to minimize the operating cost of system.

4.2.2 Management of Battery energy storage system

One of the main important factors in having BESS is the battery management, but in order to have better understanding about management of battery we need to know the battery in detail. The most important factor in battery life is rate of discharge and depth of discharge.

Impact of depth of discharge and rate of discharge on battery life: In order to optimally manage battery packages in a multi-battery energy storage system, it is necessary to investigate the characteristics and behavior of the employed batteries. Batteries have a limited life which is usually described as the number of charge/discharge cycles at different DODs. The battery life highly depends on some parameters such as depth of discharge, rate of discharge, temperature, equivalent series resistor, charging method and also the material used in the battery [26].

In this paper, the impacts of most important parameters, rate and depth of discharge, on the battery life are studied. The study of these parameters provides a better

understanding about control and management of batteries in a MBMS. The common definition of battery failure (end of battery life) is based on losing 20% of its nominal capacity. In this paper, life of a battery is defined as the amount of throughput energy, E_{Thro} which a battery can store/release during its life at a reference DOD as shown in (19).

$$E_{Thro}(DOD_{ref}) = Cap_{bat} * DOD_{ref} * Num_{cycles}(DOD_{ref}) \qquad (19)$$

where Cap_{bat} is the rated energy capacity of the battery and $Num_{cycles}(DOD_{ref})$ is the number of battery life cycles at DOD_{ref} [27].

The life consumption rate, LCR, is defined as the rate of throughput energy which a battery stores or releases at each time instant and can be calculated in (20).

$$LCR = P * F(DOD) * G(ROD) \qquad (20)$$

where P is amount of energy released/stored in a second, F is the weighting factor related to the current DOD and G is the weighting factor related to rate of discharge, ROD.

By calculating the LCR of a battery at each time instant, battery remaining life, BRL can be written in (21), where T is seconds the battery operated so far.

$$BRL\,(T) = \frac{E_{Thro}(DOD_{ref}) - \sum_{t=1}^{T} LCR\,(t)}{\frac{\sum_{t=1}^{T} LCR\,(t)}{T}} \qquad (21)$$

Following subsections describe the procedure to calculate functions "F" and "G" for different batteries.

In order to better understanding of impact of DOD, we need to come up with an accurate calculation and investigation on how the DOD has impact on the battery life. Operation of a battery at high DOD, may dramatically decrease its life. Table 5 is an

example of life cycle versus DOD for a 12v, 246 Ah VRLA battery which is used as the reference battery in this paper.

Table 5- Life cycles versus depth of discharge for the reference battery

DOD	10%	25%	40%	55%	70%	85%	100%
cycle	6915	2616	1488	958	654	463	402

To model the impact of DOD on LCR, it is necessary to obtain function F. To calculate F, the number of cycles and DODs from table I cannot be used directly, because the battery does not follow a fixed charge/discharge pattern during its operation. First step in calculation of F is to define life cycle of a battery as a continuous function of its DOD. The data sheets provided by battery manufacturers are usually a table of limited numbers of DOD versus life cycles.

Having the life cycle curve, throughput energy of a battery at different DODs can be calculated according to (19). Throughput energy of a battery at DOD equal to K (in percentage) can then be divided equally between 1% increment intervals in DOD from 0 to K (0 to 1, 1 to 2, ..., K-1 to K). All incremental throughputs are then multiplied by their corresponding value of F, added together and put equal to total throughput energy at the reference value. Assuming the reference DOD is equal to 1% in this work, function F at DOD equal to K can then be written in terms of its values at lower DODs as shown in (22).

$$F(K) = \frac{K * E_{Thro}(DOD_{ref}) - E_{Thro}(K) * \sum_{j=1}^{K-1} F(j)}{E_{Thro}(K)} \qquad (22)$$

where $\sum_{j=1}^{K-1} F(j)$ is summation of all weighting factors prior to the weighting factor of DOD equal to K.

Figure 29 shows the calculated values of function F at different DODs for the reference battery. It can be seen that operation of battery at higher DODs increase the impact of DOD on LCR of the battery.
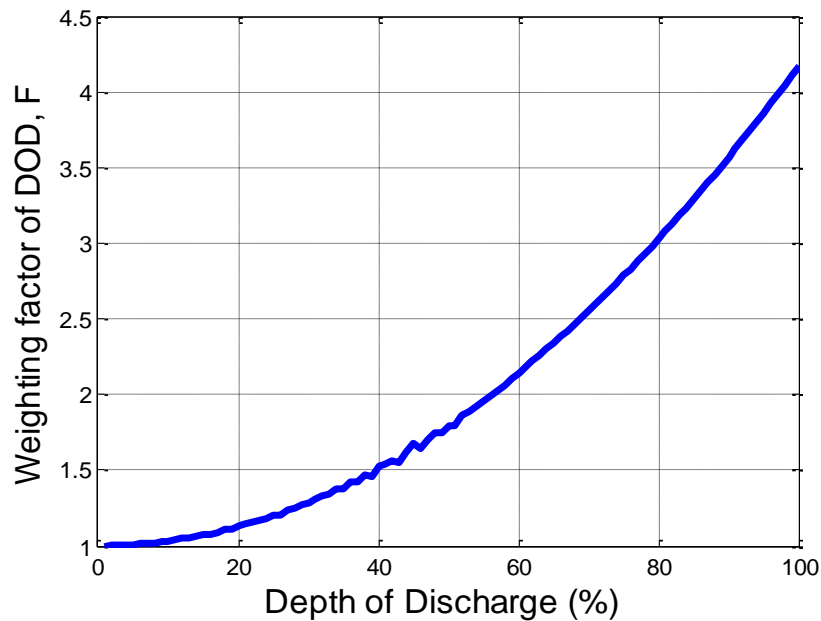
Figure 29- Weighting factor related to DOD for the reference battery

In order to better understanding of impact of rate of discharge (ROD), we need to come up with an accurate calculation and investigation on how the ROD has impact on the battery life. Charge and discharge of batteries at different rates result in different discharge capacities. Available energy of a battery highly depends on its ROD [28]. In other words, if a battery discharges at a high rate, the battery gets fully discharged by releasing less energy compared to its rated capacity. The rate that fully discharges a

battery in one hour is called Columbus (C) rate. Table 6 shows the relation between ROD and the length of time that reference battery takes to discharge from a full charge state up to the cut-off voltage of 10.8 volt.

Table 6- discharge rates and available energy in a charge/discharge cycle

Time	10m	30m	1h	2h	4h	10h	20h
Power	4528	2896	1733	993	598	280	147

Considering ROD and time, the available released/stored energy of the battery can be calculated as shown in (23).

$$E_{released} = \text{discharge time} * \text{discharge Power} \qquad (23)$$

According to Table II, if battery discharges at 1 C then total released energy in a charge/discharge cycle equals to 1733 Watt-hour (23) whereas, the released energy at 0.05 C equals 2940 Watt-hour. Therefore we can conclude that the LCR at 1 C is 1.7 (2940/1733) times more than LCR at 0.05 C. In other words, if the battery gets discharged at 1 C, the life of battery is getting consumed 1.7 times faster than 0.05 C ROD. In this way weighting factor G related to ROD can be calculated by finding the ratio of released energy at 0.05 C (reference ROD) and released energy at other discharge rates as shown in (24).

$$G(ROD) = E_{released}(0.05C)/E_{released}(ROD) \qquad (24)$$

Using (24) and the data in table II, value of G at different discharge rates for the reference battery is calculated and plotted in Figure 30.
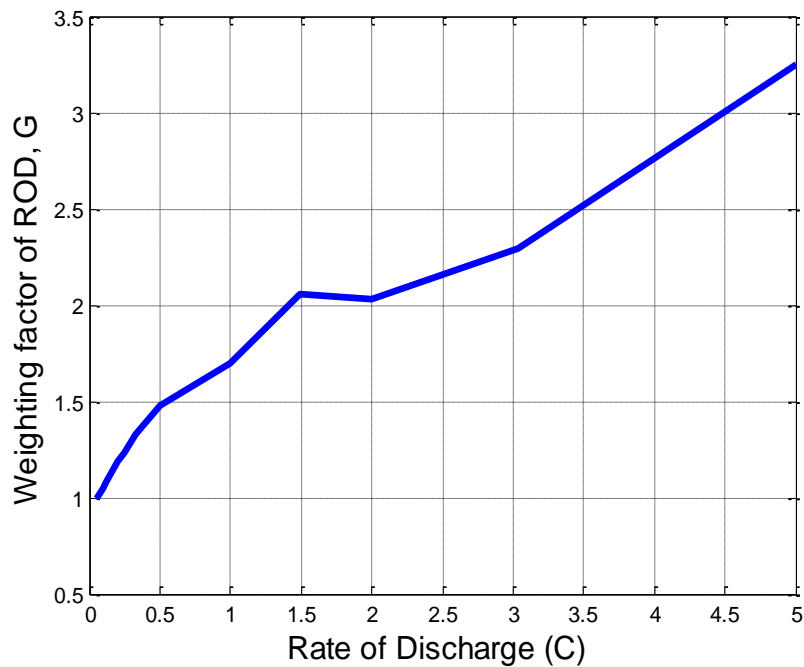
Figure 30- Weighting factor related to ROD for the reference battery

The MBMS proposed in this paper controls charge and discharge power of all batteries in a microgrid according to their individual characteristics. At the first step, MBMS collects all batteries' data including size of battery, power cap, cycle life, and discharge capacity. Then the management system calculates the weighting factors related to DOD and ROD (F and G) and unit price of energy for each battery which equals to the capital price of the battery over its throughput energy.

During each time step of microgrid operation, the MBMS measures voltage and DOD of all batteries and receives the total power which needs to be absorbed/released by the batteries from the microgrid energy management system. The MBMS then uses this information to define the overall operating cost of batteries as written in (25).

$$Cost\ (P_1, \dots, P_N) = \sum_{i=1}^{N} (P_i * C_i * F_i(DOD) * G_i(P_i)) \qquad (25)$$

Subject to:

$$\begin{cases} P_{total} = \sum_{i=1}^{N} P_i \\ 0 < |P_i| < P_{cap-i} \end{cases} \qquad (26)$$

where P_i, C_i, and P_{cap-i} are the charge/discharge power, the unit price of energy, and the power cap of the ith battery respectively. P_{total} is the total power which batteries need to charge/discharge.

By substituting (26) in (25) and then taking partial derivatives of the cost function with respect to batteries' power as in (27), and solving the resulting system of N-1 equations and N-1 unknowns, optimal values of $P_1, \dots, P_N$ can be calculated which results in the minimum operating cost for all the batteries.

$$\begin{cases} \dfrac{\partial Cost\ (P_1, \dots, P_N)}{\partial P_1} = 0 \\ \quad\vdots \\ \dfrac{\partial Cost\ (P_1, \dots, P_{(N-1)})}{\partial P_{(N-1)}} = 0 \end{cases} \qquad (27)$$

Finally MBMS assigns the calculated optimal power to each battery. This procedure is repeated at each time step of the microgrid operation. Figure 31 shows the flowchart of multi-battery managements system.
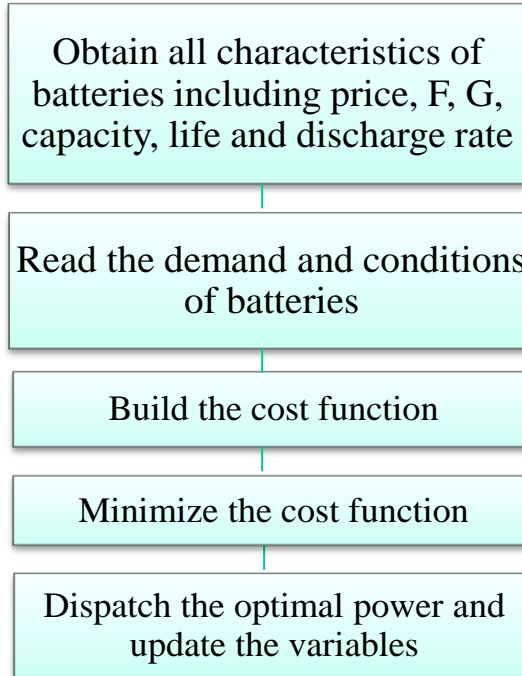
Figure 31- Flowchart of multi-battery management system

It is worth mentioning that if some batteries are already fully charged or discharged they will be excluded from the operating cost optimization procedure during consecutive charge and discharge events respectively.

Case study I: In this case study, two identical batteries A and B with characteristics similar to the reference battery are used. Since both batteries are in similar operating conditions, the MBMS divides the total charge and discharge power at each time step equally among the two batteries.

The control unit of micro grid considers the wind turbine generator, real time price of electricity, SOC of battery and the load to make decision of power flow in the microgrid. The other employed control unit is utilized to manage the multi- battery system which is main focus of this section.

Case study I: Figure 32 shows the overall batteries operating cost versus the contribution factor of battery A. The contribution factor of battery A is defined as the ratio of battery A power to the total charge/discharge power. As expected in this case, the minimum operating cost occurs at contribution factor of 0.5 where battery A is exactly providing half of the total charge/discharge power.
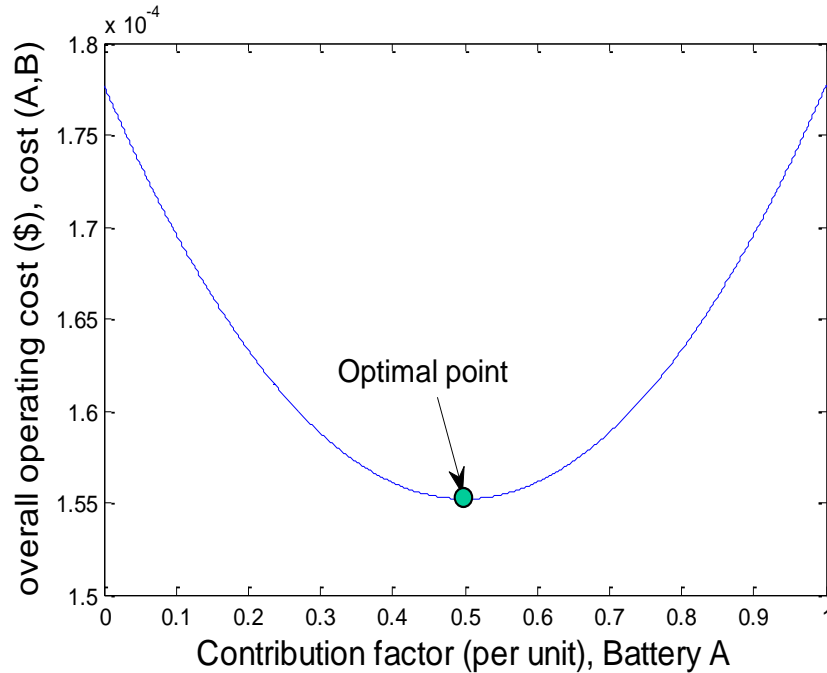
Figure 32- Overall operating cost versus participation of battery A, case study *I*

Case study II: In this case study, battery A and B are similar to the reference battery except that battery A has a shorter life cycle equal to 50% of the reference battery figure 33 shows the overall operating cost versus contribution factor of battery A for this case study.

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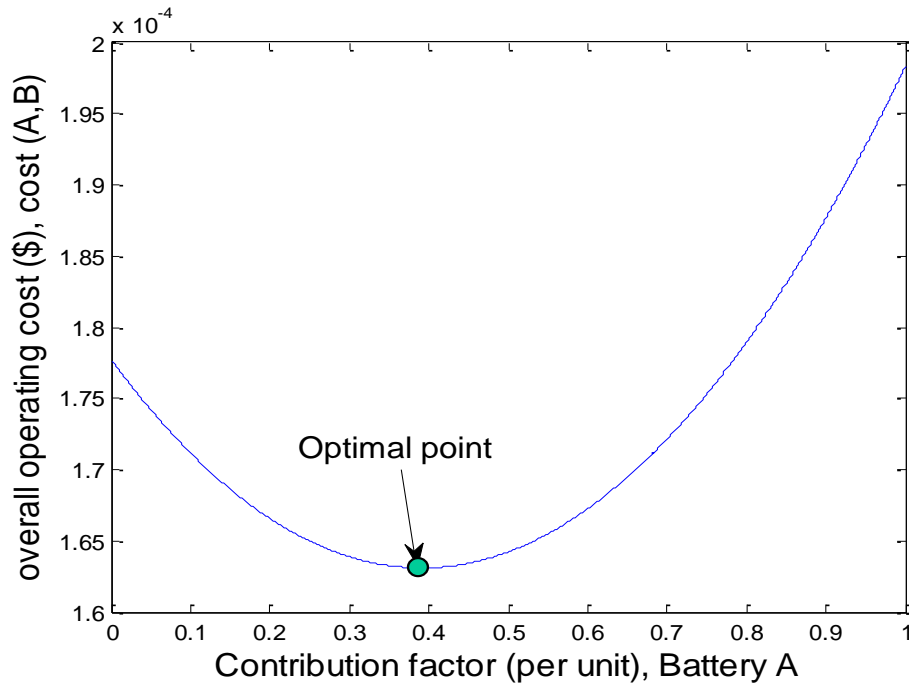
Figure 33- Overall operating cost versus participation of battery A, case study *II*

It can be seen that the minimum operating cost in this case occurs when contribution factor of battery A is less than half (about 0.4) because battery B has a longer life cycle which results in a lower unit price of energy compared to battery A.

Figure 34 shows state of charge (SOC) and the consumed life of battery A and B during a day. It can be seen that SOC variations in battery A throughout the day is less than battery B due to its shorter life which results in higher unit price of energy.
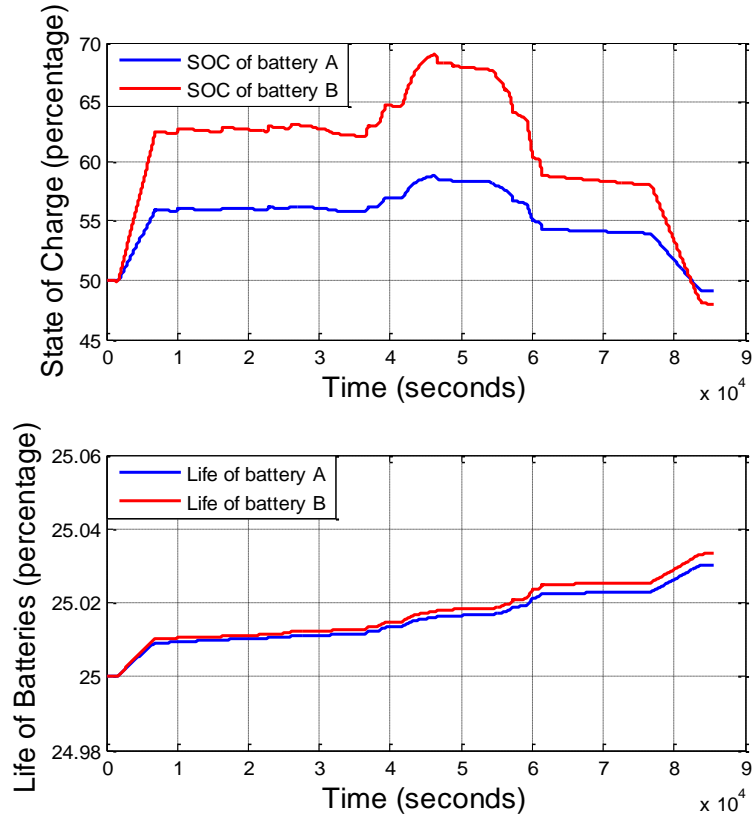
Figure 34 - SOC and consumed life of battery A and B, case study *II*

Table 7 compares the total operating cost of batteries in case study II when using the proposed MBMS with a benchmark management system which splits the total power among two batteries proportional to their rated capacity. It can be seen that the proposed management strategy results in 12.4% savings ($ 505 in 4 years) in the operating cost compared to the benchmark scenario

TABLE 7-Comparison of MBMS and benchmark management system

Battery name	Initial SOC	Final SOC	Consumed life in a day	MBMS cost in 4 years	Benchmark cost in 4 years
A	50	48.6%	0.0285	1,862	2,708
B	50	48%	0.0315	1,694	1,353

Case study III: In this case study battery A has a higher initial SOC (50%) compared to battery B (25%), but all other characteristics for both batteries are similar to the reference battery. State of charge (SOC) and the consumed life of battery A and B during a day are depicted in figure 35.
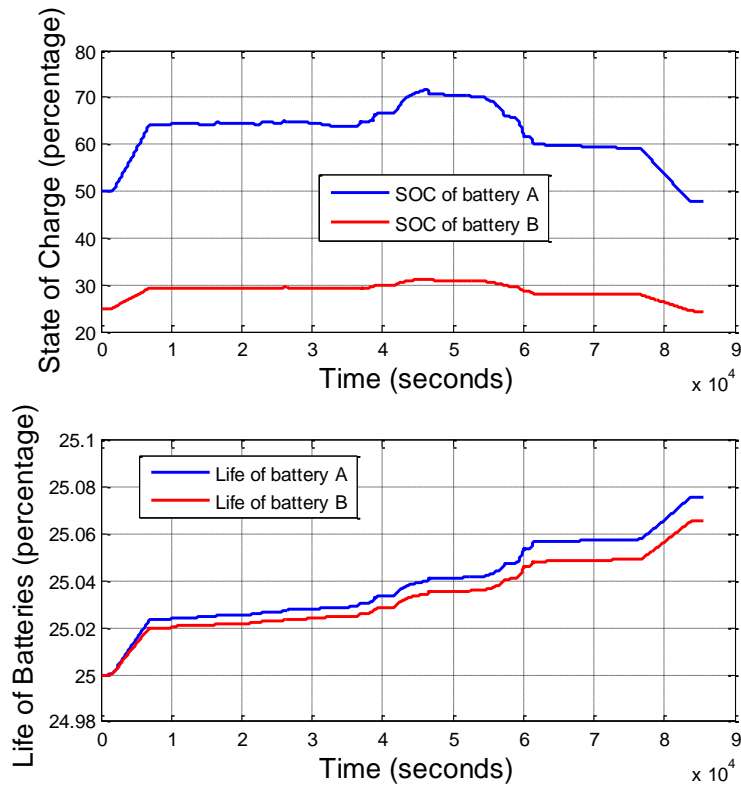
Figure 35- SOC and consumed life of battery A and battery B, case study *III*

Although the DOD is very important in finding the optimal dispatch powers for each battery, the impact of rate of discharge does not allow that all the power get dispatched from the battery with the lower DOD. Figure 9 shows that battery A with lower DOD (higher SOC) charges and discharges 40% more compared with the battery with higher DOD. The MBMS operates both batteries in a way to minimize the operating cost of batteries at each time instant.

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4.3   Economical comparison of different energy storage systems

In the literature many types of ESSs are studied. Due to huge cost of ESS in wind power generation, a careful financial review and comparison between ESSs is necessary. In this paper, first we mathematically build a model and then find if having ESS is financially feasible and which one is more beneficial. The comparison considers the power rating and cost of the ESSs' materials. Total cost of ESS includes capital cost, maintenance and operational cost. The capital cost is the price of tower (blade and generator), frame, protection devices, power electronics, wire, control units, ESS plus tax and installation fee. The operation cost consists of fee for the technicians and utilities and the maintenance cost consists of replacing the damaged parts and mechanical services. Although the battery is the least expensive ESS, the cost of battery is the major concern of investors in operating cost. Price of battery is provided by some websites [29].

It is assumed that the generators uses the MPPT control in order to convert the wind energy to mechanical energy as much as possible [30] and by applying different methods, the power fluctuations become acceptable for the power grid. Different methods in reduction of power fluctuation are as follows:

- Battery energy storage systems

- Dumping power and changing the MMPT control

- Hybrid energy storage system

- Advanced hybrid energy storage system

- A single HESS for a wind farm

Battery energy storage systems: In this section, the suggested mathematical model is presented. This mathematical model after some modifications can be applied to other methods.

Mathematical model: The profit can be calculated by (1) which is the difference of revenue and cost. Equation (28) is rewritten as in (29).

$$\text{profit} = \text{revenue} - \text{cost} \tag{28}$$

$$P\ (\$) = R\ (\$) - C\ (\$) \tag{29}$$

The income is calculated by selling the energy which is KW-h unit and the price for the energy unit value is set by ISO. Equation (29) is modified to (30).

$$P = \sum_{i=1}^{N} E(KW.h) * \Phi(\frac{\$}{KW.h}) - C(\$) \tag{30}$$

E and Φ are the energy and energy price respectively. Maintenance cost is also considered in (31).

$$P = \sum_{i=1}^{N} P_{inj}(KW) * t * \Phi\ (\frac{\$}{KW.h}) - C\ (\$) - M\ (\$) \tag{31}$$

The energy is based on hourly energy production; therefore the time which is in second has to be converted into hours, as shown in (32).

$$P = \sum_{i=1}^{N} P_{inj}(KW) * \frac{\Delta t}{3600} * \Phi\ (\frac{\$}{KW.h}) - C\ \&\ M\ (\$) \tag{32}$$

In (33), if the generation is done by more than one wind turbine, all of the wind turbines are considered.

$$P = \sum_{j=1}^{M} \left(\sum_{i=1}^{N} P_{inj}(KW) * \frac{\Delta t}{3600} * \Phi\left(\frac{\$}{KW.h}\right) - C\ \&\ M\ (\$) \right) \tag{33}$$

The capital cost of ESS has two terms, energy and power. The cost of battery in terms of energy and power capacity is considered in (34).

$$P = \sum_{j=1}^{M} \left(\sum_{i=1}^{N} P_{inj}(KW) * \frac{\Delta t - t_r}{3600} * \Phi \left(\frac{\$}{KW.h} \right) - C(E \& P) \& M (\$) \right) (34)$$

The values on the battery label are not the operational power and energy. The battery's efficiency in terms of power and energy have to be considered as shown in (35).

$$P = \sum_{j=1}^{M} \left(\sum_{i=1}^{N} P_{inj}(KW) * \frac{\Delta t}{3600} * \Phi \left(\frac{\$}{KW.h} \right) - \left(\alpha \frac{P_{max}}{\eta_{power}} + \beta \frac{E_{max}}{\eta_{energy}} \right) \& M (\$) \right) (35)$$

Other costs such as the power electronic costs and the frame of ESS are considered as shown in (36).

$$P = \sum_{j=1}^{M} \left(\sum_{i=1}^{N} P_{inj}(KW) * \frac{\Delta t}{3600} * \Phi \left(\frac{\$}{KW.h} \right) - \left(\alpha * \frac{P_{max}}{\eta_{power}} + \beta * \frac{E_{max}}{\eta_{energy}} \right) \& M (\$) + F(\$) \right) (36)$$

A single wind turbine can work for many years (i.e. 25 years) and has income for the whole life, as shown in (37).

$$P = \left\{ \sum_{h=1}^{K} \sum_{j=1}^{M} \sum_{i=1}^{N} P_{inj}(KW) * \frac{\Delta t}{3600} * \Phi \left(\frac{\$}{KW.h} \right) * \frac{1}{(1 + r)^k} \right.$$

$$\left. - \left(\alpha * \frac{P_{max}}{\eta_{power}} + \beta * \frac{E_{max}}{\eta_{energy}} \right) + M(\$) + F(\$) \right\} (37)$$

It is worth mentioning that the maintenance cost, M ($), always exists and it is constant (the salary for operators, checking and lubricating the wind turbines. On the other hand, fixed first cost, F ($) is constant but just has to be paid at the beginning. The maximum revenue for wind turbine which is equipped with battery ESS is shown in (38).

$$P = \max\{\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N} P_{inj}(n,m,k) * \frac{\Delta t}{3600} * \Phi(n,k) * \frac{1}{(1+r)^k})$$

$$- \left(\alpha * \frac{P_{max}}{\eta_{power}} + \beta * \frac{E_{max}}{\eta_{energy}}\right) + M(\$) + F(\$)\} \tag{38}$$

The power-wise characteristic of battery and energy-wise characteristics of battery, alpha and beta, can be calculated as shown in (39) and (40) respectively:

$$\alpha = \sum_{i=1}^{I} (C_{power} * \frac{1}{(1+r)^{(i-1)T_B}} - O_{power} * \frac{(1+r)^K - 1}{r\,(1+r)^T} + I_{power} * \frac{1}{(1+r)^{(i-1)T_B}} - S_{power}$$

$$* \frac{1}{(1+r)^{i\,T_B}}) \tag{39}$$

$$\beta = \sum_{j=1}^{J} (C_{energy} * \frac{1}{(1+r)^{(j-1)T_B}} - O_{energy} * \frac{(1+r)^K - 1}{r\,(1+r)^K} + I_{energy} * \frac{1}{(1+r)^{(j-1)T_B}} - S_{energy}$$

$$* \frac{1}{(1+r)^{j\,T_B}}) \tag{40}$$

C, O, I and S are the capital cost, operation cost, installation cost and salvage value respectively. The capital recovery factor is applied for better comparison, as shown in (41).

$$CRF = \frac{r\,(1+r)^T}{(1+r)^T - 1} \tag{41}$$

The present value is shown as in (42)

$$\text{Present value} = \frac{1}{(1+r)^k} * \text{Future value} \tag{42}$$

The reason that we used $(i-1)T_B$ and not just T_B, in (30) and (31), is because at the beginning the battery comes with the wind turbine. Although the life of battery is not constant, in this paper it is assumed that the average life of battery is 5 years. , but in the comprehensive model which we used, we considered all these items. Other than the

presented formulas above, some other terms have to be considered as well which the constraints of the model are, as shown in (43) to (49):

$$P_{gen}, P_{bat-min}, P_{bat-max}, P_{inj} \text{ and } P_{exch} \geq 0 \tag{43}$$

Injected power equals to summation of generated power and exchanged power of DC-link and ESS.

$$P_{inj}(n, m, k) = P_{gen}(n, m, k) + P_{exch}(n, m, k) \tag{44}$$

If the wind turbine works at its rated power value, there are some upper and lower limits for injected power.

$$P(i+1)_{inj} \leq P(i)_{inj} + P_{acc-fluctuation} \tag{45}$$

$$P(i+1)_{inj} \geq P(i)_{inj} - P_{acc-fluctuation} \tag{46}$$

Exchanged energy of storage system and DC-link is limited to the maximum power of battery and its minimum value.

$$P_{bat-min} \leq P_{bat} \leq P_{bat-max} \tag{47}$$

ESS's maximum releasing energy rate equals to ESS's maximum absorbing energy rate.

$$P_{bat-min} = -(P_{bat-max}) \tag{48}$$

Generated wind power is always positive and limited to wind turbines rated value.

$$0 \leq P_{gen} \leq P_{gen-max} \tag{49}$$

A case is studied for better understanding for readers. In this part, we calculate the total revenue of applying BESS to the wind farm. The lead acid and sodium sulfur

batteries which are the most common batteries. The different costs related to the battery production are provided [31, 32].

A wind profile during a day with the minute resolution is shown in figure 36.
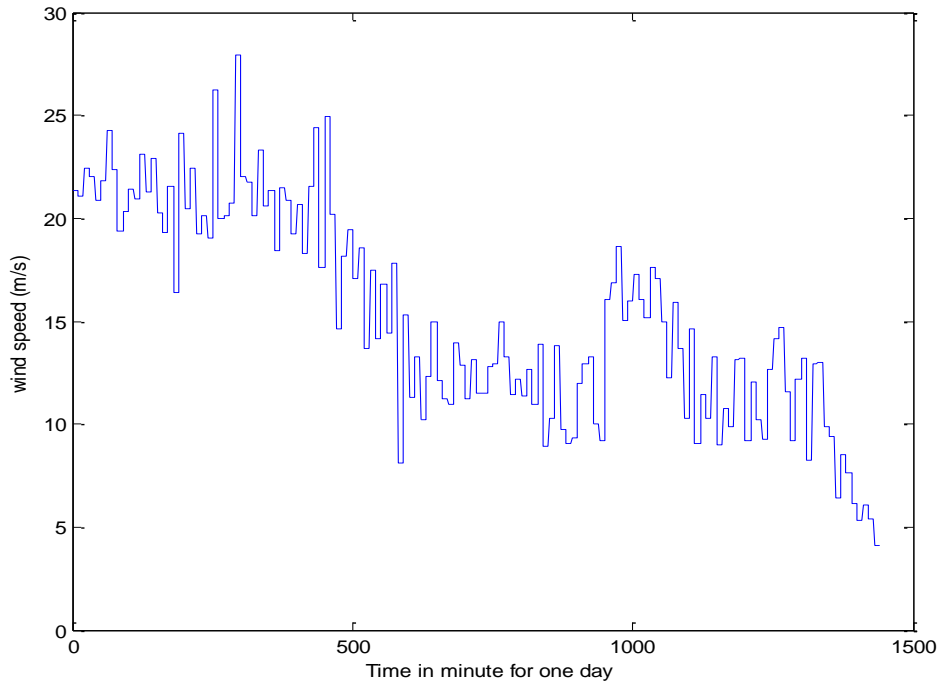
Figure 36- Wind profile (recorded wind speed) in a day with the resolution of minute, Feb 1st

2009, Audubon
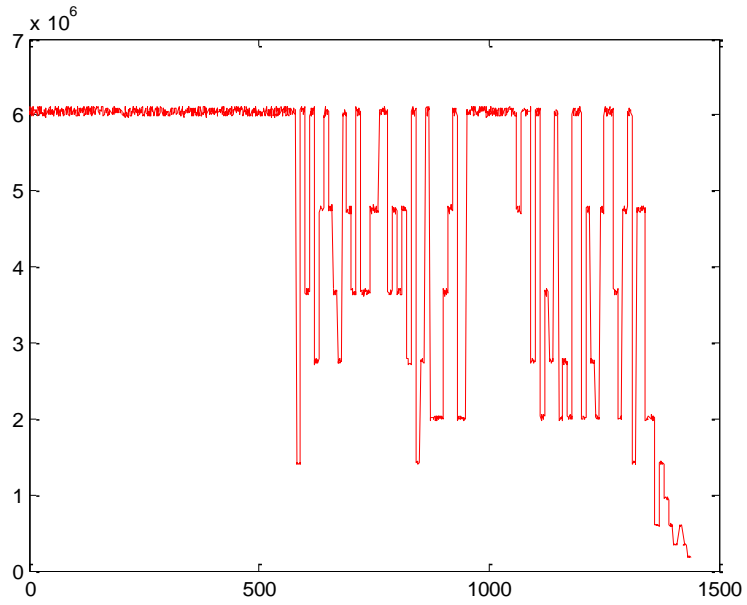
Figure 37- Generated power without power fluctuation reduction in a day with the resolution of minute

(1440 minute)
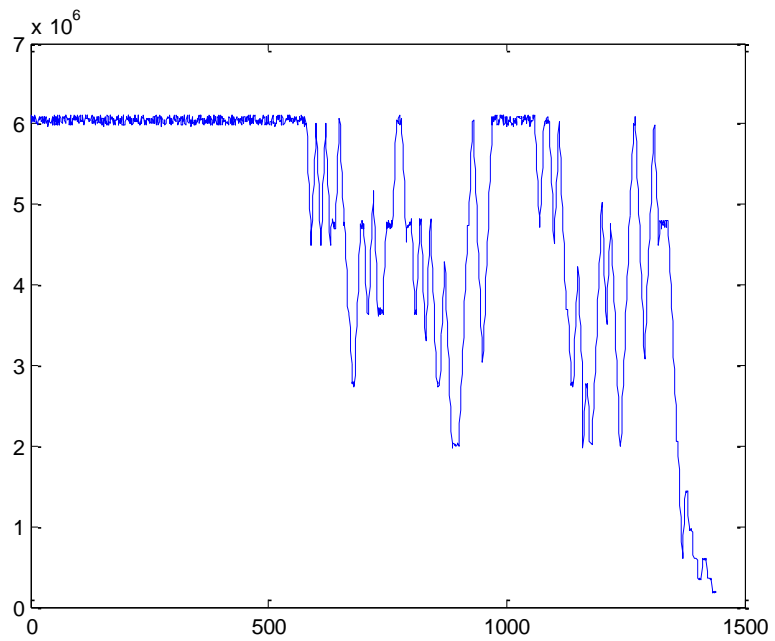
Figure 38- Reduced power fluctuation of wind turbine (acceptable power fluctuation for the power

grid)

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Figure 37 and figure 38 show the unacceptable generated wind power and acceptable generated wind power related to the wind profile respectively. Using the studied equations, cost, income and total benefits of applied BESS to a wind farm is calculated and shown in table 8.

Table 8: statistical results of application of BESS to a wind farm

Year	Income	Cost	Revenue	net present value
	Credit	debit	Balance	
1	6417260.64	71549410.54	-65132149.9	($62,627,067.21)
2	6198716.16	27899.964	6170816.196	($56,921,800.75)
3	6576202.08	27899.964	6548302.116	($51,100,384.02)
4	6081846.69	27899.964	6053946.728	($45,925,444.98)
5	5841097.92	3999647.95	1841449.972	($44,411,907.34)
6	6198716.16	27899.964	6170816.196	($39,535,021.66)
7	6417260.64	27899.964	6389360.676	($34,679,632.67)
8	5684493.12	27899.964	5656593.128	($30,546,415.48)
9	5980171.68	3999647.95	1980523.732	($29,154,925.77)
10	6258319.2	27899.964	6230419.236	($24,945,877.78)
11	5781494.88	27899.964	5753594.916	($21,208,452.23)
12	5823566.85	27899.964	5795666.888	($17,588,495.80)
13	6298054.56	3999647.95	2298406.612	($16,208,132.35)
14	6218583.84	27899.964	6190683.876	($12,633,166.66)
15	5940436.32	27899.964	5912536.356	($9,350,145.10)
16	6300391.17	27899.964	6272491.208	($6,001,210.76)
17	6417260.64	3999647.95	2417612.692	($4,760,073.09)
18	5860965.6	27899.964	5833065.636	($1,880,707.86)

19	6278186.88	27899.964	6250286.916	$1,085,943.47
20	6220920.45	27899.964	6193020.488	$3,912,357.18
Total	122793945	87966501.7	34827443.66	

The positive net present value (NPV) in year 19 and 20 shows that discount rate in this project is even greater than 4% discount rate. The average capacity factor in this study is around 32% and the price is 42 cent per KW-h. Total earned revenue from this design is $ 34,827,443.67 (from 9 wind turbines with the 6 MW rated power through 20 years). The other aspect of application of BESS to a wind farm is power fluctuation's limitation. The acceptable fluctuation for 6 MW wind turbine is less than 150 KW per 10 minute (250W). If the acceptable fluctuation is different from the a250watt, the result changes considerably, as shown in Table 9.

Table 9: different power fluctuation limitation and obtained revenue from a wind farm

Power fluctuation limits	Changes in revenue, R%	Total revenue
250 KW per 10 minute	0.31328711	$ 38,469,760.19
200 KW per 10 minute	0.29598426	$ 36,345075.55
150 KW per 10 minute	0.28362509	$ 34,827,443.67
100 KW per 10 minute	0.25890674	$ 31,792,179.91
50 KW per 10 minute	0.18475169	$ 22,686,388.61

Dumping power and changing the MPPT control: in this method, instead of having ESS, the unacceptable increase in generation is dumped as heat or the MPPT changes to

not generate undesirable increase in the generation and when there is unacceptable decrease in the generation, the owner either have to pay the penalty of by some electricity from the power grid. The mathematical model changes in both revenue and cost. There is no cost of battery but less revenue. There may be cost of purchasing electricity from the power grid or paying the penalty.

Hybrid Energy Storage System: The proposed HESS in this paper is combination of supercapacitor and battery. The huge cost of battery in term of power is replaces with the price of supercapacitor. The supercapacitor is very expensive but it last as long as wind turbine and no replacement or maintenance cost is necessary. After some modifications, the total revenue for application of HESS method is shown in table 10.

Table 10: the statistical results of application of HESS to the wind farm (a HESS to a wind turbine) in 20 years

Wind turbine cost	$ 66,420,000
converters cost	$ 23,381
Battery cost	$ 12,957,700.235
Supercapacitor cost	$ 2,329,146.15
Total cost	$ 82076434.18
Total income	$ 123,919,707.3
Total revenue	$ 41819892.15
NPV (with 4% discount rate)	$ 8,074,363.99

Advanced Hybrid Energy Storage System: by applying new designs of HESS, the batteries inside the HESS even last longer than regular HESS. Small amount of power

electronics price is added to cost but due to longer life of battery, the total revenue increases. The total revenue for application of HESS method is shown in table 11.

Table 11: the statistical results of application of advanced HESS to the wind farm (a HESS to a wind turbine)

Wind turbine cost	$ 66,420,000
converters cost	$ 33,250
Battery cost	$ 9,718,275.15
Supercapacitor cost	$ 2,329,146.15
Total cost	$ 78,845,654.12
Total income	$ 123,854,918.8
Total revenue	$ 4,500,9264.7
NPV (with 4% discount rate)	$ 10,266,387.89

Application of a single ESS to a wind farm: the other improvement in the ESS application is that instead of having an ESS for each wind turbine, a big ESS is employed for the whole wind farm. Due to cancelation of the peaks of different wind turbines generations, the needed amount of power and energy for the HESS decreases which consequently increases the revenue.

The application of a single ESS to a wind farm is illustrated as shown in figure 39.
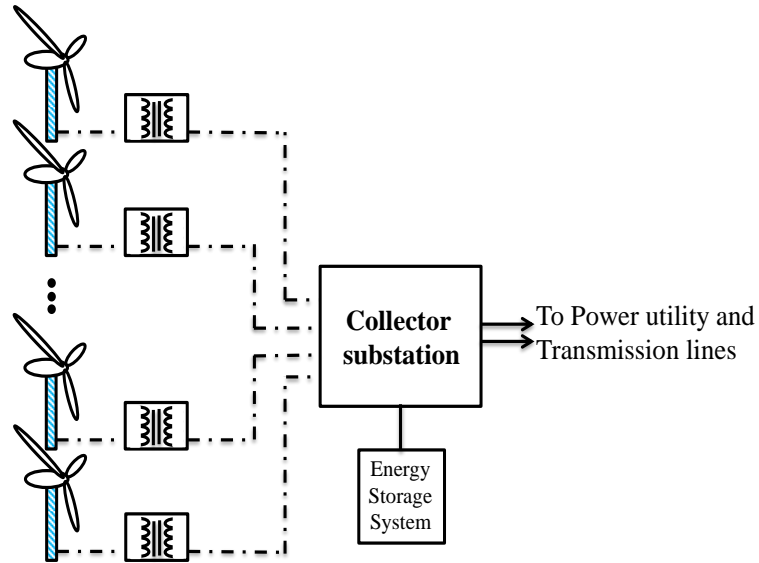
Figure 39- Application of single ESS to a wind farm

For example, if 9 wind turbines generate power and at the specific time, 4 of them have increase in generation and 5 of them have decrease in generation the total generated power's fluctuation is not 9 times bigger than power fluctuation a wind turbine. The total revenue for application of an advanced HESS to a wind farm is shown in table 12.

Table 12: Application of single ad-HESS to a wind farm

Wind turbine cost	$ 66,420,000
converters cost	$ 30,000
Battery cost	$ 8,746,447.6
Supercapacitor cost	$ 2,096,231.5
Total cost	$ 77612045.81
Total income	$ 123,830,824.8
Total revenue	$ 46218778.17
NPV (with 4% discount rate)	$11,226,835.84
NPV (with 6.2% discount rate)	$15,776.96

In this case, less fluctuation is generated and less pressure on the batteries allows us to replace batteries after longer time. In addition we same some power converters by having one power converter instead of 9 power converters.

Although the discount rate used in market almost equals to 4%, many investors do not invest their money at this rate. For this sake, the discount rate in this paper is 6% for the best design in order to be matched with real market (the Maximum discount rate which can be applied to this paper equals 6.241695%).Table 13 and 14 are provided to compare different method of power fluctuation reduction.

Table 13: Comparison of different method revenue in power fluctuation reduction

Applied Method	Changes in revenue, R%	Total revenue Different method
Power curtailment	0.24546127%	$30,141,157.47
BESS	0.28362509%	$34,827,443.67
HESS	0.34056966%	$ 41,819,892.15
Advanced HESS	0.36654303%	$ 45,009,264.70
Ad-HESS to a wind farm	0.37639297%	$ 46,218,778.17

Table 14: Table of cost for different methods in reduction of power fluctuation for a wind farm

Applied Method	Power electronic and its cost	Additional cost	Battery replacement cost
Power curtailment	Back to back converter	Considerable energy loss	0
BESS	+9 DC-DC converters	Number of batteries	Too much
HESS	Considerable, +18	Supercapacitor and	Considerable

	DC-DC converters	batteries	
Advanced HESS	Considerable, +18 DC-DC converters	Supercapacitor batteries and control blocks	Very few
Advanced HESS to a wind farm	Considerable, 2 big converters	Supercapacitor batteries and control blocks	Minimum number

It is worth mentioning that these numbers are for the region with the wind profile shown in figure 29. If the average winds fluctuation changes, these provided numbers change. Possible cases are as follow:

Profile 1: if the wind speed's fluctuation is very small, in this case BESS is the most profitable. In this case the cost of power for the battery is not necessary.

Profile 2: if wind speed fluctuation is high but the average wind speed does not change very much, then the supercapacitor energy storage is the most proper ESS. In this case the power of ESS is needed and energy capacity is not very important.

Profile 3: changing the MPPT and dumping the generation as heat is very useful for the regions which has wind speed with the very high fluctuation but the average wind speed does not change very much. It is not economic to buy ESS.

Profile 4: if the winds speed fluctuation is high and the average of wind speed changes considerably, the most suitable ESS is HESS. It is worth mentioning that the ad-HESS usually works better than HESS and applying a big ESS for the wind farm is always better than having number of ESS for the wind farm.

5. Chapter Five: Prediction and Impact of Prediction in Wind Power Generation

Due to not having correct amount of generation by the wind power, many decision makers do not like the wind power. By having an acceptable prediction for wind power many problems in power market which is involved with the wind power can be solved. Independent system operator (ISO) is the responsible to manage the power generation and load. The prediction of power helps ISO to set the amount of dispatch power for each single generator.

Many wind power prediction models are studied in literature [33, 34, and 35]. The wind power prediction has impacts on the power grid operation [36, 37]. This paper includes wind analysis, state space analysis and Kalman filtering for wind speed prediction. The other presented method is very applicable and a use the wind speed forecast which finally is able to predict the wind power 48 hours ahead.

5.1   Application of Kalman filter on wind power forecasting

In the application of Kalman filter to wind speed prediction, find state space and initial value is necessary. Since the state space is calculated using the spectral density function, by finding the characteristics of wind speed and applying the Kalman filter the prediction

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is done. A case is studied for better understanding of the process. The wind profile is shown in figure 40.
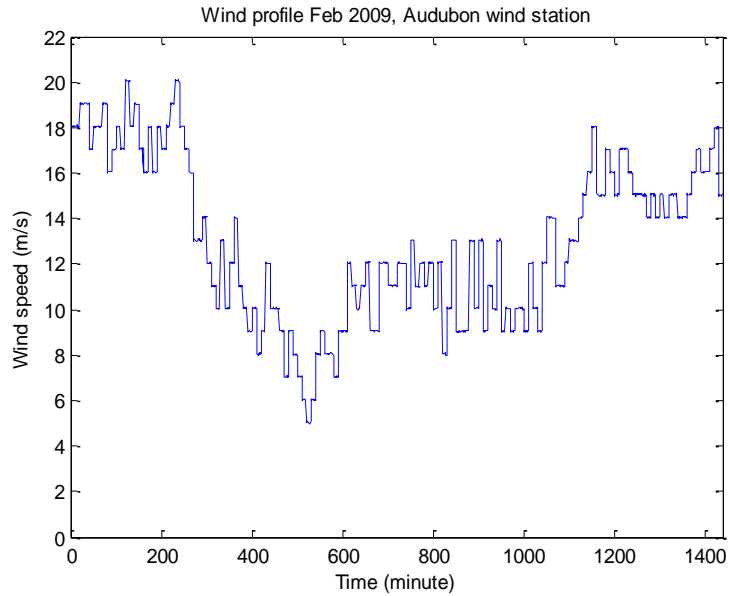
Figure 40- Wind profile in Audubon wind station in a day, [38]

The white Gaussian noise is added to the actual data in order to check the robustness of the prediction method. Although wind speed has not a function but for the initial guess, we can assume it is sinusoidal function with a 24 hour period, because it is expected that the wind blow faster in early morning and slower during noon as shown in figure 41.

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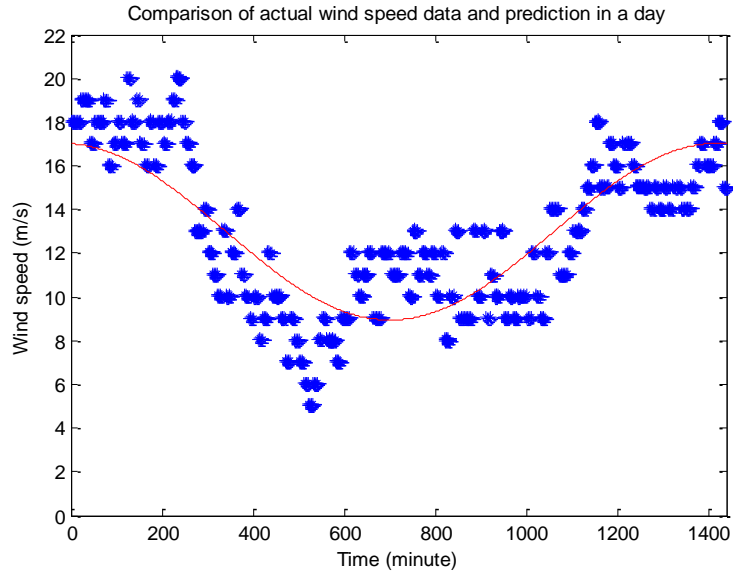
Figure 41- Comparison of initial guess and actual data of wind speed in a day (with resolution of minute),

[38]

The difference of initial guess and provided data we can find the error as shown in figure 42.
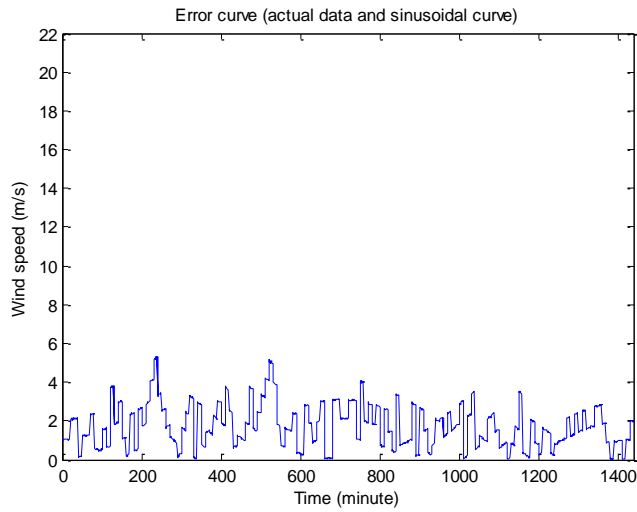
Figure42- Initial guesses error which is the difference of actual data and initial guess (resolution of one min),

[38]

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The fitted Gauss-Markov curve to the power spectral density, PSD, can calculate the state transition matrix of the system, which is needed for Kalman filtering. The most fitted Gauss-Markov curve can be found by utilizing least square method using MATLAB, as shown in figure 43.
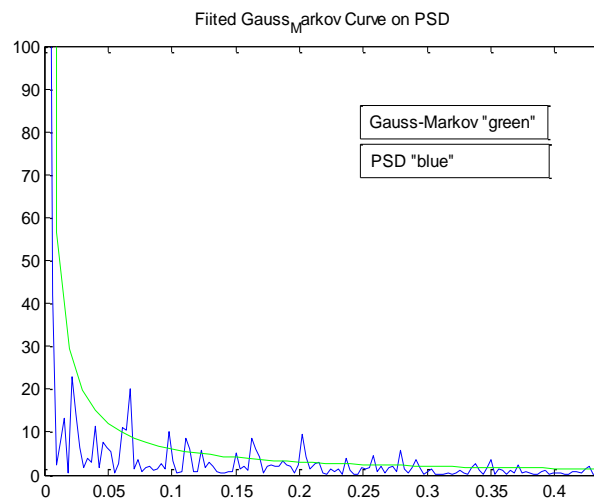
Figure 43- Comparison of fitted Gauss-Markov curve with PSD, [38]

By having the initial guess and STM, the Kalman filtering can be applied to data and the prediction is provided as shown in figure 44 and figure 45, for prediction time horizon of 2 minutes and 60 minutes, respectively.
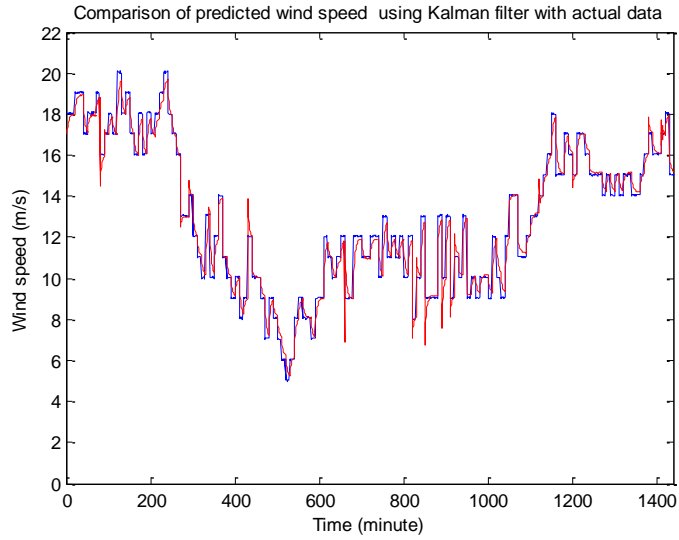
Figure 44- Wind speed forecasting (prediction length of 2 minutes), [38]
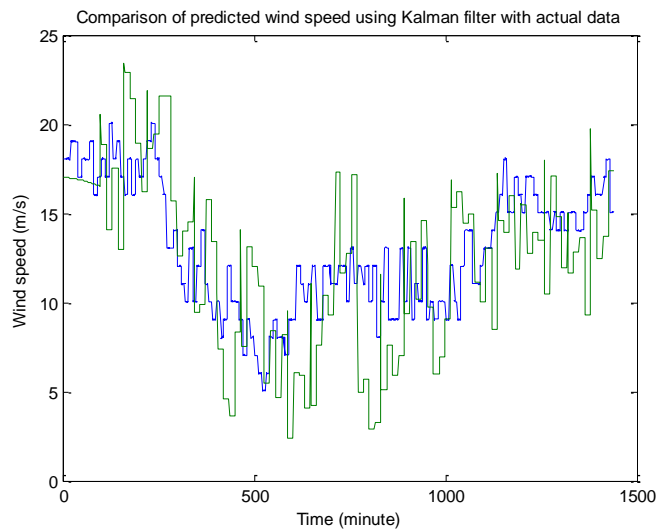
Figure 45- Wind speed forecasting (prediction length of 60 minutes), [38]

5.2   A practical method for predicting the wind power

Weather forecast system is being done by many websites but the accuracy of wind

speed forecast is still needs to be improved. Based on the problem raised by GEF-com

2012, a prediction method is presented, [22]. The problem is explained first and then the

method and then the results. The wind direction is in a wide range and there are 7 wind

turbines in a wind farm, as shown in figure 46.
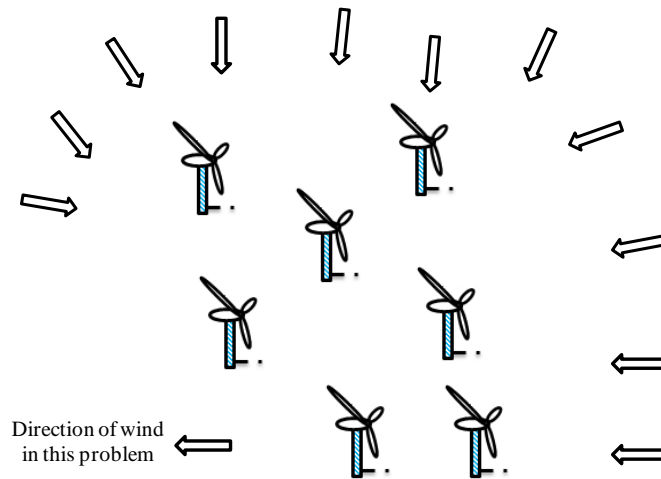
Figure 46- Seven wind turbines and the directions of blowing wind

There is a historical data for almost 500 days (between 2009/7/1 to the end of 2010)

without any missing wind speed and wind direction for each wind turbine. For the second

500 days (first day of 2011 to 2012/6/28) in each week, two data set for 48-hour are

missing and our goal is to predict these missing data sets as shown in figure 47.
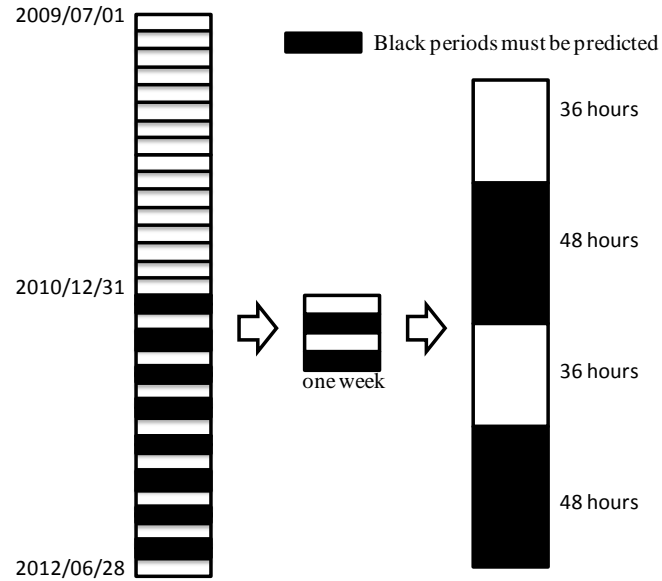
Figure 47- There are two missing observations in each week after 2010 (approximately 150 missing periods which have to be predicted)

In order to find the missing data, we applied the pattern recognition (PRM). The data set before missing data is called the reference data. The reference data is compared with the all historical data before the time of reference data. The most fitted data set with the reference data set is our objected data to find. The next data set after the objected data is assumed is our missing data set. The closest data-set to the reference data-set can be found by the least square method, LSM. Since we found the wind speed and wind direction, it is time to find the wind power. This step is done by Mapping as shown in figure 48.
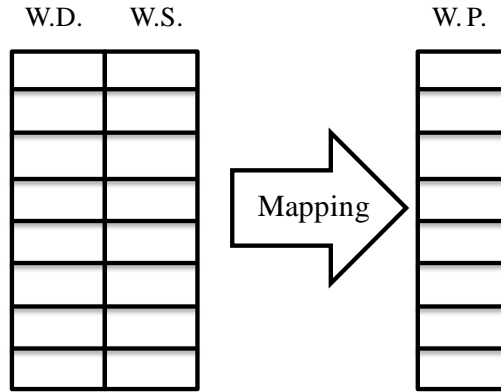
Figure 48- Mapping of two variables (wind speed and wind direction) to one variable (wind power)

After implementing the steps of the method, the result is submitted to the Kaggle website and they provide us the accuracy of the result. The result of a simple prediction method called the Persistence method is 35.4% while our method provide us the result with the 17.2% error.

In many remote areas, renewable energy sources can make a significant contribution to the power generation. A relatively small-scale conventional power plant such as a diesel engine can cooperate with the renewable generation systems to meet the load demand in the microgrid. In this study, a wind farm consisting of ten 100kW wind turbines and a 500kW diesel power plant (a diesel engine coupled with an electrical generator) is employed to supply the power to the loads in the microgrid system. A lithium-ion battery is also applied to cooperate with the generators. Different components of the microgrid model are listed as follows:

- Wind farm including 10 small wind turbines

- BESS

- Diesel generator

- Load

The application of PV panel is not included in this paper but it is recommended to install PV panel in the microgrid. The PV panels can provide more power during the day time when the wind speed is relatively low. This wind-solar complementary characteristic is very useful and promising which can be a future work after this study.

The lithium-ion battery is employed to work as an energy storage system. There are many equivalent circuits of batteries, and the battery's equivalent circuit studied in this paper is shown in figure 49 [39].

Figure 49- Battery equivalent circuit

The state of charge (SOC) of the battery can be expressed in (50). The loss is the dissipated power in the form of heat caused by the internal resistors of the battery and also the switching loss of the converter.
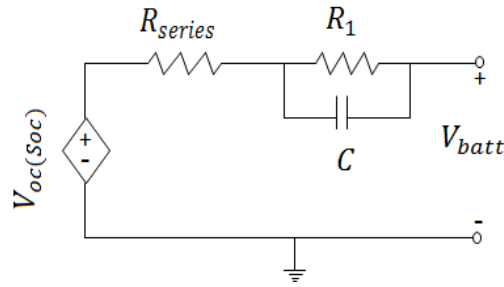
$$\text{SOC (t)} = \frac{1}{C}\int_0^t i(\tau)dt + SOC_{initial} - \frac{loss}{C} \tag{50}$$

5.3   Application of prediction in wind power smoothing

The wind does not blow constantly but if one knows how much wind will blow in the next one hour, using the energy storage system, he/she can help smoothing of wind power. For example, if there is a high wind in the next one hour the energy storage system does not need to have high SOC while if the controller does not know about the coming high wind, it may keep the SOC of battery within the predetermined ranges. Even if there is a need to battery releases some power to keep the output power as desired, the controller does not allow the ESS release energy which causes the SOC exceeds the lower bound.

Electricity pricing needs a very careful analysis. In this study, hourly price data published by Midwest ISO is used [40]. Loads in remote areas usually include residential buildings, pumps, motors, etc. The essential part in the microgrid is a central control unit which aims to control and manage the power flow in the grid in terms of optimal cost and system stability. It also aims to utilize the stored energy in the battery to supply the increased load. Meanwhile, the power provided by the diesel generator requires to be controlled in a coordinated manner.

The dynamic programming needs the prediction of power and price which can be expressed as a time sequence model. There are many papers focusing on the price and power prediction [41], [42]. In this paper, the Kalman Filter prediction is employed [43]. The state equation of the power generation prediction is shown in (51) and (52).

$$\dot{X}(t) = A\,X(t) + B\,U_1(t) \tag{51}$$

$$Y(t) = C\,X(t) + DU_2(t) \tag{52}$$

$X(t)$ is the power generation, $\dot{X}(t)$ is the prediction of the power generation, $U_1(t)$ and $U_2(t)$ are system noise and measurement noise respectively and finally, $Y(t)$ is the measured data. The noise in this study is the white noise characterized with zero mean and variance. Using Kalman filter, the prediction is accomplished and the results of 3 hour-ahead prediction and 24 hour-ahead prediction are shown in figure 50 and figure 51 respectively. The data comes from the AUDUBON wind station for the period between 1-1-2008 to 1-2-2008 [8].
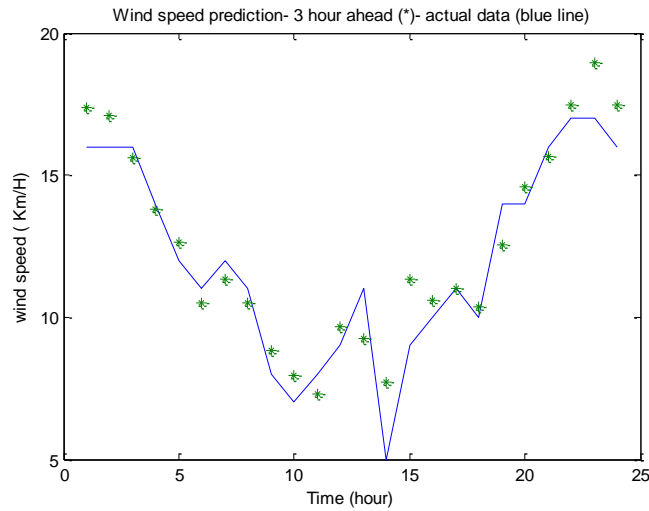

Figure 50- 3-Hour ahead wind speed prediction
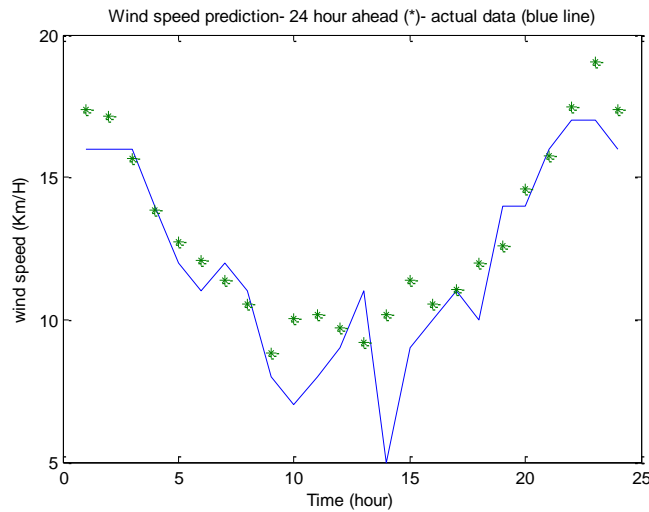
Figure 51- 24-Hour ahead wind speed prediction

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As shown in the above figures, the average result by 3-hour ahead prediction is much better than the 24-hour ahead one in terms of errors. Another advantage of 3-hour ahead prediction is that it can detect the sharp changes whereas 24-hour ahead one cannot do that, but the advantage of 24-hour ahead prediction is that it can provide the prediction result in a longer window. Having access to the data prior to the present time or the time of measurement allows the designer to design a more stable system and a more reliable energy management unit in the power grid. The prediction is done in many steps which are provided in [43]. The price prediction can be done using the same method and the initial value for the real time price is a sinusoidal function which has a peak during the day with a period of 24 hours.

5.3.1 Application of dynamic programming in wind power generation system

The dynamic programming applied in this study manages the power flow among the wind turbines, diesel generator, storage system, and loads. The load, prediction of wind power, power generation, and SOC of battery are the state variables, and the input is the control on the power flow which aims to minimize the cost. The cost function of the dynamic programming is function of states(x) and inputs (u) is shown in (53).

$$J = \sum_{1}^{n-1} DP\,[x(k), u(k)] \tag{53}$$

Equation (53) can be rewritten as (54).

$$J = \sum_{1}^{n-1} [p\,(k)][u_{w2l}(k) + u_{b2l}(k) + u_{d2l}(k)] \tag{54}$$

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where, p(k) is the electricity price at the time k and u_{w2l}, u_{b2l}, and u_{d2l} are the flow of power from wind turbine to load, battery to load, diesel generator to load respectively. All the inputs show that the electricity can be sold to the load for profits. Making profit indicates that the inputs are positive.

The requirement of the optimization is formulated as shown in (55) to (59).

$$u_{d2b}(k) + u_{w2b}(k) - u_{b2l}(k) = P_{charge}(k) \tag{55}$$

$$u_{b2l}(k) - u_{w2b}(k) - u_{d2b}(k) = P_{discharge}(k) \tag{56}$$

$$u_{d2l}(k) + u_{w2l}(k) + u_{b2l}(k) = P_{load}(k) \tag{57}$$

$$u_{w2l}(k) + u_{w2b}(k) = P_{wind}(k) \tag{58}$$

$$u_{b2l}(k), u_{w2b}(k), u_{w2l}(k), u_{d2b}(k), u_{d2l}(k) \geq 0 \tag{59}$$

In other words, the power flows from the battery, the wind farm and the diesel generator to the load, and also the power may flow from the wind farm and the diesel generator to the battery as shown in (60) to (62).

$$P_{charge}(k) = \int_0^{hour} i(t)\,U_{soc}\,dt \tag{60}$$

$$P_{discharge}(k) = -\int_0^{hour} i(t)\,U_{soc}\,dt \tag{61}$$

$$SOC_{min} \leq SOC\,(k) \leq SOC_{max} \tag{62}$$

where U_{soc} is the voltage of battery which depends on the SOC of battery. In addition, the maximum and minimum charge/discharge current should be considered since specifications can be provided by the manufacturers. It is worth noting that the minimum

SOC is 40% so as to avoid deep discharge. If the battery's SOC goes below this level, the life of battery will be severely shorten [26].

Due to free wind, the wind power generation almost does not need any production cost after installation of the wind turbine. Therefore, the least expensive power delivered to the load can be generated by the wind power and the second least expensive one is through the stored energy in the battery unless the SOC of battery is less than the minimum limit. If the battery delivers energy to the load while the SOC of battery is less than the predetermined value, the battery will suffer from permanent damage. As a result, the total cost of generation will be increased a lot. The charge or discharge power of battery cannot remain constant which depends on the SOC of battery as shown in above figures. According to the corresponding figure, it is recommended to keep the SOC of battery between 50% and 85% level.

In this section, the results and the figures of dynamic programming are shown to illustrate the presented idea in this paper. Figure 52shows the hourly load curve for the residential house. By applying the dynamic programming to the microgrid system, the SOC of battery changes is shown in figure 53.
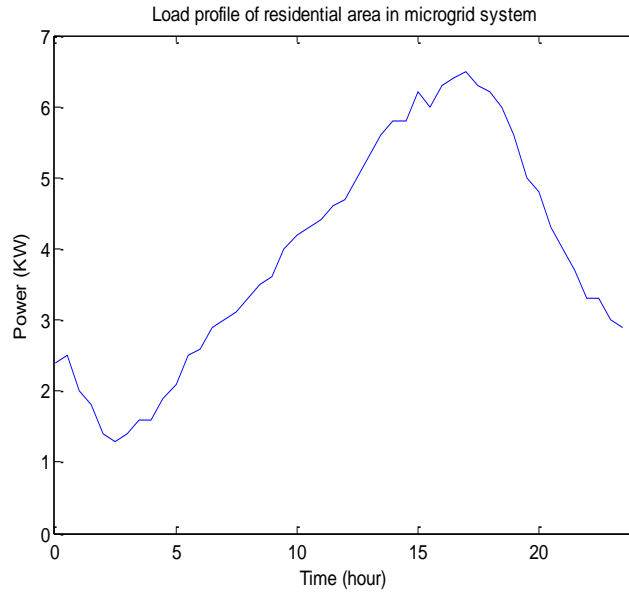
Figure 52- The hourly load curve within a day
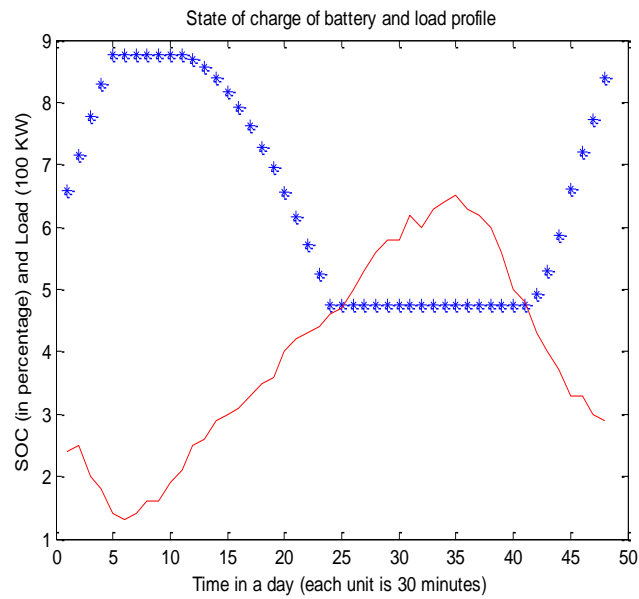
Figure 53- The hourly load curve (red line) and SOC of battery (blue stars) within a day

There may be a considerable amount of wind power available during the day but the whole power can be consumed by customers in the microgrid. The power delivered to the

load is generated by the wind farm according to the load demand. The available wind power and wind power delivered to the load is shown in figure 54.
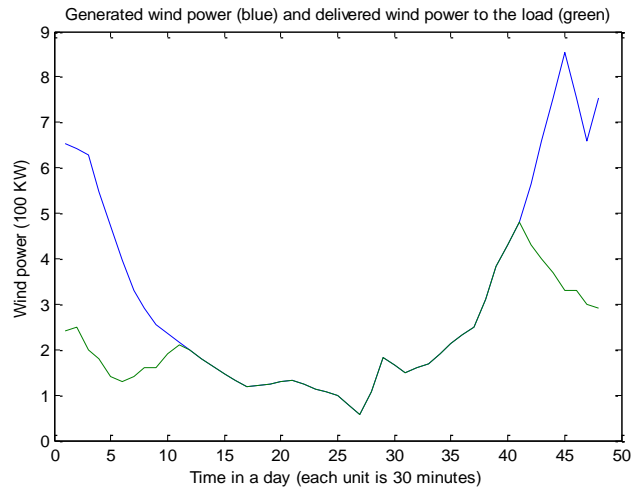
Figure 54-The available wind power and wind power delivered to the load

Figure 55 shows how much power is needed by the load, what portion of it is provided by the wind power (either stored in the battery or directly delivered by the wind turbines), and the amount of power generated by the diesel generator.
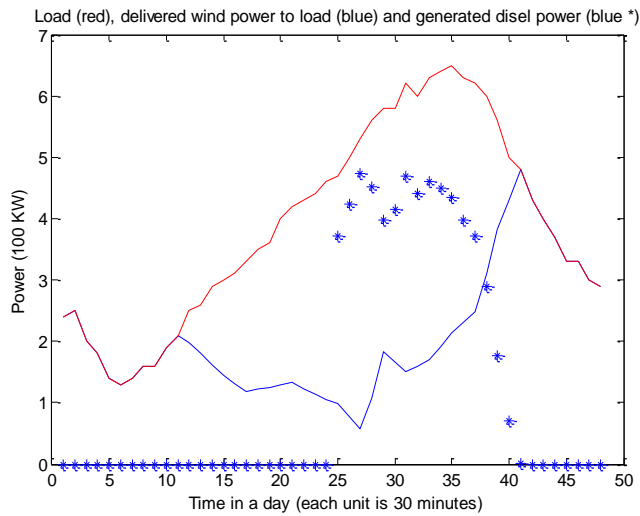
Figure 55- Load power and its composition

For the case study in this work, a couple of wind turbines and a single energy storage system are taken into account with the parameters of turbines and ESS summarized in table 15.

Table 15: Value of parameters used in microgrid model [45]

Air density	Power coefficient	Wind rating speed	Blade area	Wind turbine rated power	BESS Energy capacity
1.1229	0.42	20 m/s	530 m^2	1 MW	3.5 MW-h

The SOC of battery is a very critical factor considered in this study. If the battery is fully charged, it does not have the ability to absorb any wind energy as needed when load power is low. On the other hand, if the SOC of battery is below the predetermined value, the life span of battery will greatly decrease.

When a long-term prediction option is available in the design, it can be very useful. In other words, when the controller gets to know that in the next couple of hours there is a high wind coming, then the controller releases the energy of battery into the microgrid and does not rely on the diesel generator even though its SOC is close to the predetermined low bound. As discussed in previous section, the long-term ahead prediction may not have an acceptable accuracy and on the other hand a short-term ahead prediction has a slow dynamics. That is why short-term and long-term predictions are combined in this work. The purpose is to update the long-term prediction using the short-term one. Therefore it is good to have the wind speed prediction 24 hours in advance but also to have the next few hours of wind speed predictions with better accuracy. This technique reinforces the dynamic programming in the long term.

6.   Chapter Six: Future work

Some of the works I have done as conference papers are just the idea or a proof of concept. They can be improved by considering all available conditions and also taking to the account of minor terms. For example, for the battery management system, I only considered the rate of discharge and depth of discharge as two major terms in battery life consumption rate while we can also consider the heat, loss, etc.

The future work of mine can be to solve the issues for each work and make them very comprehensive and accurate. For example the design of BESS can be a journal paper. In the BESS conference paper, two major terms (number of life cycle and depth of discharge) in determining the life of battery are considered while there are at least 3 more terms (temperature, efficiency and loss). In addition, in the conference paper the life of battery is assumed to be constant while highly depends that how the battery get charged and discharge. The last improvement would be that the different scales of wind turbines have to be considered while in the conference paper just one size for the wind turbine is investigated. In other words, for different size of wind turbines which we may need different size of battery energy storage system we may have different conditions which needs to be considered.

The same improvement can be done for the hybrid energy storage system. In other words, more factors than number of life cycles, depth of discharge can be considered such as rate of discharge, heat, loss as well as different sizes of wind turbines.

For the proposed battery life estimation methods, based on the material of battery and its chemicals we may subject to some changes and also we need to consider all the terms that have impact on the battery life if we want to have very accurate life estimation. There are at least seven terms which I just considered the two major terms.

In the prediction of wind speed section, the methods still can be improved by having better neural network system (in pattern recognition method) and by training them instead of using the default parameters which I did in my conference papers.

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8. Appendix

List of conference papers:

- H. Babazadeh, W. Gao, X. Wang, "Controller Design for a Hybrid Energy Storage System Enabling Longer Battery Life in Wind Turbine Generators," 43rd North American Power Symposium, Aug 2011-published.

- Hamed Babazadeh, Wenzhong Gao , Jin Lin , Lin Cheng " Sizing of battery and supercapacitor in a hybrid energy storage system for wind turbines", Transmission and Distribution Conference and Exposition, IEEE PES, 7-10 May (2012) p.1-7- published.

- Hamed Babazadeh, Wenzhong Gao, and Kurtis Duncan, "A New Control Scheme in a Battery Energy Storage System for Wind Turbine Generators" Power and Energy Society General Meeting, 2012 IEEE. Date: 22-26 July 2012- published.

- David Wenzhong Gao, Hamed Babazadeh, and Li Lin, "A Practical Sizing Method of Energy Storage System Considering the Wind Uncertainty for Wind Turbine Generation Systems", 5th Green Technologies Conference, 4-5 April 2013-published.

- H. Babazadeh, Wenzhong Gao , Lin Cheng ; Jin Lin "An Hour Ahead Wind Speed Prediction by Kalman Filter", Power Electronics and Machines in Wind Applications (PEMWA), 2012 IEEE: 16-18 July (2012), p.1 - 6 - published

- Hamed Babazadeh, Wenzhong Gao, and Ashton Webberley 48 Hour Ahead Wind Power Generation Prediction for a Wind Power Plant- to be submitted

- Hamed Babazadeh, Wenzhong Gao, Zipping Wu, Yan Li, "Optimal Energy Management of Wind Power Generation System in Islanded Microgrid System", NAPS 2013 Manhattan, Kansas, USA- published

List of journal papers:

- Hamed Babazadeh, Wenzhong Gao, Jin Lin and Lin Cheng, "An Intelligent Controller Design to Increase the Battery Life Time in Hybrid Energy Storage System of Wind Turbine Generators"- to be submitted

- Hamed Babazadeh, Wenzhong Gao, "Analysis of Power Fluctuation Reduction in Wind Turbine Generator Systems"- submitted

- Wenzhong Gao, Hamed Babazadeh, " A New Management System for Battery Energy Storage System in Large Wind Turbine Generators" - to be submitted