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Impacts of Energy Storage in Distributed Power Generation: A Review

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Abstract— **Distributed Generation (DG) in the form of Renewable Power Generation systems are currently preferred for clean power generation. However due to their intermittent and unpredictable nature, energy storage needs to be used to ensure that the load is met at all times. There are many possible options for energy storage and the most popular and technologically matured option, batteries, is the subject of this paper. This paper explores the importance and necessity of batteries within DG systems, especially with renewable power generation systems. The paper looks at different varieties of batteries with a specific emphasis on lead-acid batteries. To integrate batteries into renewable energy system models, the system and the energy storage, must be simulated to test the impact on as well as optimise the sizing of the system in terms of cost and efficiency. As batteries are a fairly large capital investment in the system, it is crucial to ensure maximum life span. This is done by using a controller to control the charging and discharging cycles of the battery. There are currently many methods of modelling batteries as well as techniques for controlling the battery within the system. Some of these are discussed in this paper.**

Index Terms-- battery models, energy storage, lead-acid battery, distributed generation, battery controller

I. INTRODUCTION

Renewable Power Generation systems in the distributed generation (DG) context are being increasingly preferred for power generation. As we come closer to the end of our finite supply of fossil fuel resources, being able to use them sparingly as well as refining ways of generating electricity without them becomes increasingly important. At the same time the adverse effects on the environment of burning fossil fuels have been acknowledged and the move towards cleaner methods of energy generation is imperative. There are many advantages to this form of power generation especially within remote areas where access to established grids is limited due to distance and the cost of extending the grid is too high. However, there are currently some difficulties associated with renewable power generation systems which must be addressed. Firstly, renewable energy is by nature intermittent and unpredictable. Secondly, the supply of energy fluctuates as well as the load needed. This creates imbalances within the system and the potential for load to be unmet by supply.

There are a few ways of introducing stability into the system to ensure that there is always sufficient supply for the load needed. Hybrid systems have a better chance of being able to supply the load more consistently as they combine more than one type of renewable technology with different times of low generation and high generation, such as wind and PV hybrid. PV generation is dependent on daylight hours and irradiance levels and wind power generation is independent of irradiance levels, but solely dependent on the wind activity. This distributes the consistency of supply more evenly, but in some cases this will not be sufficient.

Energy storage is introduced in order to maintain the energy balance within the renewable energy system with consistency. It enables energy to be stored when there is an excess of supply and supplies excess energy to the loads to compensate for the deficit of supply. Apart from ensuring reliability of supply, energy storage fulfils other functions such as load leveling and enhancing power factor and quality of supply [12].

The paper is organised as follows: Different forms of energy storage currently in use are reviewed in Section II. Section III further specifies the operation of batteries and the types of batteries available for power system applications, outlining their advantages and disadvantages. Various battery models for a lead acid battery are discussed in Section IV as well as their implementation. Section V overviews a variety of battery controllers.

II. OVERVIEW OF ENERGY STORAGE

Energy storage is a vital part of DG systems. There are currently many options in terms of storage. For large scale application, Compressed Air Energy Storage (CAES) and Pumped Hydro Storage (PHS) can be used.

CAES uses excess power generated by the power station to compress air during off peak periods. During peak periods this air is then decompressed in a compression chamber before being fed to turbines, increasing energy production during peak periods. [6]

PHS uses two water reservoir storage areas, one above the other, to store energy. This is done by pumping water from the

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lower reservoir to the upper reservoir during off-peak periods and then, during peak load hours, allowing the water to flow from the upper reservoir to the lower reservoir, turning a generator and converting the energy back into electricity [14]. This ensures availability of water over a whole year for arid and semi-arid countries without large river systems.

Hydrogen Fuel cell storage is effective for long and short term storage and consists of three main stages, an electrolysing stage, a hydrogen storage stage and the fuel cell stage. In the electrolysing stage, off-peak energy is used to electrolyse water to create hydrogen ions. This hydrogen is then stored in the hydrogen storage stage until the peak load requires more energy. At this point the fuel cell starts combining the hydrogen with oxygen resulting in a chemical reaction forming water. The energy from this reaction is harnessed and converted to electrical energy. [7]

For high power efficiency application, flywheels, super-capacitors and superconducting magnetic energy storage (SMES) can be used.

Flywheels use off-peak energy to rotate a rotor attached to a wheel within a vacuum. Energy is then conserved in kinetic form until it is needed. When electrical energy is in high demand, the kinetic energy is then used to generate power [12].

Super-capacitors are conventional capacitors with increased surface area and a double layer of charge which enables a higher energy density than conventional capacitors to be stored. Super capacitors have a high power density, but relatively low storage ability when compared with other forms of energy storage such as batteries [12].

SMES uses off peak energy to pass DC current through a coil made of superconductive wire. This then creates a magnetic field around the coil in which energy is stored. The coil can charge and discharge very quickly giving a quick response to the system needs [6].

Chemical storage or battery is the most popular and frequently used method of energy storage. There are many types of storage within this category with the two main types being flow batteries and normal cell batteries. Flow batteries are used for large scale applications. The electrolytes are kept separately in reservoir tanks and moved into the electrochemical cell using pumps. When the electrolytes flow through the electrochemical cell, the chemical energy is converted to electrical energy [3]. Power delivered is dependent on the rate at which the electrolytes enter the electrochemical cell and are converted. These batteries are deemed 75-85% efficient and have a long life span. Due to the fact that the electrolytes are stored separately, very little self discharge occurs. Flow batteries are quite a costly storage solution as they involve other elements, such as pumps to move the electrolytes between the reservoirs and the electrochemical cell [14].

There are many types of cell batteries which will be discussed in more detail in the following section of this paper.

A.1 Storage Method Selection

The selection of an optimal system is based on many different criteria. Some criteria which can be used for optimisation are:

- Reliability – the ability of the system to meet the load at all times.
- Efficiency – the ability to use the components in a way as to minimize losses.
- Cost – the lifecycle cost of the system including the initial investment plus running costs over the lifespan of the system.
- Technical maturity – commercial availability and proven reliability of the technologies used
- Life span – the length of time that the system will be able to operate
- Environmental impact – the impact that each component and therefore the overall system will have on the area surrounding it [8][2]

The parameters used for optimisation of the system are decided depending on the project and the project stake holders.

A.2 Multi Criteria Decision Making (MCDM)

Multi Criteria Decision Making Management (MCDM) can be used to aid in system selection. This is done by looking at various criteria of proposed systems such as those outlined above. These criteria are assigned priority order in terms of what is most important for the system. The criteria are separated into qualitative and quantitative components. Qualitative components are ratings assigned by the system designers to the different relative attributes of the systems being evaluated such as environmental impact and technological maturity. Quantitative components are components that have concrete data associated with them such as efficiency and life span. These tables are then combined to assess each system being proposed in the order of priorities given before [2].

With regard to DG systems such as a PV-wind generation system, important aspects are efficiency, maturity and therefore reliability of the storage method as well as cost. Looking at the possible energy storage methods, SMES has the highest efficiency of the methods discussed. However, SMES is a relatively new technology and is very expensive due to the use of superconductive wiring in the coil. Hydrogen storage and super-capacitors, as relatively immature methods of storage, are not preferred for applications where support is not readily available. The efficiency of hydrogen storage also does not qualify the cost of the system. For a small power application, the use of CAES as well as PHS is not justified as there are large initial costs involved with the systems, especially in the case of PHS. In terms of CAES, whilst being a relatively cheap form of energy storage, the location of the system is limited by the presence of underground compressed-air storage. While flywheels are efficient and low cost systems, their self discharge rate is high and the energy density that they can supply is low. This makes them unsuitable for these types of applications. Chemical storage in the form of batteries is the ideal solution for Distributed Generation systems as there are no auxiliary systems which need to be run in conjunction with batteries. In addition, batteries are a very mature form of storage and can yield high energy density at low cost. The following section focuses on the different types of cell batteries available.

III. Overview of Cell Battery

Cell batteries are currently the most used form of energy storage in DG renewable energy systems. Cell batteries come in various forms and various types. When comparing batteries amongst each other, important comparison criteria are: possible depth of discharge of the battery, cost, number of charge/discharge cycles the battery can tolerate, efficiency, self-discharge, maturity of the technology and energy density.

B.1 Lead Acid Batteries

Within the cell battery group, lead acid batteries are the cheapest and most popular battery. They can tolerate a depth of discharge of 75% and have a life span of 1000-2000 cycles on this depth of discharge. Lead acid batteries are 72-78% efficient and are currently the most matured battery technology [3].

B.2 Lithium Ion (Li Ion) Batteries

Lithium ion batteries are mostly used within portable electrical equipments, such as on laptops. This is because they have a very high efficiency of almost 100%. In addition, they have a lifespan of 3000 cycles at a depth of discharge of 80% [3]. However, lithium ion batteries are very expensive and therefore are not currently considered for larger applications where a larger energy density is needed.

B.3 Sodium Sulphur (NaS) Batteries

Sodium sulphur batteries are efficient batteries which work well with the pattern of daily charge and discharge. Sodium sulphur batteries have a lifespan of 2500 cycles for a depth of discharge of 100%, 4500 cycles for a depth of discharge of 90%, and 6500 cycles for a depth of discharge of 65% [15]. Sodium Sulphur batteries have an efficiency of 89% but must be kept at a temperature of 300°C. While these batteries themselves are not expensive, maintaining the battery at 300°C requires energy which decreases the overall efficiency of the storage system and increases the cost [3].

B.4 Nickel Cadmium (NiCd) Batteries

Nickel cadmium batteries have efficiency between 72 and 78%. They can store up to 27MW of power which makes them very useful. Nickel Cadmium batteries have a lifespan of 3000 cycles with a depth of discharge of 100% and are thus well suited to the daily discharge and charge of a renewable energy system. They have high self-discharge rate losing between 5 and 20% of charge held per month [3]. However, they are also expensive and toxic [12].

B.5 Zinc Bromine (ZnBr) Batteries

Zinc bromine batteries have an efficiency of 75% and negligible self-discharge. They have high power and energy density [3]. The technology related to zinc bromine batteries is still relatively new and therefore not as technologically mature as others. In addition, these batteries are toxic [12].

Within these types of batteries, lead acid and nickel cadmium are the most technologically advanced [3]. The ease of use of lead acid batteries as well as their low cost make them the preferred type of energy storage. Lithium ion batteries, whilst having high efficiency and lifespan at high depths of discharge, are currently too expensive to be used in large applications. Sodium sulphur batteries are expensive and there is additional need to maintain it at 300°C for optimal use. While Nickel cadmium batteries have a good lifespan with 100% depth of discharge, they have a very high self-discharge rate, making them less ideal for long term energy storage. Zinc bromine batteries are relatively immature in their technology and use, so still have to be proved in their application. This paper will focus on lead acid batteries, which have been proven in their use in isolated power systems and which remain the cheapest option in terms of cell batteries. The need for maintenance and their short lifespan is still an area where improvements need to be made, but when compared with other battery types, specifically for an isolated hybrid renewable energy system, where low costs are very important, lead acid batteries are still considered the best option and are discussed in more depth.

IV. Lead-Acid Batteries

Lead acid batteries are currently the form of batteries most found in power applications. While they have a good energy density, their power density is limited and therefore the amount of energy that can be supplied to the system and the time taken to charge the battery is significant. However, lead acid batteries are still the best option for their combination of performance and cost [6]. Lead acid batteries have a relatively short lifespan and therefore need to be replaced periodically. They are therefore still the limiting factor in isolated power generation effectiveness.

Due to the inherent unpredictable nature of renewable energy systems and the absolute dependence of the power generated on climatic conditions, it is very important to simulate all components of the system together before implementation to ensure that the power supply needed for the load is met at all times. The battery forms a crucial part of this modelling as the battery increases the output predictability of the system by compensating for energy deficit in times when insufficient renewable energy has been generated and by storing the excess energy in times when plentiful renewable energy has been generated. Therefore the extent to which the battery can store and supply energy is very important within a standalone system and must be simulated under all conditions to ensure that the system will be able to meet its need.

Modelling of lead acid batteries can be done in a number of ways depending on the necessary accuracy of the simulation as well as which parameters need to be taken into account. Some methods of battery modelling need experimentation to ascertain the characteristics and plot response curves for the battery, by measuring voltages and currents during the charge and discharge processes. These are effective in gaining technical knowledge on the battery, but not very helpful in actual simulation for optimisation and system behaviour analysis purposes [18]. Another way of modelling the battery is by using an electrical equivalent circuit to represent the various parameters and characteristics of the battery and ascertain their values or equations to represent their values at different points in the process. Various battery models are discussed in this section.

C.1 Simple Model

The simple battery model, as shown in Fig 1, represents the battery by the open circuit ideal voltage and a fixed resistance. This model is very simple as it does not take the battery internal resistance or state of charge into account, both of which are very crucial to accurate dynamic modelling of the system. This model can be upgraded by changing the fixed resistance for a variable resistance which is dependent on the state of charge of the system [4]. This can then be used for applications where the state of charge is irrelevant to calculations, such as for sizing a system where the system has a fairly constant charge.

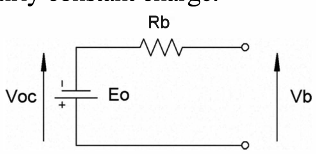

Fig.1. Simple Circuit Model

C.2 Thevenin Battery Model

The Thevenin Battery Model, as shown in Fig 2, uses an ideal voltage source, the internal battery resistance in series with the ideal voltage source and two parallel branches connected in series to the rest of the circuit to determine the battery voltage. The first parallel branch contains a resistor which represents the battery over-voltage resistance and the second parallel branch contains a capacitor which represents the capacitance between the electrolyte and the electrodes. None of these parameters are dynamic parameters and therefore this model is also limited in its dynamic accuracy as it does not take the state of charge of the battery into account [4][8]. This model can be used effectively for applications which do not need to consider the dynamic state of charge.

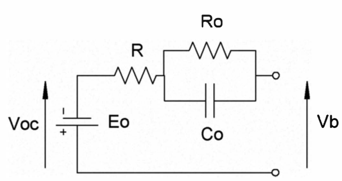

Fig.2. Thevenin Battery Model Circuit

C.3 Non - Linear Dynamic Battery Model

To improve accuracy on the Thevenin Battery Model established above, the non-linear dynamic battery model is introduced as shown in Fig 3. This model uses a capacitor C_b to represent the charge of the battery and a shunt resistor R_p to represent its self-discharge. Two parallel branches are connected to the circuit, each containing a resistor, R_{id} and R_{ic} respectively, and a diode, each diode facing the opposite direction. This is to enable different resistances to be used to model the charging and discharging behaviour of the internal resistance of the battery. Following this, 3 parallel branches are connected to the circuit. Similar to the Thevenin battery model, the first branch contains a capacitor, C_o, which represents the static charge between the electrolyte and the electrodes. The second and third parallel branches contain resistors, R_{do} and R_{co} respectively, and a diode, each facing opposite directions. These resistors, R_{co} and R_{do} represent the over-potential resistance and the under-voltage resistance respectively during charging and discharging. This model represents the state of charge of the battery as well as the internal resistance and therefore gives a high modelling accuracy. As all these components change with the state of charge of the battery, it is complicated to derive equations for each parameter and tests must be carried out on the battery to validate the model [4][8]. This model can be used for modelling systems dynamically, to assess the value of the battery voltage at each point. This allows the system to be optimised in terms of its size to ensure that the load will always be met by the energy supply.

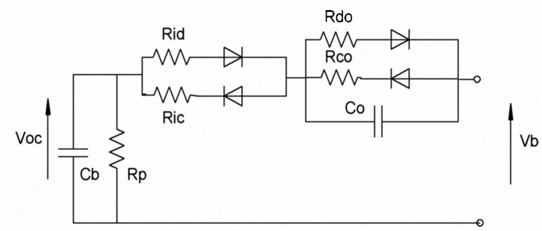

Fig.3. Non-linear Battery Model

An improvement on this model is suggested by [8] where the battery EMF is modelled as a voltage source, E_o, dependant on the state of charge of the battery. The self-discharge is still represented by the shunt resistor, R_p, shown across the voltage source in Fig 4. Three parallel branches are connected to the circuit, with the first branch containing the capacitor, C_o, representing the static charge between the electrolyte and the electrodes. The second and third branches contain resistors and diodes, R_d representing the resistance of the battery as it is discharging, and R_c representing the resistance of the battery as it is charging. The diodes control the direction of the flow of current. All of these parameters can be determined by fitting the curves with those supplied by the battery manufacturers. A charging test will only need to be done to determine the charging resistance. This does suggest an easier but accurate way to model the battery circuit.

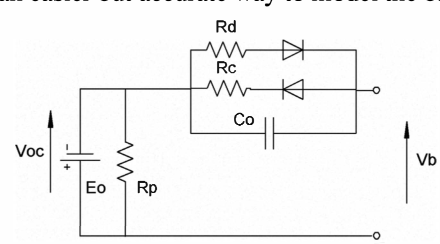

Fig. 4. Improved Non-linear Battery Model

Depending on the application and the accuracy required, one of these models can be selected and then modelled with simulation software such as Matlab Simulink to yield an accurate representation of a lead acid battery. This can be used to analyse the performance of the battery in the dynamic system within all phases of its lifecycle. Various battery size parameters can be used within this model to optimise the size of the battery used by modelling the various batteries and ensuring that over the dynamic life of the hybrid system enough energy is generated and the load will always be met. Some of these battery models can also be used to calculate the State of Charge (SoC) of the battery at any point in its lifecycle. The SoC needs to be calculated for the system to have accurate knowledge of the state of the battery and therefore be able to control the system. Battery controllers are used to control the charging and discharging cycles of the battery.

V. Battery Control and Management

Batteries form a large part of the capital investment of the D.G. systems, and therefore it is important to preserve and extend the battery life where possible [17]. This means ensuring that the battery always remains within the maximum and minimum boundaries of State of Charge (SoC) set out by the manufacturers; that the battery is not allowed to stay at a low SoC for long periods of time and that high frequency of partial charging and discharging is avoided. There are different techniques of controlling this and some of these will be discussed in this section.

D.1 High level supervisory control

Torres-Hernández et al [16] use high level control using a supervisory controller in a wind and PV hybrid generation system. The supervisory control consists of 5 modes. In Modes 1 and 2, the PV and wind systems generate enough energy to supply the load as well as charge the battery. In Mode 3, PV and wind supply at their maximum capability and the battery supplies stored energy to meet the load. In Modes 4 and 5, the load is greater than what the PV, wind and battery can supply and the supervisory control connects to the grid to enable the necessary load to be met. In Modes 1, 2, and 3 sliding mode control is used to get the supply to meet the load. This is done by monitoring the power needed by the load and the power of the power generating mechanism and controlling the DC output using a DC-DC convertor to match them. This control is very effective as constraints can be added into the system as needed and each mode can be controlled separately; for example, in Mode 3, the battery is only used until it reaches the minimum allowed SoC. At this point, the system transitions to another mode.

Another use of sliding mode control and high level supervisory control is presented by Valenciaga et al [17] in a PV-wind hybrid system with battery storage. This system operates using 3 modes. Wind is chosen as the primary energy generation mechanism and therefore mode 1 is used when just the wind power generated is sufficient to power the system. This power is regulated using sliding mode control. In mode 2, more energy is required by the load, so the wind power is generated at its maximum and solar energy generation then tracks the load power. In both mode 1 and 2, the battery is recharged and therefore adds to the load on the system. In mode 3, further energy is required and the battery is utilised along with the wind and PV power generated to supply the load.

D.2 Directional Convertor control

Hasan et al [5] use a high efficiency bidirectional convertor system with high gain buck-boost operations and a battery charger controller. The battery charger controller monitors the DC bus power and the SoC of the battery and depending on the monitored values puts the battery in charge, discharge or halt mode as shown if figure 1.

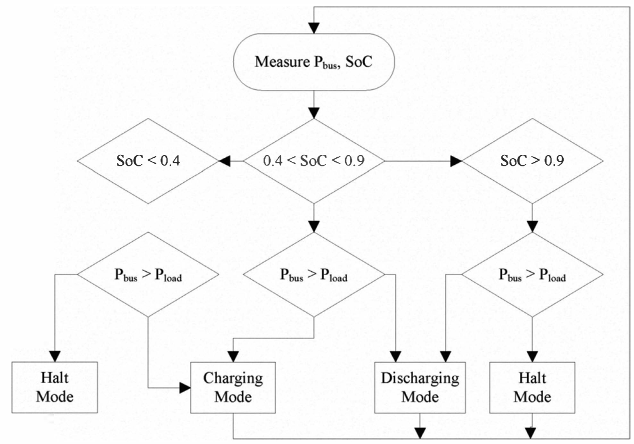

Fig. 5. Bidirectional Convertor Control Algorithm [5]

Qiang et al [10] use a four directional converter system within a hybrid wind-PV system with battery storage. The four directional DC-DC convertor is a four winding transformer which has two input stages, connected respectively to the wind generation system and the PV generation system and two output stages, connected to the load and battery storage respectively. This system also functions using modes where the 4 directional convertor becomes a 2, 3 or 4 port convertor dependant on which inputs and outputs are in use.

D.3 Battery Management Control System

Kaiser et al [9] have developed a system using parallel strings of batteries which are each switchable in or out of the circuit. Each string is monitored in terms of its SoC and State of Health (SoH). A DC-DC converter is connected to the DC bus and each string via a switch to be used for intensive full charging. Each string is then monitored separately and only used within approved range of SoC. If the SoC reaches the minimum value, the battery string is detached from the load using a switch. In addition, the controller takes account of the age and stability of each battery string and does an intensive full charge of each battery string every 14 days using the DC-DC converter for higher and more constant charging currents. The SoH and ageing characteristic of each battery string is determined by a capacity test which is done every 6 months.

Each of these methods has advantages and disadvantages and the nature of the system in which it is to be implemented is a very crucial part of the decision process. A Battery Management Control system or high level supervisory control system would be very useful within a complex system, but would possibly become overcomplicated and uneconomical for a simpler system. Directional Convertor control could be implemented very well in a smaller system. The amount of control and flexibility of the system to adjustment may also be a criterion when choosing which battery controller to use.

VI. Conclusion

Energy storage is deemed necessary and important within DG renewable energy systems to ensure stability of the system. While a variety of energy storage techniques have been discussed within this paper, batteries were found to be the most proven and easily used energy storage type for the considered application. Lead acid batteries are seen as the primary solution due to the fact that they are cost-effective and have the efficiency needed for the system. There are many possible ways of modelling batteries, some of which have been outlined in this paper. These models vary in complexity and accuracy and therefore the model chosen must match the application for which it is needed. Energy storage is still the main limiting factor in terms of renewable power generation systems especially within an isolated context, where the main electrical grid is not available as a backup should the load not be able to be met. Therefore, whilst lead acid batteries have been identified as a good solution for the hybrid PV and wind power generation system currently, more research needs to be done to find more reliable, efficient and maintenance free solutions to enable the expansion of renewable power generation systems to larger and more remote areas where support is not readily found.

Battery controllers which control the charging and discharging of the battery are found to improve the lifespan of the battery and various techniques were reviewed. These techniques were deemed appropriate for systems depending on the size and complexity of the system to be implemented.

Battery controllers will form an important aspect of the author's further work within the context of hybrid renewable energy Systems for Rural Electrification within South Africa. In rural applications, where less economic infrastructure exists and system support is not readily available it is crucial to extend the battery life as much as possible to avoid the unnecessary cost of early replacement as well as the need for technical support for the system more often than necessary. This research will be used to make these hybrid renewable energy systems more efficient and self-sustaining for longer periods of time.

VII. Acknowledgment

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