Optimisation of a photovoltaic battery ultracapacitor hybrid energy storage system

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Received 27 November 2011; received in revised form 19 May 2012; accepted 7 July 2012
Available online 8 August 2012

Communicated by: Associate Editor Arturo Morales-Acevedo

Abstract

Autonomous photovoltaic panels are intermittent sustainable energy sources which require energy storage to balance generation and demand, as photovoltaic generation is time and weather dependent. Traditionally batteries are the most common storage technology for photovoltaic systems. Photovoltaic batteries can encounter extended periods of low State of Charge (SOC), resulting in sulphation and stratification, reducing battery lifetime.

Standalone photovoltaic systems are often used in remote areas away from the national grid for water irrigation system, requiring dc motor starting resulting in high inrush current, cathodic protection systems for oil and gas pipelines, emergency phones, warning signs, and telecommunication repeater stations, resulting in pulse discharging of the battery. A combination of depleted battery SOC and high burst current can result in premature loss of load due to stringent battery Low Voltage Disconnect (LVD) limits implemented by the battery management system.

A combination of Valve Regulated Lead Acid (VRLA) batteries and ultracapacitors in a Hybrid Energy Storage System (HESS), which increases the power density of the overall system, is examined. Operating the ultracapacitor bank under high power conditions reduces the strain of large current extraction from the battery bank. The addition of the ultracapacitor bank presents the need for a methodology to optimise the photovoltaic system to prevent excess battery storage.

This paper outlines the methodology utilised to optimise the combination of photovoltaic panels, batteries, and ultracapacitors for a given solar radiation and load profile employing Matlab software.

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Keywords: Optimisation; Photovoltaic; Battery; Ultracapacitor

1. Introduction

Diminishing supplies of fossil fuel, peak oil and the environmental impact of fossil fuels on the environment has encouraged a growth in sustainable energies such as wind and solar power. Significant growth was seen by the photovoltaic industry in 2010, when the global installed capacity grew by 17 GW from 23 GW in 2009 to 40 GW in 2010 (European photovoltaic industry association, 2015).

Autonomous photovoltaic systems are generally used in remote locations, due to the expense encountered in extending the national grid. A variety of isolated applications, for example domestic applications, water irrigation, and telecommunication repeater stations, have different power requirements. A water irrigation system utilising a dc motor is an example of a photovoltaic load which requires peak power several times the normal operating power of the load.

The current required to initially start the dc motor is significantly greater than the current necessary to keep the
motor running in steady state. Typically the starting current of the motor could be six times the steady state current.

In photovoltaic systems that employ battery only storage, fast power variations, as described for a dc motor load, considerably reduces the battery lifetime because of high discharge current (Van Voorden et al., 2007). In this case the battery capacity must be large enough to account for the increased current discharge at start-up, even though the current surge only needs to be met for a few seconds at a particular time.

Fig. 1 illustrates a photovoltaic system which includes a HESS encompassing both batteries and ultracapacitors. Ultracapacitors have a greater power density than batteries, allowing the ultracapacitors to provide more energy over a shorter period of time. Conversely, the batteries have a higher energy density compared to the ultracapacitors to supply the base load requirement (Burke, 2000; Conway, 1999). The addition of an ultracapacitor bank to the storage system extends the life of the battery bank, as it does not experience high current discharge, which in turn reduces the system lifetime cost (Gao et al., 2005; Dougal et al., 2002; Liu et al., 2005).

Battery Management Systems (BMSs) which control the charge/discharge of power to/from the batteries in photovoltaic systems monitor the battery terminal voltage. When high currents are discharged from the battery bank, a significant voltage drop can be seen across the battery terminals which can lead the BMS to disconnect the battery prematurely. In the hybrid system the ultracapacitor supplies the peak currents with the battery supplying the lower average current. This utilises the battery more efficiently and reduces the risk of premature loss of load (Kuperman and Aharon, 2011).

The addition of the ultracapacitor to the photovoltaic storage element necessitates a methodology to optimise both technologies in the HESS to avoid over/under design of the system, which could lead to increased system lifetime cost or unsatisfactory Loss of Power Supply Probability (LPSP). LPSP is the probability that the photovoltaic panels and energy storage system is not capable of supplying the load when required. Therefore it is the fraction of the load that cannot be supplied in the operating time period, ranging from 0 to 1, with 0 being the load met at all times and 1 the load never being met.

A number of different methods are employed for the optimisation of intermittent generators, such as wind turbines and photovoltaic panels, in autonomous systems. These methods include intuitive, analytical methods, and system simulation approaches (Hontoria et al., 2005). The genetic algorithm (Vosen and Keller, 1999) and the simulation based (Koutroulis et al., 2006; Ekren and Ekren, 2009) optimisation techniques average the generation and load profiles on an hourly base to determine the component size. The process of using averaged data is satisfactory when the energy requirement is being considered. However the magnitude of the peaks in power is damped. Therefore when considering the effects of peak power on the battery storage system, shorter time horizons are required to capture the effect of the power spikes on the battery voltage.

This paper describes a methodology developed to optimise the various elements in the photovoltaic system taking into account peak power requirements given the solar

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**Nomenclature**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BMS</td>
<td>Battery Management System</td>
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<tr>
<td>ESB</td>
<td>Electricity Supply Board</td>
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<tr>
<td>HESS</td>
<td>Hybrid Energy Storage System</td>
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<tr>
<td>LOLE</td>
<td>Loss of Load Expectation</td>
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<tr>
<td>LPSP</td>
<td>Loss of Power Supply Probability</td>
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<tr>
<td>LVD</td>
<td>Low Voltage Disconnect</td>
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<tr>
<td>SAIDI</td>
<td>System Average Interruption Duration Index</td>
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<tr>
<td>SOC</td>
<td>State of Charge</td>
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<td>VR</td>
<td>Voltage Regulation</td>
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<td>VRLA</td>
<td>Valve Regulated Lead Acid</td>
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Fig. 1. Photovoltaic system with ultracapacitor battery HESS.
radiation on a horizontal surface and the load requirement. The optimisation process utilises a small time horizon to capture the peak power requirement and aims to minimise the system lifetime cost, while adhering to a set of constraints. The optimisation program was developed in Matlab and the results were analysed utilising a simulink model of the complete system.

2. Hybrid Energy Storage System

Generally VRLA batteries are employed as energy buffers in photovoltaic systems. Photovoltaic panels are not ideal for battery charging since they are time and weather dependent. An optimum charge/discharge strategy cannot be guaranteed resulting in poor battery life. Charge controllers are utilised to prevent over – charge/discharge of the battery by implementing voltage limit restrictions. The Voltage Regulation (VR) set point limits the maximum voltage threshold while the LVD set point determines the load cut off point.

Premature loss of load can occur due to a peak power battery voltage depression triggering the LVD limit. To prevent battery voltage drop ultracapacitors are combined with the battery bank to form a HESS. In the HESS the power required during transient spikes is provided by the ultracapacitor, reducing the battery power requirement preventing large voltage drops. There are two battery ultracapacitor HESS configurations. The passive configuration comprises a direct connection of the battery and ultracapacitor to the load, with no dc–dc conversion as shown in Fig. 2. The ultracapacitor and battery internal resistances determine the power supplied by each component. The HESS voltage is not controlled and follows the terminal voltage of the battery, leading to under utilisation of the ultracapacitor.

The second type of HESS is actively controlled. Dc–dc converters are located between the battery, ultracapacitor and the load. The converter then actively controls the power from the battery and ultracapacitor, allowing more efficient utilisation of the ultracapacitor leading to increased power capability. The ultracapacitor and battery can be operated at different voltage levels, giving greater flexibility in the design of the battery and ultracapacitor banks. The utilisation of the dc–dc converters enables a constant output voltage from the HESS (Gao et al., 2005).

In the active HESS a bidirectional dc–dc converter can be placed between the batteries and the ultracapacitors, Fig. 3. The current output of the battery is controlled with the remaining load power requirement met by the ultracapacitor. The ultracapacitor voltage becomes the bus voltage, which varies with SOC. The second dc–dc converter is required to maintain the load voltage. There is a large voltage swing on the converter input with high input current for low ultracapacitor SOC. The increased current leads to high I²R losses. Alternatively two bidirectional dc–dc converters are utilised in Fig. 4. This configuration gives the highest efficiency, reliability, and flexibility. The battery dc–dc converter is current controlled with the ultracapacitor dc–dc converter voltage controlled. The current supplied by each component is based on their SOC (Lukic et al., 2006).

3. Optimisation methodology

Optimisation of an autonomous photovoltaic system with storage is crucial as the photovoltaic panels are the only source of generation. The optimisation of the system is performed on an annual basis to minimise the system lifetime cost under a number of constraints. The constraints employed in the optimisation include the battery SOC limit, restrictions on component dimensions, and an LPSP limit. The input data required for the optimisation include the annual solar radiation and the load profile. The optimisation methodology is illustrated in Fig. 5.

To obtain the maximum energy output from the photovoltaic panels on an annual basis, the optimum fixed tilt angle for the system location is calculated based on the horizontal solar radiation of the site. A number of different models exist to estimate the diffuse solar radiation on a tilted surface. These models can be categorised as Isotropic or Anisotropic. Isotropic models assume the intensity of diffuse sky radiation is uniform over the sky dome while the Anisotropic models takes into account the brightening around the solar disk plus the isotropically distributed diffuse component from the rest of the sky dome. In the optimisation process the diffuse radiation on the tilted panel is calculated based on the Klucher model, under overcast skies the model is reduced to an isotropic model while under clear skies it approximates a clear sky model (Evseev and Kudish, 2009; Noorian et al., 2008; Armstrong and Hurley, 2010). The optimisation program varies the tilt angle from the horizontal to vertical position to determine the optimum tilt angle. The optimum tilt angle is selected as the angle at which the photovoltaic panel receives the highest global solar radiation over the optimisation horizon.

The photovoltaic energy available from the panels varies throughout the year. A trade off between increasing the number of photovoltaic panels and increasing the storage system to supply the load during periods of low solar radiation exists. To find the optimal solution the quantity of
photovoltaic panels is varied from best to worst case taking the system efficiency into account. The minimum number of photovoltaic panels required to supply the load is calculated based on the annual load energy requirement, with the maximum number of photovoltaic panels based on supplying the load for the worst day of the year. These are two extreme cases, which are not optimal and would require a large/small storage system for the minimum/maximum photovoltaic array.

The storage system is utilised as an energy buffer to supply power to the load at night time and during periods of low solar radiation. The extent of the storage elements required to supply the load throughout the year fluctuates depending on the quantity of photovoltaic panels installed in the system. The quantity of photovoltaic panels is varied from the best to the worst case and the storage system is optimised based on the power available to charge the storage elements and the load power required from the storage system. In the HESS the ultracapacitors are employed to supply the peak power requirements of the load with the average power supplied by the battery bank. The capacitance of the ultracapacitor bank is calculated based on the energy from equation (1)

\[
C_{\text{CapReq}} = \frac{2E_{\text{cap}}}{V_a^2 - V_b^2} \tag{1}
\]

where \(E_{\text{cap}}\) is the energy requirement of the ultracapacitor, \(V_a\) and \(V_b\) are the maximum and minimum operating voltage of the ultracapacitor bank respectively. In the analysis the ultracapacitor bank is allowed to discharge to half of its maximum voltage to utilise approximately 75% of the ultracapacitor energy, i.e. \(V_b = 0.5V_a\).

In the HESS the ultracapacitors are given priority charging and can be charged from both the photovoltaic panels and the battery bank to ensure they contain adequate charge to supply the high power requirements of the load which can occur at any point. As the period between the peaks in load power is unpredictable, adequate recharge of a small ultracapacitor bank cannot be guaranteed, for this reason \(E_{\text{cap}}\) is varied during the optimisation process. The minimum value of \(E_{\text{cap}}\) is calculated as the energy required to meet the largest load peak occurring during the year. To provide for peaks in load power occurring in quick succession the maximum value of \(E_{\text{cap}}\) is selected to enable the ultracapacitor to supply the day with the largest peak energy requirement. The number of ultracapacitors connected in series and parallel can be obtained by (2) and (3) respectively using the value of \(C_{\text{CapReq}}\) calculated in (1).

\[
N_{\text{CapSer}} \geq \frac{V_a}{V_{\text{Cap}}} \tag{2}
\]

\[
N_{\text{CapPar}} \geq \frac{C_{\text{CapReq}} \times N_{\text{CapSer}}}{C_{\text{Cap}}} \tag{3}
\]

where \(V_{\text{cap}}\) is the ultracapacitor voltage and \(C_{\text{cap}}\) is the nominal capacitance of the ultracapacitor.

The charge discharge profile of the HESS is adjusted to take the ultracapacitor profile into account, to highlight the energy requirements of the battery bank. The discharge rate of the battery has an effect on its available capacity as outlined by Peukert’s law, increasing the rate of discharge of the battery decreases its available capacity. The battery capacity is modified in the optimisation process according to (4) and (5) to take the impact of Peukert’s law into account.

\[
T = H \left( \frac{C}{H} \right)^k \tag{4}
\]
Fig. 5. Optimisation flowchart.
\[ Ah_{Peak} = IT \]  

where \( H \) is the rated discharge time in hours, \( C \) is the rated capacity at the discharge rate in ampere hours, \( I \) is the actual discharge current in amps, \( T \) is the actual time to discharge the battery in hours, \( k \) is Peukert’s constant which is specified by the manufacturer, typically in the range 1.1–1.3 for lead acid batteries, and \( Ah_{Peak} \) is the adjusted battery capacity (Cugnet et al., 2010).

Traditionally in photovoltaic systems the size of the battery bank is determined based on the daily load requirement and the number of Days of Autonomy (Lead acid battery guide for standalone photovoltaic systems, 1999). The Days of Autonomy outlines the number of days that the photovoltaic system can deliver full power to the load from the battery bank without charge from the photovoltaic panels, utilised to ensure the load can be maintained during rainy and cloudy periods.

The photovoltaic panel is the only charging source for the battery. In the proposed optimisation process the battery bank is calculated for each of the photovoltaic panel and ultracapacitor combinations. The number of series connected batteries is calculated in equation (6)

\[ N_{BatSer} = \frac{V_{Sys}}{V_{Batt}} \]  

where \( V_{Sys} \) and \( V_{Batt} \) are the system and battery voltage respectively. The accessible battery energy in the HESS is limited depending on the SOC limit implemented in the system as given in equation (7)

\[ E_{Batt} = V_{Batt} * Ah_{Batt} * (1 - SOC) \]  

where \( Ah_{Batt} \) is the nominal battery capacity. The charge/discharge profile of the battery bank is analysed to determine the number of consecutive days when adequate photovoltaic power is not available to fully recharge the battery bank. This value is utilised to calculate the initial number of parallel batteries required as given in equation (8)

\[ N_{BattPar} = \left( \frac{MaxDailyDischarge}{E_{Batt}} \right) * DayInadChar \]  

where \( MaxDailyDischarge \) is the maximum energy discharged by the battery in one day. \( DayInadChar \) is the number of consecutive days the battery does not maintain full SOC. \( DayInadChar \) is calculated in the optimisation program by comparing the charge/discharge profile to/from the battery bank over the optimisation horizon. This value is set to one where the battery is fully recharged every day. Both these variables are dependent on the photovoltaic array size.

A range of constraints can be implemented in the optimisation process. Constraints on the volume of the components in the system, and the LPSP are employed. The volume constraint allows restrictions on the available space for the storage elements and/or the photovoltaic panels to be taken into account when designing the system.

The LPSP is a power system reliability assessment. When the LPSP is equal to 1, the demand is never satisfied and a system redesign is required. A LPSP equal to 0, means the demand is satisfied at all times, which depending of the criticality of the load may result in overdesign of the system with increased cost. The LPSP is calculated by equation (9)

\[ LPSP = \frac{1}{T} \int_{1}^{T} ((P_{PV} + P_{Storage}) < P_{Load}) \]  

where \( P_{PV} \), \( P_{Storage} \), and \( P_{Load} \) are the photovoltaic, storage, and load power respectively. \( T \) is the time horizon over which the optimisation is performed. 8760 for time horizon of 1 year (Borowy and Salameh, 1996). In Ireland, Eirgrid the transmission system operators utilise a statistical indicator Loss of Load Expectation (LOLE) with an accepted generation adequacy of 8 h LOLE (http://www.eirgrid.com/media/Winter%202010_11.pdf). ESB Networks, the Irish distribution system operators, utilise the international measure System Average Interruption Duration Index (SAIDI), the average duration of interruption for all customers during the year. The commission for energy regulation sets the SAIDI target for ESB networks, the target was set at 152.3 min in 2010 and reduced to 141.1 min in 2011 (http://www.cer.ie/en/electricity-distribution-network-decision-documents.aspx?article=0b278e96-80f5-43e1-80ab-b23423c3c34c).

The lifetime of each of the components in the system needs to be determined in calculating the system lifetime cost. Photovoltaic panels are taken to have a lifetime of 20 years, set as the system lifetime. Ultracapacitors are not replaced during this time as they have a cycle life of greater than 500,000 cycles. To determine the number of battery replacements required throughout the system lifetime a battery life model was incorporated into the optimisation process. The battery model is an energy throughput model based on the model utilised in the Homer optimisation program (http://www.homerenergy.com/documents/MicropowerSystemModelingWithHomer.pdf). The battery throughput is the amount of energy that is cycled through the battery annually. The battery lifetime curve, supplied by the manufacturer, outlines the number of charge discharge cycles the battery can undergo at a particular SOC. The number of charge discharge cycle’s decreases as the SOC limit is decreased. To determine the lifetime throughput from the curve the average annual SOC of the battery was established and the number of charge discharge cycles was calculated. The lifetime throughput is the product of the number of cycles, the nominal voltage, the SOC, and the maximum capacity of the battery. The number of battery replacements required during the system lifetime is determined by comparing the annual battery throughput and the lifetime throughput capability of the battery in equation (10).

\[ Batt_{Replace} = \min \left( \frac{System\ lifetime}{Throughput_{node}, Batt_{Float}} \right) \]
where $\text{Throughput}_{L,\text{Life}}$ is the calculated energy throughput of the battery before failure, $\text{Throughput}_{\text{year}}$ is the actual energy throughput in the year, and $\text{Batt}_{\text{Float}}$ is the float life of the battery.

The optimisation function is to minimise the system lifetime cost, which is calculated from the capital and replacement cost of each of the system components. For simplicity only the components that are varied during the optimisation process are considered in the calculation

$$\text{System Cost} = C_{\text{capital}}(\text{PV} + \text{Battery} + \text{Ultracapacitor}) + C_{\text{Replacement}}(\text{Battery})$$

Various combinations of photovoltaic panels, batteries, and ultracapacitors which meet constraints set out in the optimisation process are presented, with the least cost option chosen as the optimal solution.

4. Simulation results and analysis

The optimisation methodology outlined in Section 3 results in the determination of the number of photovoltaic panels, the optimum tilt angle, along with the number of VRLA batteries and ultracapacitors required in the HESS. The system voltage was taken as 12 V, with the component values designed for 50 W photovoltaic panel, 18Ah VRLA battery, and 600F Ultracapacitor. The components cost utilised to calculate the system cost were €200, €70, and €45 for the photovoltaic panel, battery, and ultracapacitor respectively. One of the required inputs to the optimisation program is the solar radiation on the horizontal surface. As the solar radiation varies over the course of the year, a yearly solar radiation profile was utilised illustrated in Fig. 6, the profile was obtained from an onsite weather station located in Northern Europe (Armstrong et al., 2008).

The components of the photovoltaic system of Fig. 1 were modelled in simulink to analyse the results of the optimisation program utilising the daily load profile shown in Fig. 7 (Glavin et al., 2008). Simulations were performed assuming an initial battery and ultracapacitor SOC of 100%. The ultracapacitor utilises a physical reaction to produce power where as the battery depends on chemical reactions. The battery capacity varies with the discharge rate; high currents reduce the battery capacity leading to voltage drops. The benefits of the ultracapacitor in this situation can be seen in Figs. 8 and 9 for an un-optimised system. In Fig. 8 a voltage drop can be seen for the battery each time the motor is started. The same battery voltage is shown in Fig. 9 for the HESS.

Implementing a LVD limit of 11.8 V representing 20% SOC in the photovoltaic system with battery storage would trigger the limit every time the motor was started in Fig. 8, this could result in the motor burning out from repeated attempts to start. In Fig. 9 the high power requirement of the motor is supplied by the ultracapacitor, the battery does not experience the voltage drop. Employing the same LVD limit on the battery in the HESS extends the operating time of the system by approximately 16 h. Increased battery capacity is required in the system of Fig. 8 to enable the motor to be started throughout the day without breaching the LVD limit. This could result in a large battery pack, increasing the lifetime system cost as generally batteries need to be replaced every 3–5 years.

Active and passive HESS configurations were investigated to find the best arrangement. The active system allows both the battery and the ultracapacitor to be operated at different voltages, allowing better utilisation of the individual components. The ultracapacitor can be discharged down to a predefined limit similar to the battery SOC limit. Setting the ultracapacitor SOC limit at 50% utilises 75% of the available energy of the ultracapacitor.

A yearly optimisation was performed for the load described in Fig. 7 repeated daily, with the solar radiation profile illustrated in Fig. 6. The results of the optimisation are outlined in Table 1, for the number of photovoltaic panels, batteries, ultracapacitors along with the system lifetime cost and the days of consecutive inadequate recharge experienced by the battery over the year for varying SOC limits. The optimum fixed tilt angle for the site to produce the maximum annual energy from the photovoltaic panels was found to be 36° facing south. No restrictions on component volumes were implemented in the cases described in Table 1.

Lowering the battery SOC limit reduces the system cost as more energy is made available from the battery bank. For each of the SOC limits, the optimised system returns the battery to 100% SOC for the majority of the year except for two periods of extended low solar radiation, illustrated in Fig. 10 by the daily maximum SOC of the battery bank, for the HESS system with a battery SOC limit of 20%. Returning the battery bank to 100% SOC each day helps prevent sulphation and stratification (Dunlop and Farhi, 2001; Wong et al., 2008). Fig. 11 shows the battery SOC during the period of low solar radiation occurring in December.

The optimisation process is performed over the course of a year taking component lifetime into consideration when calculating the system cost. Therefore due to the short lifetime of the battery it was found to be more economical to increase the number of photovoltaic panels required to supply the load during periods of low solar radiation, generating dump energy during the periods of high solar radiation. There was no penalty cost placed on the dump energy as the cost associated with the generation of photovoltaic power is taken as zero, apart from the initial system and battery replacement cost.

The ultracapacitor SOC over a 3 day period in December is displayed in Fig. 12; this is representative of the ultracapacitor operation throughout the year. The active HESS of Fig. 4 was implemented in the design and the minimum operating voltage of the ultracapacitor was set to 6 V in the optimisation process. The ultracapacitor in the system is given priority and recharged by both the photovoltaic panels and the battery bank. Therefore the
ultracapacitor is maintained at a high SOC. The number of series ultracapacitors could be decreased utilising more of the energy available in the ultracapacitors to reduce the system cost, as the dc–dc converter will generate the power at the required load voltage.

From Fig. 8 the battery storage system needs to be optimised taking the voltage drop at motor start up into account, resulting in an increased battery bank and therefore increased system lifecycle cost as seen in Table 1. The HESS system cost remains lower for all SOC limits in comparison to the Battery system, however greater benefit can be seen with the SOC limit set at a high level, as only a small voltage drop would be acceptable before the LVD limit would be triggered by the battery storage system.

The SOC limit of 20% was found to give the lowest HESS system cost as the majority of the available energy in the HESS can be utilised for the periods of low solar radiation which can occur for several days.

The HESS with a 20% SOC limit for the battery bank was examined for volume restrictions on the individual component in the system. The number of panels for this...
case was restricted to 15 panels, a reduction of 12 panels. The reduction in the number of photovoltaic panels lead to the number of consecutive days the battery experiences inadequate recharge increasing to 8, with the number of batteries required to satisfy the SOC limit increasing to 40. With the reduction in the number of photovoltaic panels there is a need to increase the energy storage of the HESS to enable the load to be supplied for the extended periods of low solar radiation. As the number of photovoltaic panels is reduced the amount of dump energy produced during the year also diminishes. The increase in the number of batteries required and their replaced cost increases the system cost by approximately 62% to €17,225. The Battery daily maximum/minimum SOC over the course of the year can be seen in Fig. 13. Compared to Fig. 10 the battery bank is not as frequently recharged to 100% SOC during the winter period.

A sensitivity analysis limiting the number of batteries to 7 in the HESS system with a battery SOC limit of 20% was also performed. Limiting the battery bank in the storage system necessitates a large photovoltaic array to be installed, to generate the daily power requirement of the load as the battery bank is not large enough to provide for the load for an extended period of time. In this situation the number of photovoltaic panels is nearly doubled to 51.

Increasing the system cost by approximately 22% to €12,875. The large number of photovoltaic panels also increases the amount of dump energy produced during high solar radiation. The daily battery maximum/minimum SOC can be seen in Fig. 14. The large number of photovoltaic panels can be seen in Fig. 14. The large number of photovoltaic

<table>
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<tr>
<th>SOC limit</th>
<th>Hess system</th>
<th>Battery storage system</th>
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<tr>
<td></td>
<td>No PV panels</td>
<td>No battery</td>
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panels returns the battery array to 100% SOC for the majority of the year but the reduction in the number of batteries means the batteries are discharged to a lower SOC. Comparing the lifetime system cost of both sensitivity analysis highlights further the impact the battery bank has on the lifetime cost due to number of battery replacements required during this period.

The system size and lifecycle cost can be reduced if the loads supplied were non-critical and an LPSP of greater than zero is considered. Throughout the majority of the year the batteries in the system are maintained at a high SOC in the HESS. If the system was allowed to drop the load for a short period of time during prolonged periods of low solar radiation which only occurs twice during the year the battery bank could be reduced. Setting the LPSP to allow 8 h loss of load in the optimisation process reduces the system cost by approximately 4% to €10,175. This is achieved by reducing the size of the battery bank, a loss of load of approximately 4 h was observed during the period of low solar radiation at the end of the year.

The benefit of the HESS can be seen in Table 1 for a motor load that is repeatedly started throughout the day. This will not be the case for all applications. The load profile of Fig. 7 was adapted for two situations, a motor started daily at 4am for 45 min, and a motor started daily at 5pm for 45 min. The results of the optimisation are outlined in Tables 2 and 3 for the profile of the motor started at 4am and 5pm respectively. The results of Tables 2 and 3 are similar, and follow the trend of those in Table 1. The addition of the ultracapacitor reduces the system lifetime cost, with the greatest benefit seen when the battery SOC limit is high.

5. Conclusions

A sustainable energy system consisting of a photovoltaic array with a battery ultracapacitor HESS to supply a non-grid connected load was introduced. The impact of including the ultracapacitor in the photovoltaic system was analysed. The batteries and ultracapacitors complement each other in terms of their power and energy densities.

Electrical loads that contain motors can have power spikes of between three and seven times their rated wattage at start-up, while loads requiring large capacitors to be charged at start up can result in a power surge up to three times their rated wattage.

A DC system was analysed in this paper but the same principals apply to AC systems. In an AC system the inverter must be sized to take into account the starting power requirement of the load, with the battery bank being sized to handle the voltage drop due to the high current surge. Otherwise the drop in voltage could cause the inverter to shut down.

The battery bank supplies power to the load through chemical reactions, with the capacity of the battery...
depending on the discharge rate. Peak power loads requiring high power reduce the battery capacity, resulting in a voltage drop. When the battery is at a low SOC the voltage drop can trigger the LVD limit leading to the load being shut down prematurely. The ultracapacitor in the HESS provides the peak power, alleviating the battery voltage drop, maintaining the load for a longer period of time.

A methodology to optimise the HESS was described. The optimisation process was performed for a peak power load with the results analysed with a simulink system model. It was found that an ultracapacitor battery HESS should be employed to minimise the system lifetime cost of an autonomous photovoltaic system operating a load with a high peak to average power requirement. An active HESS configuration makes best use of the available ultracapacitor energy. To further reduce the cost the SOC limit for the battery should be low to utilise as much battery energy as possible. If feasible no limits should be place on the number of components in the system, as this can significantly increase the cost. Finally utilising a LPSP of greater than zero reduces the number of batteries needed to cover the longest period of low solar radiation.

For the load profiles assessed, the cost saving incurred by employing the ultracapacitor battery HESS over battery only storage varied depending on the SOC limit. For the load profile with the motor started every hour, the cost saving between the two storage systems changed from approximately 153% for a SOC of 90% to approximately 11% for a SOC of 20%, with the cost increasing by approximately 242% if the SOC limit is increased from 20% to 90%.

Acknowledgment

This project was supported by Enterprise Ireland under the Commercialization Fund in Technology Development (CFTD).

References


