Improvement of Battery Lifetime using Supercapacitors and Current Controller

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***Abstract*— Decrease in conventional resources has led to high reliability on renewable energy resources for generation of power. The batteries are main source of storage for these power resources and the main investments in these projects are on battery storages. Thus it is important to maintain them on proper grounds. Due to variable characteristics of renewable generation, the batteries used in renewable power system undergoes many partial and irregular charge or discharge cycles. This has a detrimental effect on battery lifetime and thus replacement leads to increase in project maintenance costs. This study imposes a method for improving battery lifetime in small scale wind energy power system by the use of battery supercapacitor hybrid energy storage system. The supervisory controller incorporating hysteresis comparator is described and projected long term benefits of the proposed system are assessed by simulation. The analysis is presented for the potential improvement in battery lifetime that is achievable by diverting short term charge or discharge cycles to a super-capacitor energy storage system. This study introduces a method by which supercapacitor battery energy storage system and supervisory controller can be evaluated analyzed for an application area to be considered. The experimental results are presented to demonstrate system feasibility by using MATLAB simulink.**

***Index Terms*— Battery storage, supercapacitors, renewable resources, wind power, supervisory controller.**

I. INTRODUCTION

A. *System Overview*

Due to the variable characteristics of renewable generation, batteries used in renewable-power systems can undergo many irregular, partial charge/discharge cycles. This can also have a detrimental effect on battery lifetime and can increase project cost. Secondary lead-acid batteries may have a typical service life of less than 1000 full-cycle, and often constitute a large proportion of the total cost of a renewable energy project. [1].

The aim of this study is to develop a system to prolong expected battery lifetime, thus reducing battery-replacement costs. This can be a significant advantage, particularly in remote areas, where access can be difficult and costly. In contrast to secondary batteries, super capacitors also known as “electrochemical double-layer capacitors” (EDLC), or “ultra capacitors ,”offer higher power density and increased cycle life (of the order of 10^6 cycles) but have a considerably lower energy density.[2].

Super capacitors currently find use as short-term power buffers or secondary energy storage devices in renewable energy, power systems and transport applications. Combining two or more energy storage systems permits the beneficial attributes from each device to be utilized. [3]-[7]. The aim power generation of this study is to utilize the inherently high cycle life of super capacitors in a battery/super capacitor hybrid energy storage system to improve battery life time.

Lijun et al have shown that the active hybridization of batteries and super capacitors can yield an improvement in the overall energy storage system power handling.[3]. It has been shown theoretically that peak power of the energy storage system can be enhanced, internal losses be reduced and discharge life of the battery be extended with the usage of ultra-capacitors. Wei et al have demonstrated that a battery-super capacitor hybrid has lower battery costs, a general increase in battery life and higher overall system efficiency.[6].

Haihua et al have proposed a composite energy storage system with both high power density and energy density for micro grid applications.[12]. One similarity between these studies and others is that the battery is used to provide the low-frequency component of total power demand whereas the super capacitor provides the short-term or high-frequency component. This has the effect of reducing transient fluctuations in the battery power profile.[8]-[11] . The work presented here also adopts this approach, and extends previous studies by providing new results which quantify the potential increase in battery cycle lifetime due to the addition of super capacitor energy storage and describes a means of system implementation and analysis. [11].

B. *System Description*

The proposed system is demonstrated with a low power and low battery voltage wind energy conversion system configured, as shown in Fig 1, is considered. Here the generated ac voltage from the wind turbine is rectified and fed to the battery and load via a dc/dc converter operating under maximum power point tracking (MPPT) control [13]. A dc/ac power converter is used to the convert the battery dc voltage to single-phase ac in this case to supply an ac load. The proposed system and analysis can also be applied to systems in which the low-voltage battery is interfaced with a regulated dc bus at a higher voltage for power transfer. However, to demonstrate the underlying principle of the system, in this example the battery voltage is used as the effective dc-bus voltage as has been done previously.

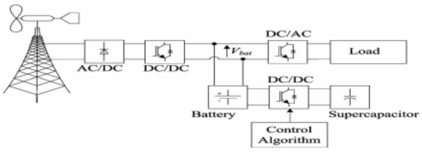

Fig 1.Wind-energy conversion system configuration

II. CURRENT-CONTROLLED DC/DC CONVERTER

Turbulent wind power variations and short-term load variations become the cause of batteries to undergo frequent charge/discharge cycling in remote-area wind-power systems. The dc/dc converter under the proposed control strategy filters transient variations from the battery charge-profile by diverting them to/from the supercapacitor module. The converter control strategy therefore must be capable of fast, dynamic bidirectional current tracking. Hysteretic current-mode control maintains tight regulation of the inductor current in dc/dc converters [14] and gives robust performance irrespective of variation and uncertainty in operating conditions [15].

In addition, this control strategy overcomes the sub-harmonic oscillation instability that occurs at duty ratios above 50% with conventional PWM current-mode control [15], [16], which requires the added complexity of slope compensation to resolve [17].

In buck-derived converters, the inductor current is directly proportional to the output current. In contrast, with boost and buck/boost topologies, the inductor current to output current relationship contains an effective duty ratio term making the implementation of boost and buck/boost topologies in this application significantly more complicated.The use of a synchronous buck-converter configured is suited to low voltage battery grids as the supercapacitor voltage can readily be maintained at a higher level than that of the battery. Examples of such systems can be found in small-scale distributed generation [2], [10], [18] and telecom base-station applications [19], [20].

A. *Current Controller*

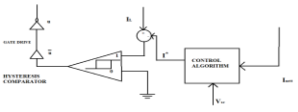

Fig 2.Current controller

Assuming ideal components, the governing equation for the inductor current in the Fig.2 is as discussed in :

$$L\frac{d\,IL}{dt} = \mathrm{Vsc.u} - \mathrm{Vbat} \qquad (1)$$

The objective of the current controller in this case is to maintain the converter output current by regulating the inductor current to track the command reference current I*. This is done by modulating the power-electronic switch control signal, *u*, using the following strategy.

A switching function $\sigma = 0$ can be defined as discussed in [21]:

$$\sigma = IL - \dot{I} = 0 \qquad (2)$$

where I*= command reference current.

A switch control strategy for the signal *u* (Fig. 3.1) can be chosen to satisfy (3) such that σ and its time derivative have opposite signs. This ensures that the system will converge to the state $\sigma = 0$ and consequently the average inductor current converges to the set-point current reference I^*[21]:

$$\forall\sigma\neq0;\quad \sigma.d\sigma/dt<0 \qquad (3)$$

A switching control law, which satisfies condition (3), is defined in (4), where 2*h* is a small constant hysteresis band (100 mA in this case), lying symmetrically about the reference set-point I^*:

$$u = 1,\ \text{if } \sigma < -h$$
$$u = 0,\ \text{if } \sigma > h \qquad (4)$$

For later power conversion efficiency estimation, the approximate switching frequency *f*sw can be determined from the inductor rise and fall times (*T*1 and *T*2) in each switch position from (3.1) as follows [21]:

$$fsw = \frac{1}{T1 + T2}$$
$$= \frac{1}{(2hL/(Vsc - Vbat)) + (-2hL/ - Vbat)} \qquad (5)$$

B. *Control Algorithm*

The control algorithm was implemented using an active current-filtering approach to divert the high-frequency component of the system charge/discharge current Inet to the supercapacitor, in real time. The controller continuously monitors the incident battery current Inet and sets the converter current reference current I * to cancel the high-frequency component of Inet as shown in Fig.3. Self-discharge causes energy stored in the supercapacitor (and consequently the supercapacitor voltage) to decay. A supercapacitor voltage control loop, with a low, empirically derived static gain, K, was also added as shown in Fig. 3 to maintain the average supercapacitor voltage close to a nominal level, V^*sc such that *V*sc > *V*bat .

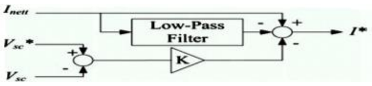

Fig 3. Control algorithm block diagram

III. SUPERCAPACITOR AND BATTERY

A. *Supercapacitor Model*

Supercapacitor effective capacitance can be described by a nonlinear function of terminal voltage [21].

However, in this study, the simplified model of Fig. 4 was used [21].

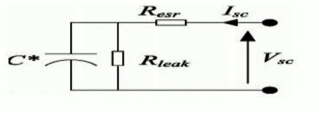

Fig .4 Simplified supercapacitor model

The effective capacitance C^*, the leakage resistance Rleak, and the series resistance Resr terms can be determined by measurement or derived from manufacturer's data, as in this simulation [23]. Supercapacitor voltage is then described as:

$$Vsc = \frac{1}{C^*} \int \left(Isc - \frac{Vsc}{Rleak}\right) dt + Isc.Resr \tag{6}$$

The required supercapacitor energy storage capacity was determined empirically by simulation. The supercapacitor module was then configured using a combination of standard commercially available [22] supercapacitor cells with parameters given in the Appendix; see Table AI. The effective total capacitance C^* and series and leakage resistances (Rleak and Resr) were calculated based on the number of series/parallel supercapacitor cells. The supercapacitor module was configured to give a maximum operating voltage of 60 Vdc. To ensure that the supercapacitor voltage is maintained at a higher level than the battery voltage at all times, a lower limit was placed on the supercapacitor operating voltage of 30 Vdc.

B. *Battery*

The reaction of lead and lead oxide with the sulfuric acid electrolyte produces a voltage. The supplying of energy to and external resistance discharges the battery.

In the present system the lead acid battery of rating is 48Vdc. Four similar 12Vdc batteries are connected in series to achieve the voltage rating. The battery was choosen according to the availability.

IV. RESULTS AND DISCUSSION

The proposed system is tested on the battery. The system comprises of the battery-supercapacitor hybrid model and a control algorithm. The overall system is tested for battery lifetime analysis. The base case results, results obtained after application of hybrid system and the control algorithm, along with graphical analysis are also described. Analytical graphical comparison is done based on the battery current output obtained during different case simulations. The aim of this project is to efficiently enhance the battery lifetime and thus reduce the maintenance cost.

A. *Proposed System simulation*

The test system was simulated in MATLAB environment and the proposed methodology has been tested and the simulated results are shown.

In all the simulated cases the source is wind generated energy. The windmill used here is constant speed windmill generating 60 V supply. The load connected to the system is varied in three steps. The table 1 shows load variation data. The Fig 6 shows the proposed DC/DC converter and controller.

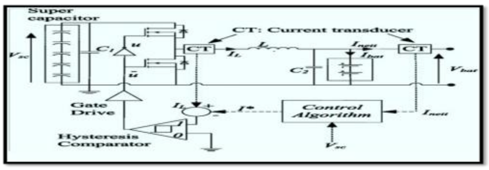

Fig 6: DC/DC converter and controller.

Table 1: Load variation data

SET TIME (min)	LOAD
0 TO 3	10 kW
3 TO 6	5 kW
6 TO 10	7.5 kW

The base case is carried over for the battery energy storage system alone. The battery rated voltage is 48 Vdc. The battery is supported by a DC/DC converter having switching frequency of each MOSFETs 10 kHz. The wind energy system supplies to the DC/DC converter through a rectifier. The connected load is varied in steps as explained before. The Fig 7 shows battery current for the battery alone system without the proposed controller. It is observed that the battery current fluctuates at a higher rate between negative and positive current for a small period of time. This states that the battery under goes large number of charge and discharge cycle in a small time span which ultimately reduces the battery life.

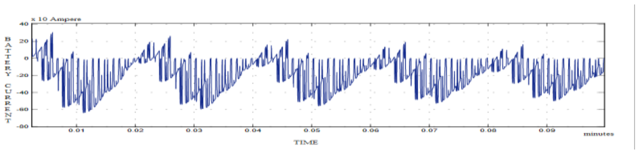

Fig 7: Battery current of battery only system

In later case the simulation was carried over with the same battery which hybridised with supercapacitor energy storage system. There are 22 cells of supercapacitor connected in series. In each cell the capacitor is rated 5000 F with a leakage resistance of 351.85 Ω and series resistance of 0.33 mΩ. The rated cell voltage is 2.7 Vdc. In this case the analysis is done in two stages.

a)Battery Charging state b)Battery Discharging state

During the charging state the supercapacitor voltage is 2.7Vdc. At this time the supercapacitor is fully charged and thus discharges and supplies the battery storage to supply the load. During the discharging state the supercapacitor voltage is 2.2Vdc or less than 2.2Vdc. At this time the battery is fully charged and thus discharges and supplies the supercapacitor energy storage. In this way the power sharing happens between battery and supercapacitor.

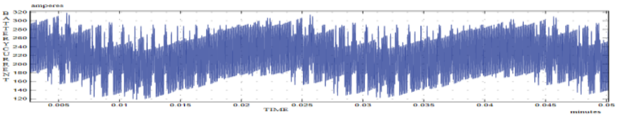

Fig 8 Battery charging current of hybrid system without controller

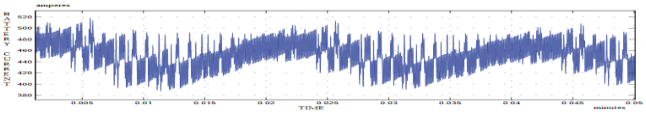

Fig 9 Battery discharging current of hybrid system without controller

The Fig 8 and Fig 9 shows battery charging and discharging current of the hybridized system without controller. Here it can be observed that the battery current is maintained in the positive region compared to the base case thus the battery does not undergo heavy charge-discharge cycles in a short span. This improves battery life in comparison with the base case analysis. But the current still fluctuates for a higher value that may be inefficient for the battery life. The table 2 shows the range of current fluctuations.

Table 2: Current fluctuation without controller

STATE	RANGE OF FLUCTUATION
Charging	200
Discharging	130

In last case case the simulation was carried over the same hybridised battery supercapacitor energy storage system along with the proposed controller. In this case also the analysis is done in two stages.

a)Battery Charging state b) Battery Discharging state

During the charging state the supercapacitor voltage is 2.7Vdc. At this time the supercapacitor is fully charged and thus discharges and supplies the battery storage to supply the load. During the discharging state the supercapacitor voltage is 2.2Vdc or less than 2.2Vdc. At this time the battery is fully charged and thus discharges and supplies the supercapacitor energy storage. In this way the power sharing happens between battery and supercapacitor.

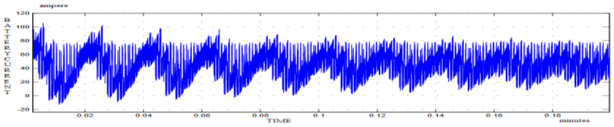

Fig 10 Battery charging current of hybrid system with controller

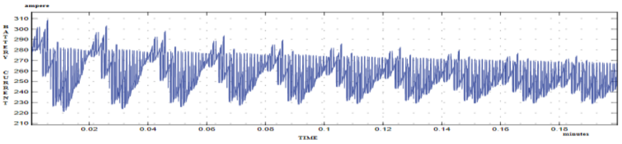

Fig 11 Battery discharging current of hybrid system with controller

The Fig 10 and Fig 11 shows battery charging and discharging current of the hybridised system with controller. Here it can be observed that the battery current with the application of the proposed controller the range of battery current fluctuations has reduced almost by 50%. This enables efficient working of the system and in this way improves the battery life. The table 3 shows the range of current fluctuations.

Table 3: Current fluctuation with controller

STATE	RANGE OF FLUCTUATION
Charging	100
Discharging	80

VI.CONCLUSION

This study investigated the use of supercapacitors to improve expected battery life cycle over a period of power-profile typical of a small, remote-area wind-energy conversion system. The results show that by diverting transient power variations due to turbulence and short-term load variations to a supercapacitor module, battery life cycle can be quantifiably increased. It has also been shown that the battery current maxima can be significantly reduced using the proposed system. This has an unmodelled benefit in terms of potentially further increasing battery life as high-current cycling increases battery failure rates. A versatile current controlled dc/dc converter design has been described, which was used to verify the feasibility and performance of the proposed system implementation. A detailed simulation strategy has been demonstrated, providing a means by which supercapacitor control strategies can be evaluated in the context of an off-grid wind-energy conversion system.

VII. APPENDIX

Table AI

PARAMETER	DESCRIPTION	VALUE
Ccell	Cell nominal capacitance	5000 F
Rs	Series resistance (total)	0.33 mΩ
Rl	Leakage resistance	351.85 Ω
Vnom	Rated cell voltage	2.7 Vdc

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IX. BIOGRAPHIES

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