A Fixed Frequency Sliding Mode Controller for a Boost Inverter Based Battery-Super capacitor Hybrid Energy Storage System

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ABSTRACT

This paper proposes a boost inverter based battery-super capacitor hybrid energy storage systems are a popular choice for battery lifetime extension and power enhancement. Various sliding mode (SM) controllers have been used to control the boost inverter topology in literature. However, the traditional SM controllers for the boost inverter topology operate with a high and variable switching frequency which increases the power losses and system components design complexity. This can be alleviated by a pulse width modulation (PWM) based fixed frequency SM controller proposed in this paper. The SM controller is implemented using variable amplitude PWM carrier signals generated using the output capacitor voltage and inductor current measurements thus eliminating the requirement of the output capacitor currents measurement. The battery connected inductor reference currents for the SM controller are generated by a super capacitor energy controller which is responsible for the HESS power allocation. First, the theoretical aspects of the SM controller, the operation and parameter selection of the super capacitor energy controller and the super capacitor sizing for the HESS are discussed in the paper. The main advantage of the proposed SM controller, as compared with the traditional double loop (DL) control method, is in eliminating possible DC current injection into the grid when the equivalent series resistance (ESR) values of the boost inductors become unequal due to the tolerances and temperature variations. The necessary simulation results are explained in detail.

KEY WORDS: Battery, Supercapacitor, Sliding mode controller, hybrid energy storage system and MATLAB/Simulink.

1. INTRODUCTION

A Super Capacitor (SC) (also electric double-layer capacitor (EDLC), also called super cap, ultra capacitor or Gold cap) is a high-capacity capacitor with capacitance values much higher than other capacitors (but lower voltage limits) that bridge the gap between electrolytic capacitors and rechargeable batteries. They typically store 10 to 100 times more energy per unit volume or mass than electrolytic capacitors, can accept and deliver charge much faster than batteries, and tolerate many more charge and discharge cycles than rechargeable batteries.

Super capacitors are used in applications requiring many rapid charge/discharge cycles rather than long term compact energy storage: within cars, buses, trains, cranes and elevators, where they are used for regenerative braking, short-term energy storage or burst-mode power delivery. Smaller units are used as memory backup for static random-access memory (SRAM). Super capacitors may have either symmetric or asymmetric electrodes. Symmetry implies that both electrodes have the same capacitance value, yielding a total capacitance of half the value of each single electrode (if \(C_1 = C_2\), then \(C_{total} = 0.5 \cdot C_1\)). For asymmetric capacitors, the total capacitance can be taken as that of the electrode with the smaller capacitance (if \(C_1 >> C_2\), then \(C_{total} \approx C_2\)).

2. PROPOSED CIRCUIT CONFIGURATION

In this paper, a fixed frequency SM controlled boost inverter based battery-super capacitor HESS is proposed. The SM controller is implemented using variable amplitude PWM carrier signals which are generated using the output capacitor voltage and inductor current measurements which allow operation without using the output capacitor currents measurement. The battery connected inductor reference currents for the SM controller are generated by a super capacitor energy controller which is responsible for the HESS power allocation. A super capacitor sizing method for a given application is also presented. The performance of the proposed SM controlled, grid connected battery-super capacitor HESS is experimentally verified using a laboratory prototype. Furthermore, the performance of the SM controller is compared against a DL controlled boost inverter based battery-super capacitor HESS. The main advantage of the proposed SM controller, as compared with the traditional DL control method, is in eliminating possible DC current injection into the grid when the ESR values of the boost inductors become unequal due to the tolerances and temperature variations.

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The main merit of the proposed buck–boost converter is that its voltage gain is quadratic of the traditional buck–boost converter, so that it can operate in a wide range of output voltage, i.e., the proposed buck–boost converter can achieve high or low voltage gain without extreme duty cycle. Moreover, the output voltage of this new transformer less buck–boost converter is common-ground with the input voltage, and its polarity is positive. The PID controller compromise the transient response, such as settling time, overshoots, oscillation.
The SM techniques were extensively used to control the boost inverter topology. Unlike the DL control method, the SM control methods are robust to parameter variations and modeling errors and achieve better reference following performance. However, the existing SM controllers for the boost inverter were based on the traditional SM control technique which leads to a high and variable switching frequency operation which can increase the power losses and system components design complexity. Fixed frequency SM controllers were studied in literature for the boost DC/DC converters but not for the boost inverter.

The fixed frequency SM controller in was designed for a constant load and hence the method is not applicable to a grid connected boost inverter based HESS. A fixed frequency SM current controller was proposed in for the boost DC/DC converter, however, the method required a PI controller based outer voltage control loop to generate the required inductor current reference signals. A pulse width modulation (PWM) based fixed frequency SM controller was proposed for the boost DC/DC converter in, but the controller required a capacitor current measurement which increased the required number of current sensors in the system and this may also influence the filter performance of the capacitor due to the impedance modification of the capacitor path.

**Operation of the HESS:** The objective of the HESS controller is to maintain the inverter output voltage such that HESS satisfies the active and reactive power requirements. Moreover, the controller has to be able to allocate the fast power fluctuations and the second-order harmonic ripple component to the super capacitor. Additionally, the controller has to maintain the battery and the super capacitor (SC) within a safe operating region to ensure safe and sustainable operation of the HESS.

The DL control system for the HESS in was designed using PR controller based outer voltage control loops and PI controller based inner current control loops. However, in the voltage control loop design, the voltage drops across the ESR of the boost inductors were neglected. This results in a DC shift tracking error in the output capacitor voltages when the ESR values are significant. A simulation test was conducted to observe the effect of the boost inductor ESR values on the output capacitor voltage DC shift error using the prototype parameters. In the simulation, the ESR values of the boost inductors \( Lsc1, Lsc2, Lbatt1 \) and \( Lbatt2 \) are assumed to be equal. A significant increment in the output capacitor DC shift error can be observed with the increasing boost inductor ESR values. If the ESR values of the left hand side boost converter leg inductors are different from the right hand side boost converter leg inductors, due to the tolerances and temperature variations, then there are unequal DC voltage shifts in \( v_{o1} \) and \( v_{o2} \) and hence a DC voltage component \( \Delta V_{DC} \) appears in the HESS differential output voltage. The DC voltage component results in undesirable DC current flowing into the grid. A fixed frequency SM controller designed to overcome the issues associated with the DL control method is presented in the proposed circuit.

**Sliding mode controller analysis:** In order to design a SM controller, the four boost converter legs are considered as four subsystems with unique objectives. This way of sub-dividing a complex system into several independent single input subsystems are widely used in SM controller design for complex power converters and is known as a decentralized switching scheme. In the proposed system, the supercapacitor connected left hand side and right hand side boost converter legs are controlled to follow the output capacitor reference voltages \( v_{o1} \) and \( v_{o2} \) respectively. The battery connected boost converter legs are operated in the inductor current controlled mode to facilitate the power allocation of the HESS as explained. In this paper, the SM controller analysis is provided only for the left hand side boost converter legs, but a similar analysis can be conducted for the right hand side boost converter legs as well.

To facilitate the power allocation between the battery and the super capacitor, the converter leg is operated in the inductor current controlled mode. Since the left hand side super capacitor connected boost converter leg is used to control the output capacitor voltage \( v_{o1} \), the effect of the left hand side super capacitor connected boost converter leg on the left hand side battery connected boost converter leg operation can be modeled using a voltage source with \( v_{o1} \) amplitude. In order to satisfy the existence and reaching conditions of the SM, the control system has to be designed considering the worst case operation of the HESS. The worst case operation of the super capacitor connected boost converter leg occurs when the super capacitor supplies the total HESS power requirement.

**HESS power allocation:** The power allocation strategy design between the battery and the supercapacitor is an important aspect of a battery supercapacitor HESS. Objective of the power allocation is to divert the ripple current component and the fast power fluctuations to the supercapacitor while the battery supplies the slow varying average power component. Due to the design of the SM controller, the ripple current component is allocated to the supercapacitor.

In order to design the PI controller parameters, and also to obtain the required energy storage element sizes, the dynamic relationship between \( P_{tot} \) and the power supplied by the individual energy storage devices (\( P_{sc} \) and \( P_{batt} \)) has to be found. However, this is challenging due to non-linearity. This problem can be overcome by using a super capacitor energy controller as presented below.

In this paper, a super capacitor energy controller is employed to allocate the fast power fluctuations to the super capacitor without employing an additional filter. A PI controller is used to generate the inductor current reference signals for the battery connected boost converter legs.
Active and reactive power controller and the state of charge controller: The active and reactive power supplied by the HESS are controlled by modifying the inverter output voltage amplitude and the phase angle with respect to the grid voltage. Two PI controllers are designed. A second order generalized integrator based phase lock loop is used for the power measurement. The active and reactive power references of the HESS are modified to control the SoC of the battery within the safe operating regions. The battery SoC is estimated using an extended Kalman filter based SoC estimator.

3. SIMULATION CIRCUITS AND RESULTS

Fig.1. Proposed simulation circuit

Fig.2. Output Voltage and Current waveforms

Fig.3. Triggering pulses to the converter

Fig.4. Triggering pulses to the control circuit

Fig.5. Triggering pulses to the inverter side

Fig.6. Output voltage across the capacitor

DISCUSSION ABOUT THE RESULTS

The performance of the proposed HESS is verified using an experimental prototype. The results illustrate the operation of the HESS with a step changing output power reference signal. Here, the HESS power allocation parameters were selected to obtain 0.1rads⁻¹ gain cross over frequency and a 29F super capacitor is employed. As expected, the super capacitor responds to sudden power changes and hence the super capacitor energy level diverts from the reference value. The double line frequency component of the super capacitor current is filtered out to clearly illustrate the super capacitor response to the sudden power changes. The battery current gradually increases to supply the required power component. It can be observed that the battery supplies an additional power component to the super capacitor to recharge the super capacitor and then the battery current gradually reduces and settles down to supply the required average power component. As expected the super capacitor responds to the fast power variations while the battery supplies the slow varying power component. Additionally, it can be observed that the HESS is able to reduce the peak battery power as well as the number of battery charge discharge cycles. The super capacitor energy variation is illustrated in fig.7(a) and it is controlled around the reference energy level. From fig.7(b) it is evident that the selected capacitance value enables the operation of the super capacitor within the pre-defined voltage limits.
The battery and the super capacitor current waveforms are illustrated in fig.7(e), fig.7(f) and as required the battery supplies the slow varying current while the super capacitor supplies the fast varying current component.

![Fig.7. Super capacitor energy variation](image)

In order to observe the effect of the boost inductor ESR tolerance on the HESS output current DC component, a ±20% change in the nominal ESR value of 0.24Ω was simulated. A sample HESS output power condition of $P_{\text{HESS}}=50\text{W}$ and $Q_{\text{HESS}}=25\text{VAr}$ was considered and the boost inductor ESR values were selected. The SM controller was calculated using the nominal boost inductor ESR value. A DC component of 0.0814A which is 4.07% of the HESS rated output current was observed in the HESS output current with the DL control method. However, with the SM controller, the DC current component was only 0.0046A which is 0.23% of the HESS rated output current. According to the IEEE standards, it is required to limit the DC current injection to 0.5% of the rated current of the inverter. This result demonstrates the advantage of the sliding mode method which is robust to parameters variation and therefore is unaffected by the ESR variation.

$$L_{\text{sc}}L_{\text{batt}}R_R = \times \Omega$$

4. CONCLUSION

A fixed frequency SM controller for a boost inverter based single phase grid connected battery-super capacitor HESS was proposed in this paper. The PWM based fixed frequency SM controller was employed to overcome high and variable frequency operation associated with the traditional SM control technique. Theoretical aspects of the SM controller design were discussed and a super capacitor energy controller based power allocation method was employed to allocate the fast power fluctuations to the super capacitor without incorporating an additional filter. The power allocation parameter selection and the super capacitor sizing were discussed for a given HESS application.

The proposed control system for the boost inverter based HESS was experimentally verified using a laboratory prototype. The proposed controller was able to satisfy the HESS output power requirement while allocating the ripple current and fast power fluctuations to the super capacitor. Moreover, the selected HESS power allocation parameters and the value of the super capacitor enabled the operation of the HESS within the pre-determined super capacitor voltage limits. Compared to the traditional DL controlled boost inverter based battery-super capacitor HESS, the proposed SM controller was able to achieve better output capacitor reference tracking and
hence reduce the risk of the DC current injection into the grid when the ESR values of the boost inductors become unequal due to the tolerances and temperature variations.

REFERENCES


