Battery Energy Storage Systems

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Abstract – This paper reviewed some of the technical aspect of the utilization of battery energy storage system to solve several power systems problems particularly when connected to renewable energy systems. This paper will propose a novel design of a three-phase battery energy storage system as an interface between the supply system and the load. The proposed three-phase multi-purpose Battery Energy Storage System will provide active and reactive power independent of the supply voltage with excellent power quality in terms of its waveform. The paper will discuss the hardware configuration and software technologies currently being used to implement the proposed design. The simulation results and the hardware experimental results of the three-phase battery energy storage system will be presented and discussed.

INTRODUCTION

Renewable energy sources are increasingly being exploited for electricity generation. In the case of wind generation, the present installed capacity world-wide totals around 6000MW. In the UK, there are more than 50 wind farms with over 700 operational turbines, with total capacity of more than 300 MW installed [1]. This is only around 0.5% of the UK total electricity generation capacity, but it is likely that the proportion will continue to increase, because the resource is plentiful and the generation cost at around 3.5p/kWh is already competitive with gas. Denmark has at present a total installed wind generation capacity of more than 1500 MW, over 10 % of the total generation capacity, and has an ambitious target of 4000 MW offshore wind generation capacity by 2030 [2].

The utilization of wind energy for electricity generation has already been shown to be attractive in both environmental and economic terms, and is likely to extend offshore in the near future. The intermittent nature of wind means that power is not always available, and although accurate wind speed forecasting can improve the predictability of wind power from each generator, an energy storage system is usually required to maintain network stability and reliability.

Other renewable energy sources with intermittent or cyclic behavior include photovoltaics (PV). PV generators have daily cycles where the theoretical maximum output is within a clearly defined envelope. However, there is considerable seasonal variation. The energy from day to day can vary by a factor of ten, and the actual power at any particular time of day may be much less than the theoretical maximum, and subject to abrupt changes. PV generators are still considered expensive for grid connected application, but may soon become economically attractive, especially when they have a secondary purpose as a building cladding material, or where the generated power partly matches a building load demand, e.g. for air-conditioning.

The economic exploitation of renewable energy sources such as wind, wave, and solar for electrical power generation can be limited by the variable and intermittent nature of the supply.

Even in the normal power system, the consumer expects an electricity supply which is available at all times and provides a tight control of voltage and frequency for all appliances. The fact that all consumers are free to alter their demand at any time, coupled with the inability to store AC power, creates the underlying power system control task. This is a factor associated with the following power system operation and control problems which all relate to uncertainty:

- It is impossible to precisely forecast demand even from hour to hour,
- Power system planning hinges on forecast annual peak growth that is not known until afterwards,
- It is not possible to predict the numerous disturbances that do occur,
- Generator availability can vary unpredictably from day to day,
- System configuration constantly alters with outages of lines, cables and substation equipment.

The present method of handling uncertainty is very costly because it requires redundancy of system equipment and operation of additional generation to allow for unexpected outages or higher than expected demand. The greatest difficulties are posed by the daily peak periods, when not only the highest demand occurs but also the fastest rates of load change. The largest demand forecasting errors are at peak periods, a serious problem as the power system becoming more susceptable to disturbances as loadings increase.

Power systems throughout the world have also been affected by growing financial stringencies (due to the worldwide economic downturn) as well as being constrained by the community's environmental expectations. Both these factors have impeded the establishment of new power stations and extra transmission lines which are needed to maintain the existing levels of power system reliability. The constant threat to the reliability of electricity is posed by the uncertainty associated with power system operation, namely, the continually varying loads and the numerous perturbations and disturbances to the power system, sometimes even lead to serious interruptions. As an example, the extensive system collapse which interrupted New York in 1977, was costed at $US350 million, 20% of the value of New York's electrical network [3].

The conventional capital intensive approach for achieving reliability of supply had required long term financial decisions that are no longer possible with the uncertain rates of electricity demand growth coupled to the prevailing world economic uncertainties. The present situation undermines system security as well as reliability of supply to consumers so there is need for a new approach which would be able to reduce uncertainty.

Although there are different aspects to power system uncertainty, the main problem is set by the difficulty of demand forecasting. Demand forecasting has two aspects, short term for day to day operation and the annual peak demand on which the major cost commitments, both capital and operational, are focussed in the continuing development of the power system. Daily peak periods, because of their short duration, are associated with only a small amount of the daily energy consumption, even on the day of annual peak demand.

This paper explores the ramifications of introducing fast responding battery energy storage systems into in the power systems containing renewable distributed energy resources which, with sufficient capacity and rating, could remove the uncertainty in the intermittent nature of the renewable energy resources as well as the uncertainty due to forecasting the annual peak demand.

Energy storage can address these problems, by smoothing the net power supplied to the grid, or by enabling the energy to be stored and dispatched later (for example to supply peak demands), thus giving a higher value to the generated power.

They would also benefit the day to day operation by curtailing the fastest demand variations, particularly at the daily peak periods.

The paper will also discuss the hardware configuration and software technologies currently being used to implement some of the above objectives, in particular, the fast control of active and reactive power demand and generation when a Battery Energy Storage System is connected to the grid.

The proposed three-phase multi-purpose Battery Energy Storage System will provide active and reactive power independent of the supply voltage with excellent power quality in terms of its waveform.

PROPOSED THREE PHASE BATTERY ENERGY STORAGE (BESS) SYSTEMS

A. BESS Configuration

Figure 1 shows a three-phase implementation of the proposed BESS system connected with the utility grid. The ac system is a three-phase four-wire star system, with 110 V line to line voltage. The BESS is connected to the ac utility grid through three inductors and an isolating three-phase transformer.

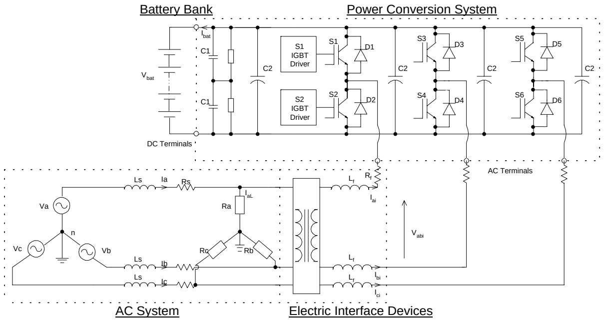


Figure 1 Three-phase system configuration

The system consists of a battery bank, power conversion system, the electrical interface devices and the AC system model was simulated before the actual implementation of the actual circuit in the laboratory.

After confirmation of the system operation by simulation, the system was built and the control system was implemented using DSP. Various experiments have been carried out to show the multi-functional capabilities of the BESS.

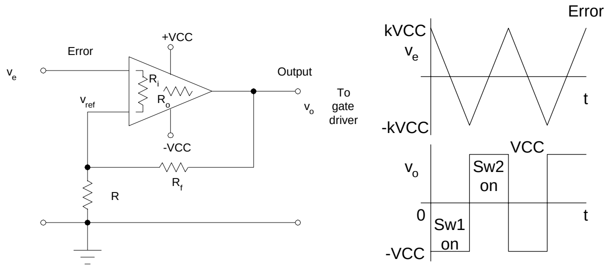
B. Simulation Results

Three control circuits to control the magnitude and phase of three individual currents based on hysteresis current control have been simulated using the BESS circuit shown in Figure 1. This technique aims to control the three-phase system source current very close to the reference three-phase sinusoidal current. A hysteresis band of 0.5A has been used. Figure 2(a) shows the circuit diagram of the control circuit for one phase. The input signal V_e (proportional to the actual current signal) is applied to the inverting input. At the non-inverting input the reference voltage v_{ref} is given by the voltage divider principle to be:

$$v_{ref} = v_o R / (R + R_f) = k v_o$$

The output v_o is ideally one of the saturation levels ±VCC. Thus, v_{ref} has one of two levels ±kVCC.

If the error signal v_o is greater than the reference signal v_{ref}, the output v_o goes negative. In this application the negative output –VCC is to be a gate signal that will lead to a change (less positive) of the error signal v_e. When the error signal v_e is negative and less than the reference signal v_{ref} (at present –kVCC) the comparator output shifts states to v_o = +VCC and the reference signal becomes v_{ref} = kVCC. The reference signal remains at +kVCC until the error signal v_e is greater than v_{ref}, at which point the cycle repeats. While the comparator output is v_o = +VCC, the output is to be a gate signal that will lead to a change (less negative) in the error signal. Figure 2(b) shows how the error signal as a function of time is transformed by the comparator to a square-wave output. The negative output voltage v_o becomes the gate signal to keep switch Sw.1 of the inverter in the on-state. The positive output voltage v_o is used to maintain switch Sw.2 on.



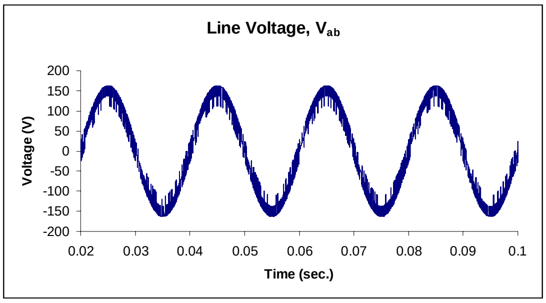
(a) (b)

Figure 2 PWM with band tolerance (a) comparator; (b) input and output signals.

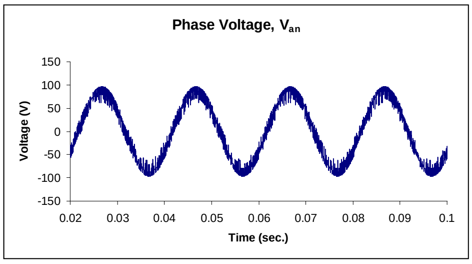
Based on this technique, the whole BESS system is implemented and the simulated results are shown in Figure 3. The simulation results are based on a BESS with the following parameters: V_{bat}=230 V; V_{an}=65.5 $V_{(rms)}$; L_s=1m H; R_s=0.01 Ω; L_f=8m H; R_f=0.01 Ω; R_L=20 Ω; L_L=40m H. These results will be compared later with the experimental results described in the next Section.

Figures 3(a)-(e) show the simulation results when the system is normally operated with BESS controlling the ac source current, which is in phase with the phase voltage. The system is inductively loaded with the load current slightly less than the controlled source current.

Figures 3(a) and (b) show the line- and phase-voltage at the point of common coupling between the BESS and the ac utility grid.. Figures 3(c), (d) and (e) show the source current, the inverter current and the load current in phase-A. The magnitude and phase of the source current is controlled at 2.83 $A_{(rms)}$ and in phase with the phase voltage. It can be observed that the source current is equal to the sum of the inverter and the load currents. Figures 3(f) and (g) show the battery voltage and the battery current, and since the sign of battery current is positive, the current is flowing into (charging) the battery. This is because the source current is controlled to be slightly higher than the load current. By controlling the source current magnitude and phase at appropriate level during the day and at night, the battery state-of-charge can be controlled to be always optimum when required.



(a)



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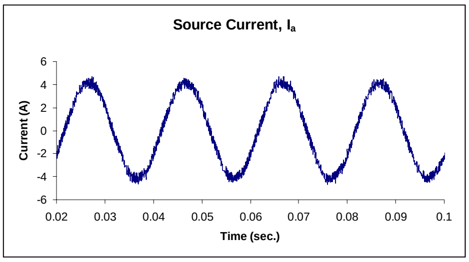

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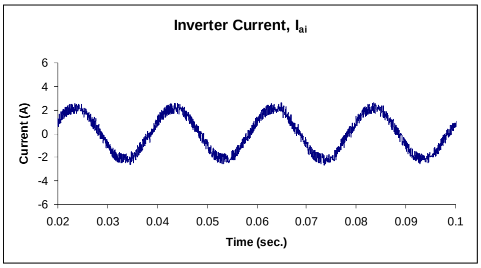

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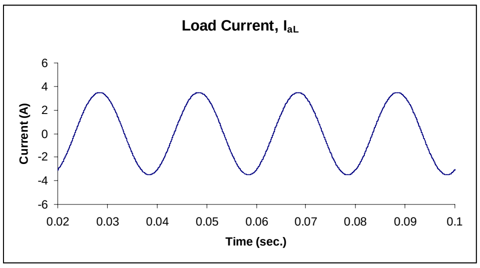
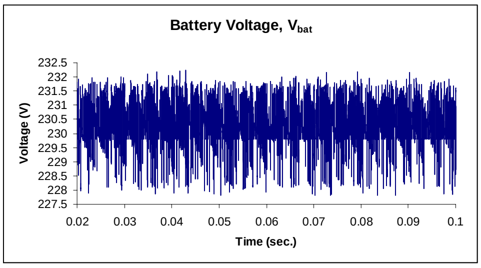
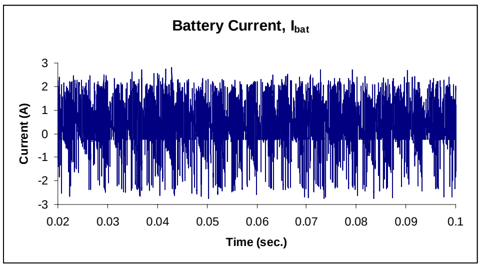


(e)



(f)



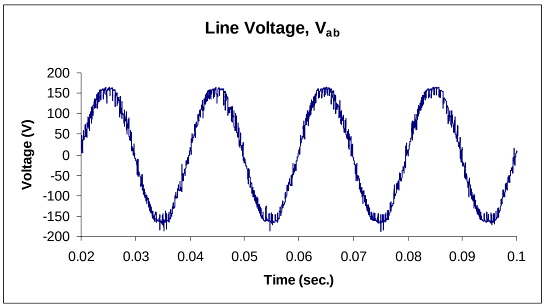
(g)

Figure 3 Simulation results (a) Line Voltage, V_{ab}; (b) Phase Voltage, V_{an}; (c) Source Current, I_a; (d) Inverter Current, I_{ai}; (e) Load Current, I_{aL}; (f) Battery Voltage, V_{bat}; (g

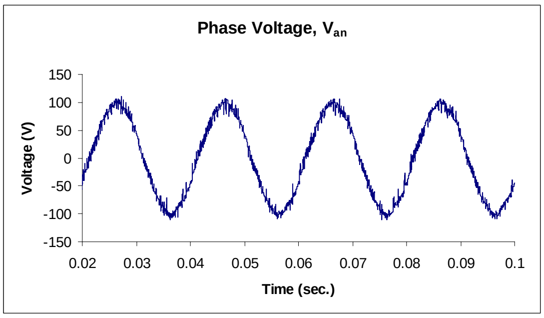
C. Experimental Results

Having confirmed that the three-phase BESS and its control system are operating properly through simulation, the actual three-phase BESS is then implemented in the laboratory. To compare the simulation and laboratory results, the same three-phase experiment as described in Section 2.2 is initially carried out. The corresponding experimental results to those given in Figures 3(a)-(i) are shown in Figures 4(a)-(g).

Comparing Figures 3(a)-(b) with Figures 4(a)-(b), very similar results are shown. Both the line voltages and the phase voltages measured at the point of common coupling show high frequency components but no low harmonics are present. More spikes can be seen in the experimental results, but this is expected. Both voltages comprise fundamental frequency and high order harmonics, which can be filtered easily by the line inductance and system transformers. In Figure 4(c), the source current is controlled at the desired value, which is very close to that shown in Figure 3(c). With nearly the same load, both the inverter currents as shown in Figures 3(d) and 4(d) are almost the same, the difference can be attributed to the slightly lower load current in the actual implementation. In Figures 4(f)-(g), the battery voltage and current are shown. As compared with that in Figures 3(f)-(f), the battery current is having larger ripple than that in Figure 4(g), since the battery model assumes that there is no line inductance between the battery and the inverter.



(a)



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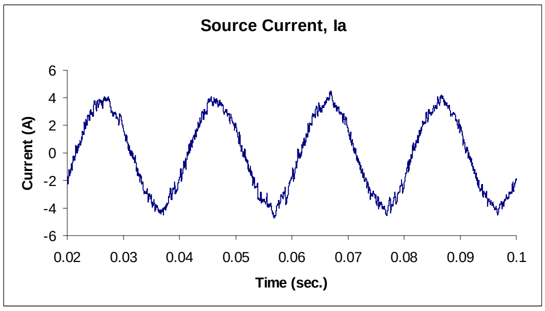

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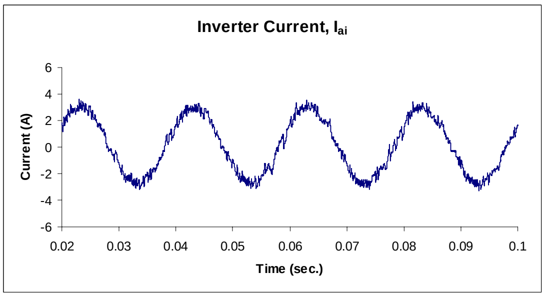

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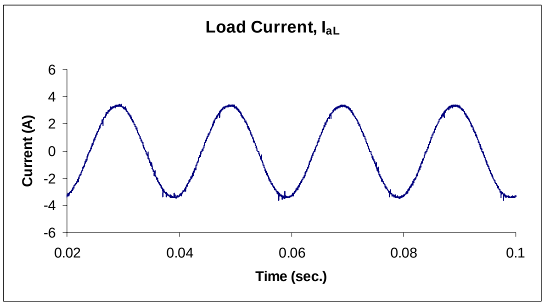

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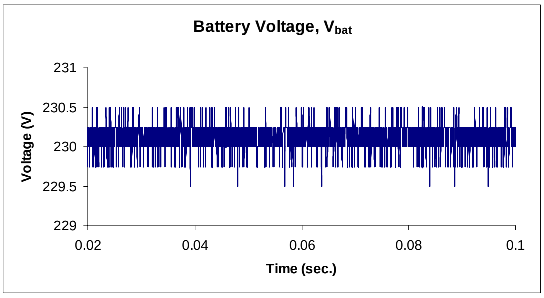

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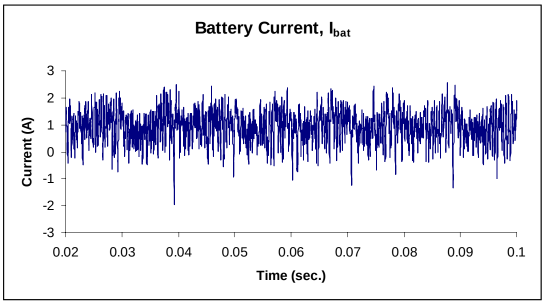


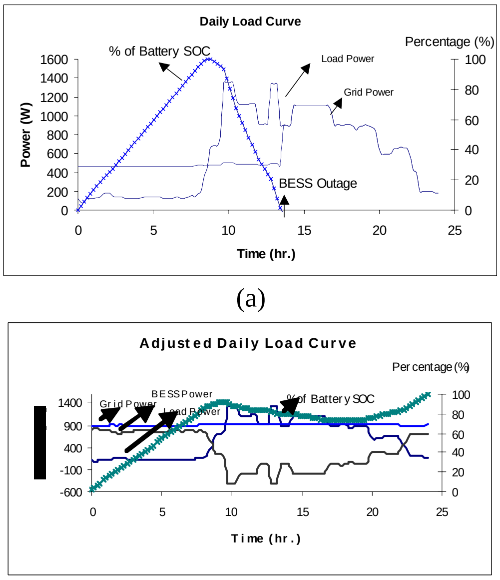
(g)

Figure 4 Experimental results (a) Line Voltage, V_{ab}; (b) Phase Voltage, V_{an}; (c) Inverter Line Voltage, V_{abi}; (d) Inverter Phase Voltage, V_{ani}; (e) Source Current, I_a; (f) Inverter Current, I_{ai}; (g) Load Current, I_{aL}; (h) Battery Voltage, V_{bat}; (i) Battery Current, I_{bat}.

D. Load leveling

The sizing of the BESS energy is given by the time integration of the load curve at which the energy of the battery is being used during the peak shaving operation. It is important to ensure that for a forecasted load curve, a calculation is carried out of the expected amount of energy that can be charged at night, so that sufficient amount of energy can be provided to reduce the peak load to a required value. The timing of the operation of the BESS has therefore to be planned ahead, otherwise there will not be enough energy to reduce the peak load at a later time. For example, Figure 5(a) shows that the BESS has been used extensively from 9 am to 1 pm to control the grid power, at 500W, and as a result it has no more energy to control the load after 1 pm. As a result, the maximum demand will now be 1100W for the whole of the month. It would be better to start the operation of the BESS at 10am, as shown in Figure 5(b), say to control the maximum demand at 900W, and hence allowing it to have control throughout the day to ensure that the 900W maximum demand is not exceeded. So, good estimation of the battery state-of-charge (SOC) is very important for the daily BESS schedule (i.e. 24 hours).

It is well known that the open circuit battery voltage, V_{soc}, can provide reliable information about the remaining energy stored in the battery. Figure 6 shows the waveform of the open circuit battery voltage at constant current discharge conditions. Since the voltage for the fully charged battery bank and for the end of discharge is equal to 257.64 V (2.26 x 3 x 38) and 199.5 V respectively. According to these voltages, the state-of-charge of battery can be estimated as 100 % at V_{soc} = 257.64 V and 0 % at V_{soc} = 199.5 V. The calculated V_{soc} is monitored at all time to prevent the battery from over-charge or over-discharge consequently damaging the battery cells and may cause BESS outage.



(a)

(b)

Figure 5 (a) Battery State-Of-Charge; (b) Adjusted Daily Load Curve

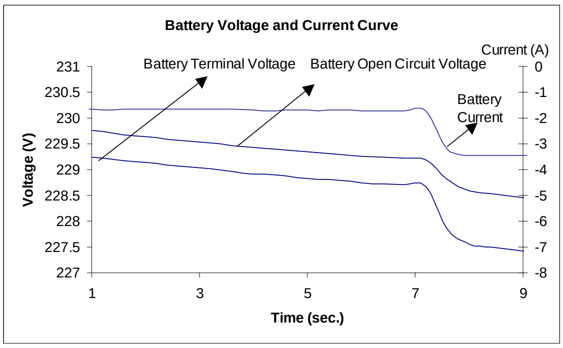


Figure 6 Battery open circuit voltage

Figure 7 shows a possible application of the BESS, where BESS absorbs power at night, and the energy is then released at day-time during heavy load condition. In this mode of operation, as far as the utility is concerned, the load is constant through the whole 24-hour period. In reality, the size of the BESS is quite small compared to the load demand and therefore, the requirement is usually to reduce the maximum demand to a specified value and let the grid power varied at times when the load is below this value, but control is applied only when the load demand exceeds the specified value. The load factor can therefore be greatly improved. Depending on the shape of the load peaks, and the tariff situation reasonable load reductions ranging from 5 % to 15 % of the peak load for peaking periods shorter than 3 hours are possible.

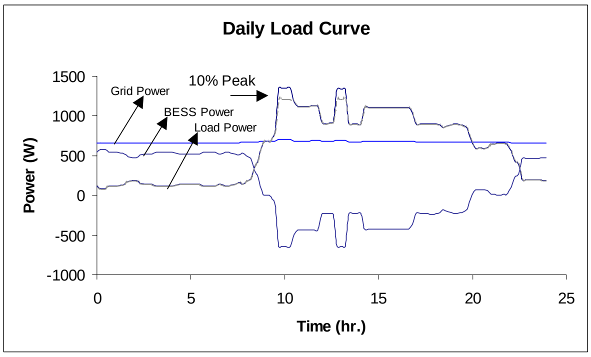
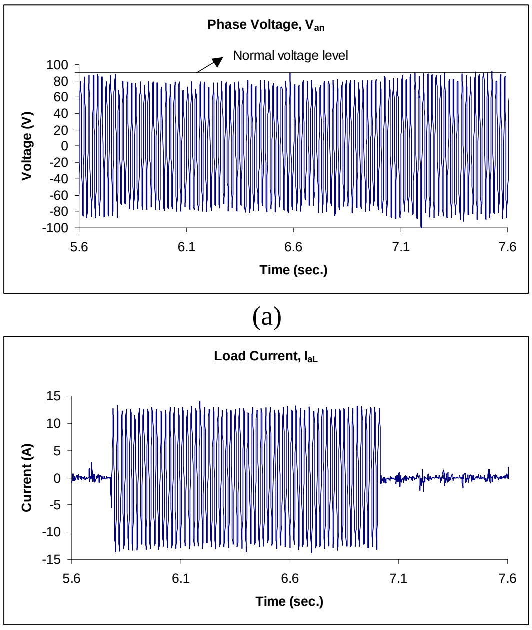


Figure 7 Daily Load Curve

E. Damping Load Fluctuation

Figures 8(a)-(b) show the effect of three-phase load fluctuation on the power system. As the load current magnitude varies, the supply current and hence the voltage at the point of common coupling vary and this can cause voltage flicker to the neighboring load. When the BESS is connected to the power system, the BESS guarantees rock solid control of the supply current as shown in Figure 8(b). As the load fluctuates, the supply current remains constant and unaffected by the load fluctuations.

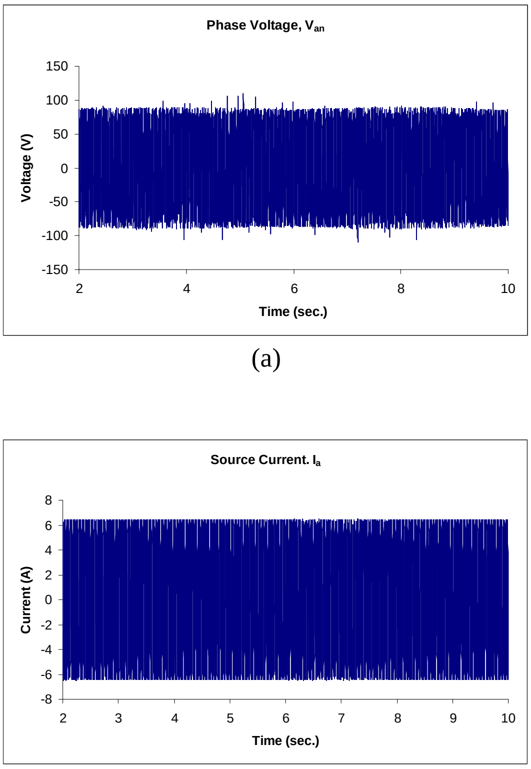
Figure 9(a) shows the phase voltage, V_{an}, of the system captured in a 8-second period. Even with the significant load fluctuation, as shown in Figure 9(c), the source current (in Figure 9(b)) is still being controlled at a constant level. All the variation in the load current are compensated by the inverter current as shown in Figure 9(d).



(a)

(b)

Figure 8 Voltage flicker due to load change (a) Phase voltage at point of common coupling; (b) Load current change.



(a)

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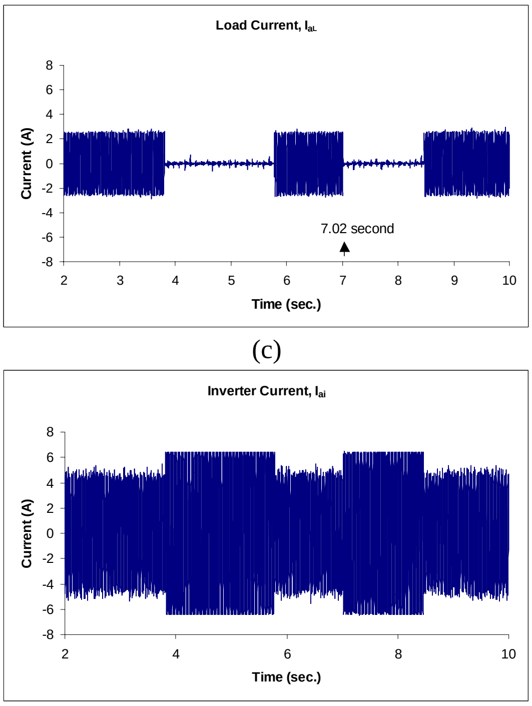

(c)

(d)

Figure 9 BESS for Damping Load Fluctuation (a) Phase Voltage, V_{an}; (b) Source Current, I_a; (c) Load Current, I_{aL}; (d) Inverter Current, I_{ai}.

CONCLUSIONS

This paper reviewed some technical aspects of the benefits of BESS in power system applications, particularly in systems with uncertainty in the energy supply and in the load demand. In addition, a three-phase battery energy storage system was proposed and implemented and both simulation and experimental results were presented and discussed. It was shown that the BESS can damp any fluctuation and become a buffer for any intermittent energy supply or load changes.

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