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Battery energy storage system for peak shaving and voltage unbalance mitigation

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Abstract

Over the last decade, the battery energy storage system (BESS) has become one of the important components in smart grid for enhancing power system performance and reliability. This paper presents a strategy to shave the peak demand and mitigate the voltage unbalance of the electrical networks using a BESS. The BESS is developed to reduce the peak demand and consequently the electricity bill of customers. With the foreseeable large use of BESS, the stress of utility companies can be reduced during high peak power demands. BESS is also equipped with the ability to mitigate voltage unbalance of the network. This indirectly improves the efficiency which in turn, prolongs the life span of three phase machines. The proposed strategy to control BESS has been developed by using the LabVIEW^{TM} graphical programming software. An experimental test bed has been setup at the Universiti Tunku Abdul Rahman (UTAR) campus to evaluate the performance of the system. The experimental results show that the BESS can effectively restrict the power demand from exceeding the pre-determined value and suppress the voltage unbalance factor within the recommended value.

Keywords: Battery energy storage system, peak demand shaving, voltage unbalance

1. Introduction

Power demand varies from time to time in accordance with customers' activities. To ensure that the varying power demand is met at all times, smaller capacity power plants such as gas power plants are usually used as standby plants during the peak demand hours. Such standby power plants operate only during the daily peak demand period, typically from 11 a.m. to 3 p.m. In Malaysia, the gas power plants use liquefied natural gas (LNG) that is comparatively more expensive than coal and diesel. Moreover, the gas power plants operate below their rated capacity, hence causing the plants to operate at low efficiencies [1]. As a result, the cost of electricity becomes high and so the electricity tariff. The natural gas is expected to be depleted in another after 36 years, based on the reserves and production ratio of 36:1. The price of natural gas is very volatile in recent years [2]. The government has to subsidize the natural gas substantially in order to reduce the cost of electricity. Therefore, the government has to find an alternative means of reducing the use of natural gas and other fossil fuels. The government has launched various programs to promote renewable energies (RE), such as main building integrated photovoltaic (BIPV) Project in 2005, new feed-in-tariffs for RE in 2012, the new forward looking RE policy in 2012 and the feed-in-tariffs for renewable energy sources [3]-[4].

The BESS appears to be one of the most popular choices in the modern electrical grid system because it provides a wide array of solutions to many key issues that affect the power system. The BESS can be used for peak demand shaving, voltage regulation, frequency control, uninterruptible power supply (UPS), spinning reserves, and so on [5]-[8]. Previous studies have shown that the BESS can be an effective solution for peak demand shaving.

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The presence of multiple renewable energy sources on the networks can adversely affect the network voltage and stability if there are no appropriate management and control systems. The most common issues are voltage rise, voltage unbalance, reverse power flow, and network losses [9]-[11]. The voltage unbalance factor caused by individual loads or DGs should be less than 1.3 % while unbalance at the point of common coupling (PCC), with aggregated effects of several loads or renewable energies, should not exceed 2 % in Europe [12]. In Malaysia, the suggested voltage unbalance factor at the terminals of a user's installation shall not exceed 1 %, for five occasions, within any thirty minutes time period [13]. Many studies show that a small voltage unbalance can result in dramatically high unbalance currents and hence incurs more losses and also deteriorates the performance of equipments such as three phase induction motor, drives and transformers [14]-[16]. The proposed BESS is able to mitigate the voltage unbalance of the network such that the voltage unbalance factor is less than 1 %.

This paper presents a BESS that can effectively shave the peak demand and mitigate the voltage unbalance issue. It consists of a battery bank with bi-directional inverters that is integrated with renewable energy sources. The system does not reduce energy consumption of the customers, but only the consumption pattern seen by the utility companies is altered from bell-shaped to flat-top. Under the commercial tariff, this flat-top pattern can reduce the maximum demand charge for commercial customers and hence the electricity bill. If such energy management system is widely spread across the country, the utility companies can reduce the use of standby power plants, hence minimising the peak demands and the cost of electricity. Apart from that, the BESS is able to mitigate the voltage unbalance of the network and improve the quality of network voltage affected by the penetration of renewable energy sources.

2. Potential Benefits of Using Energy Management System at the University Campus

Peak demand clipping strategy can effectively reduce the electricity bill for consumers and the cost of electricity for the utility companies. A survey was carried out to identify the potential benefits that the energy management system could bring to the customers. The power consumption in one of the buildings, namely SE block, at UTAR was recorded. The building block comprises of 10 tutorial rooms and 10 laboratories. Fig. 1 shows the power consumption of the building on 22 July 2012, Sunday, and 24 July 2012, Tuesday. These graphs show the typical power demand characteristics for colleges and universities in tropical countries where the power demand has a correlation with its weather. The power consumption on Sunday is low because there is no ongoing activity in the building. During weekdays, the power demand starts to rise at about 7.30 a.m. when classrooms start to be occupied. It reaches the maximum demand at 1.45 p.m. when the weather is hot and the air conditioning systems operate at high power. The power demand drops significantly after 5.30 p.m. when students start to leave the building block.

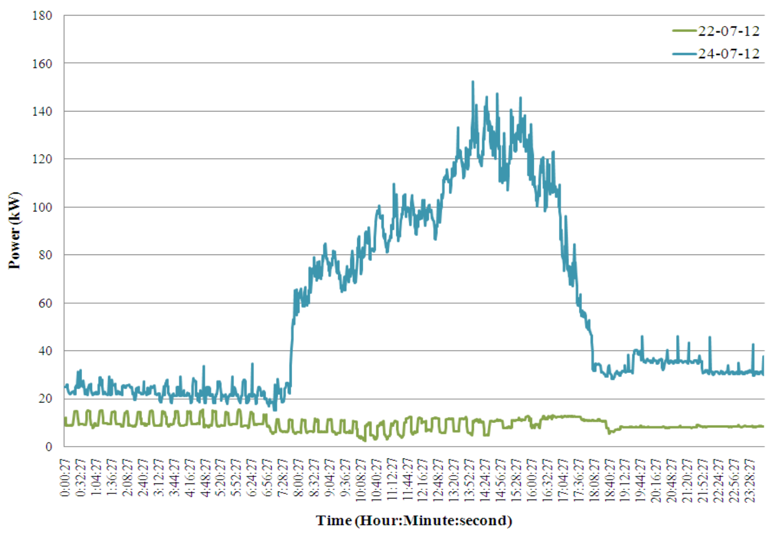

Fig. 1. Power consumption of SE block on 22- and 24 July 2012.

Load factor is a useful method to determine whether if a plant is utilizing its equipment on a consistent basis or only for a short duration. In general, low load factor results in a higher cost of electricity. The load factor can be calculated from equation 1 below:

$$\text{Load factor (\%)} = \frac{\text{Average real power}}{\text{Maximum real power}} \quad (1)$$

Table 1 shows the tabulated power measurements of SE block on 24 July 2012. It was found that the load factor is 57.4 %. The low load factor indicates that there is a great potential to save electricity bill by shaving the peak demand.

Table 1. Power measurements of SE block on 24 July 2012

Parameter	Value
Average real power from 7:30 a.m. to 5:30 p.m.	87.42 kW
Maximum real power	152.4 kW
Load factor	57.4 %

The cost of electricity per month is determined based on the total electricity usage in kWh and the peak demand charge. In order to simplify the calculation of electricity bill, assumptions are made as follows:

1. The power demand for weekdays are identical
2. The total electricity usage per month is estimated based on the average power consumption on 24 July 2012
3. The average power is multiplied by 24 hours and 20 days for a month
4. The power factor penalty is not included in the calculation

Table 2 shows the power usage and monthly electricity bill of the building under the commercial category, C1, electricity tariff. It is noticed that there is a potential to save the electricity cost up to RM 1,683 or 13.5 % of the monthly electricity bill by implementing peak demand clipping.

Table 2. Power usage and monthly electricity bill

Parameter	Unit	Unit price (RM)	Cost (RM)
Actual electricity demand			
Power usage (kWh)	27,163	0.312	8,475
Maximum demand (kW)	152.4	25.9	3,947
Monthly electricity bill (RM)	-	-	12,422
Electricity demand with peak clipping			
Power usage (kWh)	27,163	0.312	8,475
Maximum demand (kW)	87.42	25.9	2,264
Monthly electricity bill (RM)	-	-	10,739
Potential saving (RM)			1,683

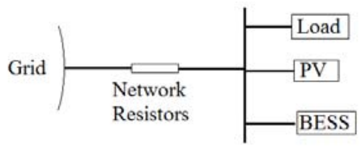

Fig. 2. Electrical diagram of the network emulator.

3. System Configuration

The battery energy storage system (BESS) consists of a bi-directional inverter that is connected to four sealed lead acid batteries with a total capacity of 480 Ah, equivalent to 5.76 kWh of energy. The National Instruments Single-Board RIO 9632XT is used to monitor the voltage level and output current in the three-phase network. The BESS is placed on a network emulator exclusively designed and developed for this research work. Fig. 2 shows the electrical diagram of the network emulator. The network emulator consists of a series of network resistors, a load bank and a photovoltaic system. The rating of the photovoltaic (PV) system is 3.0 kW. A series of resistors represents the network resistance. The load bank can be varied from 0 W to 5000 W in a step of 500 W. Fig. 3 shows the experimental set up of the network emulator.

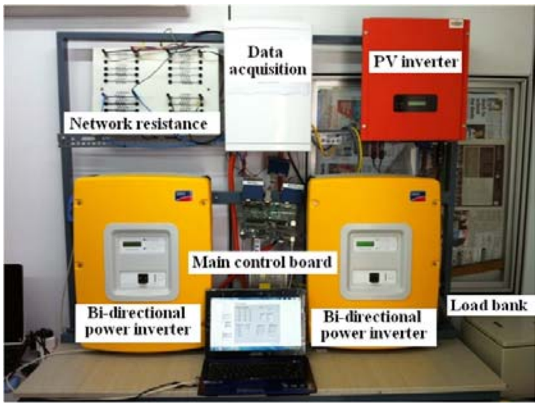

Fig. 3. Experimental setup of the network emulator.

4. Results and Discussions

Experiments were carried out to investigate the ability of the BESS to shave the peak demand as well as the ability to mitigate the voltage unbalance of the network. There are a total of three case studies in this section.

4.1. Case study 1: peak demand shaving

In this case study, the allowable maximum power demand of the network is set at 2 kW. Fig. 4 shows the peak shaving for a stair-shaped load demand in the network. The load demand increases in a step of 500 W up to 5000 W and then decreases in step of 500 W until 0 W. It can be noticed that when the load increases further from 2 kW to 2.5 kW at 600 s, the BESS begins to supply power to the network. Hence the power demand seen by the utility company is maintained at 2.5 kW regardless of the variation in the actual demand.

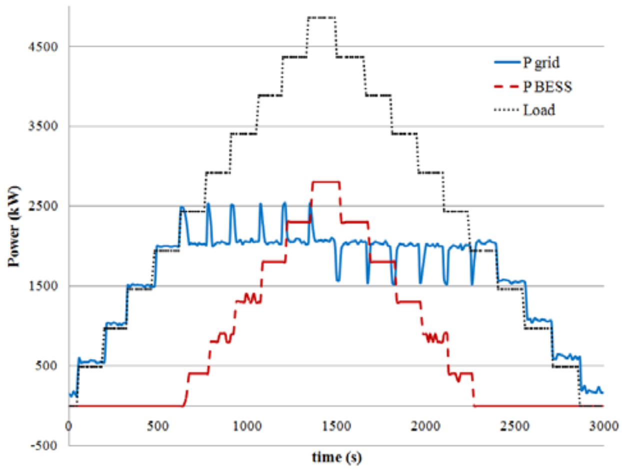

Fig. 4. Peak demand shaving for a stair-shaped load demand.

4.2. Case study 2: voltage unbalance mitigation when pv inverter and load are connected to different phases

In this case study, the PV inverter is connected to phase A and the load is connected to phase C. The objective of this case study is to evaluate the voltage conditions of the network when the PV inverter and the load are connected at different phases. Fig. 5 shows the experimental results of the network VUF, the power output of the PV inverter and the power demand. It is also noticed that the VUF rises with the load after 466s. The highest VUF recorded is 2.85 %. This experiment shows that the increase in the power output of PV results in the deterioration of the voltage balance of the network.

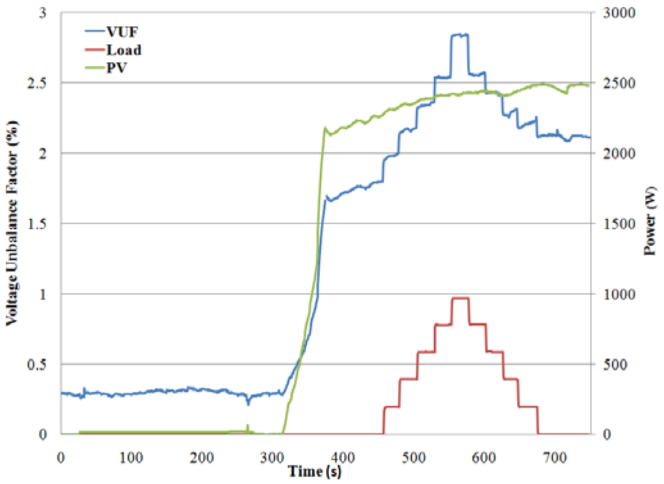

Fig. 5. Voltage unbalance factor when PV inverter and load are connected to different phases.

The strategy used to mitigate the VUF in this case study is to store the PV inverter power produced at phase A to the battery bank and supply power to the load at phase C when the VUF is greater than 1 %. Fig. 6 shows the voltage unbalance of the network after the corrective action. When the PV inverter begins to deliver power to the network, the VUF rises to 1.7 %. It takes around 60 s for the BESS to be ready to absorb power from the PV inverter at phase A. This time delay is caused by the inherent setting of the bi-directional inverter for its protection. It is noticed that BESS begins to supply power to the load at 400 s in order to maintain the network VUF to be lower than 1 %.

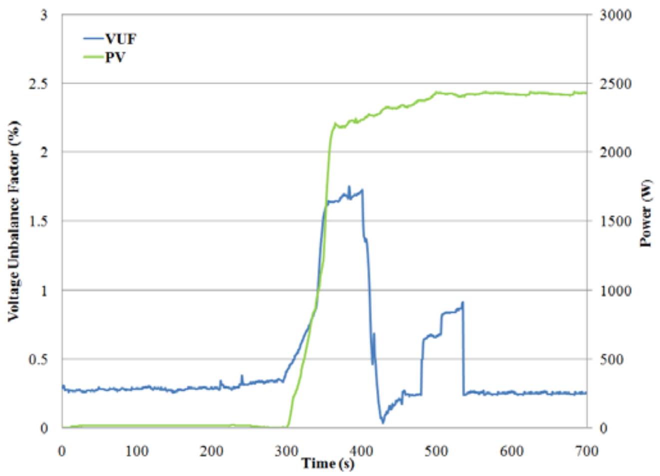

Fig. 6. VUF of the network for case study 2 after the corrective action.

4.3. Case study 3: voltage unbalance mitigation under uneven power demand with the PV inverter and load connected to the same phase with the load

The objective of this case study is to study the voltage conditions of the network when the PV inverter is connected to the same phase as that of the load. Fig. 7 shows the experimental results of the VUF, power output of the PV inverter power and the power demand when the PV inverter and the load are at the same phase. At 280 s, the PV inverter begins to inject power into the network and the load starts to increase its power demand, from 0 W, at 420s. The increment of power demand has resulted in the reduction of the VUF from 1.8 % to 0.75 % because the power from the PV inverter is absorbed by the load. This case study shows that the PV inverter can mitigate the voltage unbalance only when power injected into the network is lower than that of the load. If the power injected by the PV inverter is higher than the amount that can be consumed by the load, then the VUF will still be higher than 1 %.

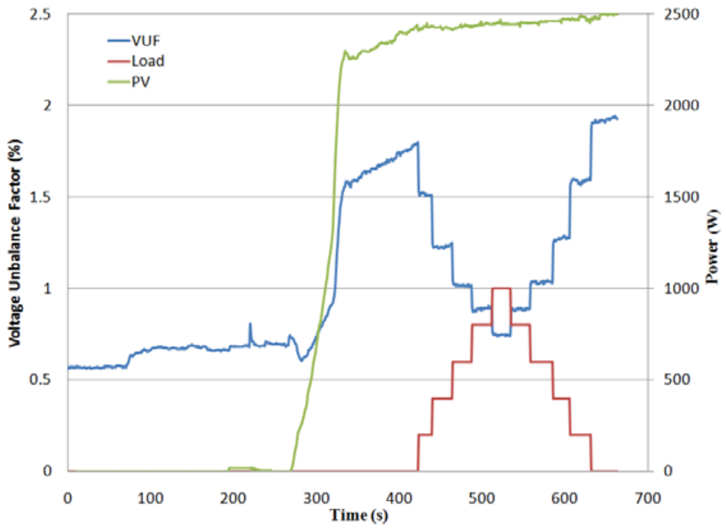

Fig. 7. Voltage unbalance factor with PV inverter and load connected to different phases.

The strategy used to mitigate the VUF in this case study is to channel the PV inverter power at phase A to the battery bank when the VUF increases to 1%. Fig. 8 shows the VUF of the network after correction action. The PV inverter begins to inject power into the network at 70 s. It takes about 60 s for the BESS to be ready to charge the batteries. At 200 s, the BESS starts to channel the PV power to the batteries, hence making the network VUF to drop from 2% to 0.43 %. When a load is connected at 250 s, the BESS begins to reduce its power absorption from the PV inverter. The load is now being supplied by PV inverter.

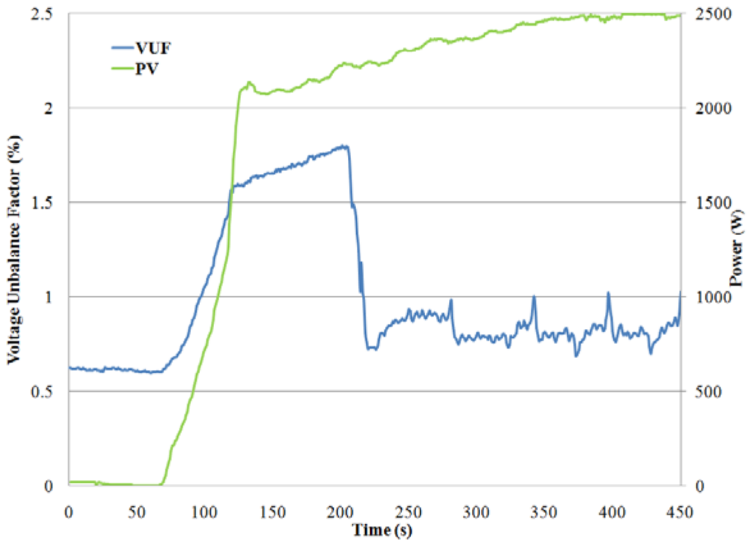

Fig. 8. VUF of the network for case study 3 after corrective action.

5. Conclusion

In this paper, a battery energy storage system (BESS) is developed for peak demand shaving and voltage unbalance mitigation. Several case studies are carried out for different scenarios of network load and PV inverter. The results obtained show that the BESS can deliver power to grid during peak demand period and absorb power from grid during the off-peak period. The BESS is also capable of handling the voltage unbalance caused by uneven load distribution and integration of PV inverters.

Further studies may analyze the optimal sizing of the BESS for peak shaving application to achieve maximal economic benefit.

Acknowledgements

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