USING A SMART GRID LABORATORY TO INVESTIGATE BATTERY ENERGY STORAGE TO MITIGATE THE EFFECTS OF PV IN DISTRIBUTION NETWORKS

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ABSTRACT

This paper shows how a high penetration of PV generation in LV distribution networks can generate voltage problems, such as voltage rise and voltage unbalance. High resolution solar irradiance data from representative days is used in a network model along with real demand profiles. To reduce the voltage problems, excess power from PV sources need to be managed. A lab based battery energy storage system interfaced through a three phase power amplifier to a Real Time Digital Simulator using "power hardware in the loop" has been used to reduce the voltage problems generated by PV generation. This shows how storage is used in real time to effectively reduce voltage problems.

INTRODUCTION

The success of a Feed-in tariff (FIT) launched in UK by the Department of Energy and Climate Change (DECC) on 1st April 2010 has increased solar power use rapidly in recent years [1]. According to [2], photovoltaic (PV) generation has continued its remarkable growth trend in 2011, even in the economic crisis (29.7 GW globally and 21.9 GW in Europe). Large penetrations of PV can pose a significant challenge to distribution networks [3]. This can be either steady state, such as voltage rise, voltage unbalance and reverse power flow [4, 5]; or dynamic, which can lead to power quality issues and reduced reliability because of solar power's inherent intermittency [3, 6]. When solar irradiance changes quickly, the intermittency in the generator output brings challenges in terms of power quality, such as voltage fluctuation.

In this paper, a high PV generation level has been applied to an LV network using high resolution (6 second) solar irradiance data measured at a domestic property in the UK. These solar irradiance profiles representing different seasons are shown in Figure 1. In order to examine and mitigate the resulting effects, a real distribution network has been modelled in a Real Time Digital Simulator (RTDS). Accordingly, problems, such as voltage rise, voltage fluctuation and voltage unbalance on the distribution networks have been measured.

Both a modelled and a lab based battery energy storage system (BESS), interfaced with RTDS, have been used to show how to reduce voltage problems caused by the PV.

RELEVANT EFFECTS OF PV GENERATION

Voltage Rise

Distributed generation, such as PV, may generate voltage rise. Without PV generation, voltage drop occurs along the feeder. However, if the PV generation exceeds the feeder loads then there may be reverse power flow and voltage rise. The installation of energy storage could play a role in this situation by absorbing surplus power from PV generation during the midday generation peak [5, 7].

Voltage Fluctuation

Voltage fluctuations are general variations of the voltage envelope or random voltage changes. The inherent intermittency or solar irradiation can cause voltage fluctuation in a distribution network [8].

Voltage Unbalance

Voltage unbalance is a power quality issue within the low voltage distribution network, exacerbated by the random location and rating of PV generators. This must not exceed 1.3% for the systems with a nominal voltage below 33kV [9]. The unbalance factor is calculated by:

$$\%VUF = \frac{Negative\ Sequence\ Voltage}{Positive\ Sequence\ Voltage} \times 100\% \qquad (1)$$

ENERGY STORAGE SYSTEM

Previous study has demonstrated the benefits of the application of BESS in distribution networks. In [5], distributed energy storage is proposed for mitigation of voltage rise problems caused by PV generators. The BESS is used to charge the surplus power from solar PV during the midday and discharge it during the evening for load peak shaving. In [7], a coordinated control of distributed energy storage with traditional voltage regulators, such as on-load tap changer transformers (OLTC) and step voltage regulators (SVR) has been proposed to solve the voltage rise problems caused by PV generators. In addition, energy storage for reducing the voltage unbalance problem has been studied in [10].

The simulation and experimental results demonstrate the BESS is very effective in mitigation of voltage unbalance factor and improving the efficiency of the distribution networks [10]. In this paper, a laboratory BESS in the Durham University Smart Grid Laboratory and a modelling BESS (built in RSCAD) have been used.

MODEL DISCIRPTION

Solar Irradiance Profile

Solar irradiance data has been collected from a domestic property in Retford, Nottinghamshire (latitude 53.3169°N and longitude 0.9408°W). In order to present and compare the worst voltage rise and voltage imbalance scenario, the solar irradiances under different days have been selected as illustrated in Table 1 and Figure 1.

Scenario	Time
Winter Sunny Day 28-Jan	9:30-10:30, 11:30-12:30
Cloudy Day 18-Feb	10:30-11:30, 13:30-14:30
Summer Day 06-Jun	10:15-11:15, 12:30-13:30

Table 1: Load and Generation Profiles Used

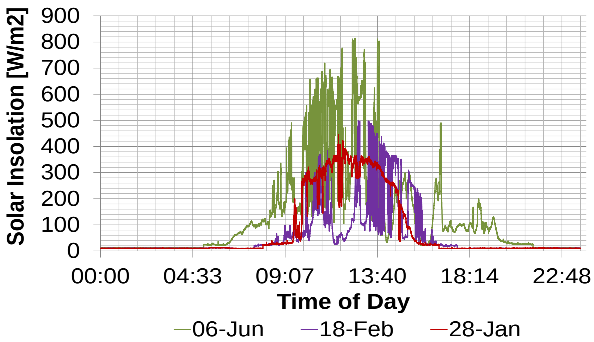

Figure 1: Three irradiance profiles used

Load Profile

A 3-phase load profile historical data has been collected from KelVAtek monitoring equipment connected to a secondary transformer. Figure 3 illustrates an example of one of the load profiles applied in this paper.

Case Study Network Structure

A benchmark radial residential urban distribution network in Northern England is considered in this paper. Using GIS and technical data provided by the DNO, a representation of this network has been developed. This network contains 406 domestic loads distributed between four ways from a secondary (11kV/400V) transformer. The 2.5 km feeder to the primary substation supplies nine other LV networks. A simplified model of the network has been used in the analysis (see Figure 3). The voltage on the output of the secondary transformer is set at 1.06 p.u.

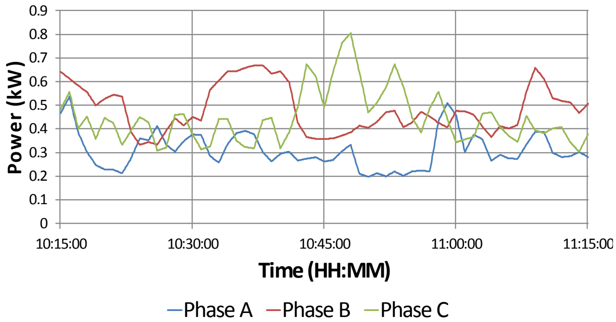

Figure 2: An example of demand profile of network

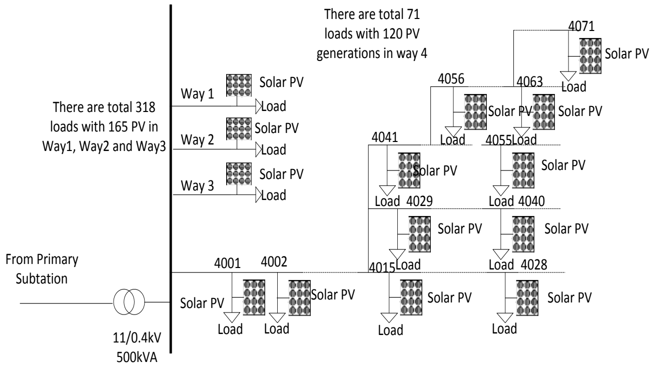

Figure 3: A benchmark radial residential urban distribution network

Energy Storage Specification

Storage is sited at the end of the longest feeder in the network. The voltage sensitivity factor (VUF) has been used to determine the import power of BESS required to offset voltage rise problem. This is defined as:

$$VSF = \left\| \frac{dV}{dP} \right\| \quad (2)$$

Thus the power required of BESS to compensate the voltage rise problem is calculated as follows:

$$BESS_{power\ required} = (V_{max} - V_{limit}) \times VSF \quad (3)$$

Where V_{max} is the maximum voltage achieved after integration of PV. V_{limit} is voltage rise limit (1.1 p.u.).

IMPLEMENTATION

A simplified network model is constructed in RTDS. A combination of lab based PV and energy storage are used together with emulated PV and energy storage units in the model. The experiment implementation in this paper is achieved using the real time power hardware in the loop (PHIL) in the Durham University Smart Grid Laboratory. The experimental network is connected to the RTDS system through 3-phase power amplifier. This contains a PV emulator, BESS and RTDS/amplifier network emulation system (see Figure 5). The RTDS uses a Newton-Raphson algorithm with time step of 50 μs.

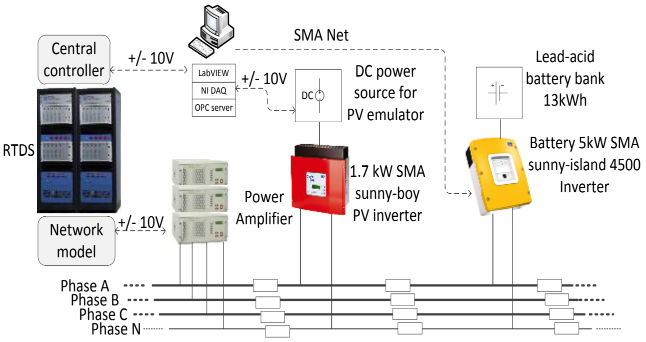

Figure 4: Layout of PHIL Emulation

The PV emulator from smart grid laboratory is a 1.7 kW programmable DC power source with a SMA Sunny-Boy inverter. The laboratory BESS includes a 13kWh lead-acid battery bank and a 5 kW SMA Sunny-Island 4500 bidirectional inverter. The control scheme of the BESS is developed in RSCAD and LabVIEW. Since it was found that lab storage capacity/rating are insufficient to solve the problem, both RTDS and lab based storage are used in conjunction with each other.

SIMULATION RESULTS AND DISCUSSION

Effects of PV on Distribution Networks

The results show that the voltage rise in the network is strongly correlated to the solar irradiance (see Figure 5). Further, the fluctuating nature of irradiance, due to passing clouds, means that there are corresponding amounts of voltage fluctuation. It can be seen in Figure 6 that the voltage problem is worse in summer/midday than in winter days as expected. Similarly, voltage unbalance increases with the amount of PV penetration (Figure 9).

Figure 7 shows the voltage cumulative distribution function for at the end of the feeder with PV periods on 6th June at two different times of day. Both are highly overvoltage. It can be seen that there is a much higher probability of having voltage greater than 1.14 p.u. from 12:30-13:30 than from 10:15-11:15 (62% vs. 39%). This implies that at time period 12:30-13:30, more charging power is required from the BESS to reduce voltage rise than from 10:15-11:15.

Understanding the fluctuation and severity of the voltage problem in this way is important because it affects the control strategy of any BESS to fix voltage problems in different seasons and at different times of day.

Use of BESS to Fix Voltage Problems

The effect of storage on fixing the voltage problem is investigated for the period 10:15 to 11:15 on 6th June. Here, the BESS is controlled in such a way as to enter charging mode if voltage is higher than a threshold value (1.1 p.u.) and the import power is calculated based on voltage sensitivity factor (as described above). As shown in Figure 8 and Figure 9, this improves the conditions in the network as follows:

- The magnitude of the voltage is brought within legal limits- fixing the overvoltage problem;
- The voltage fluctuation is reduced leaving a smoother voltage profile (the voltage standard deviation is reduced by 84%);
- The voltage unbalance factor has been reduced to within legally acceptable levels (less than 1.3%).

By improving the conditions in the network, the use of BESS can therefore be said to increase the permissible penetration of PV in LV distribution networks. Further, the use of a variable power demand into the BESS is effective in that it allows a lower rise in the battery state of charge (SOC) than would happen if the battery is charged at a constant rate (Figure 10). This enables lower capacity and so cheaper storage to be used.

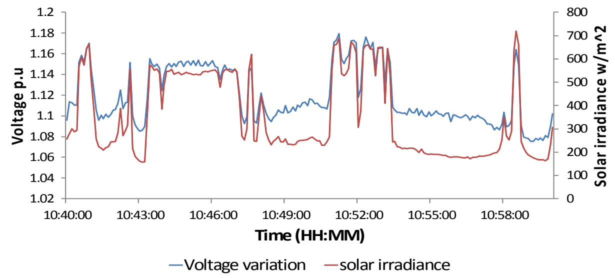

Figure 5: Voltage variation with solar irradiance, 10:40-11:00, 6th June

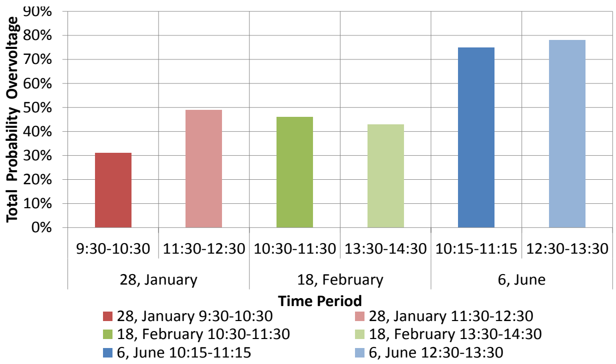

Figure 6: Total probability of overvoltage (greater than 1.1 p.u.) for the different simulations

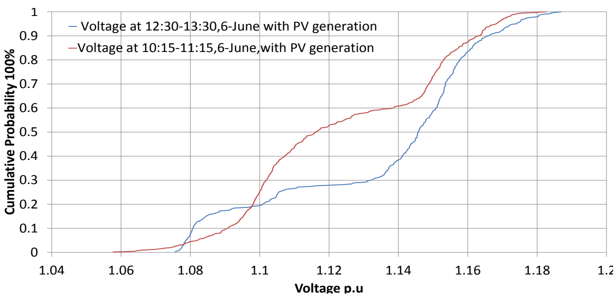

Figure 7: Cumulative distribution function of voltage at the end of feeder at 6th June

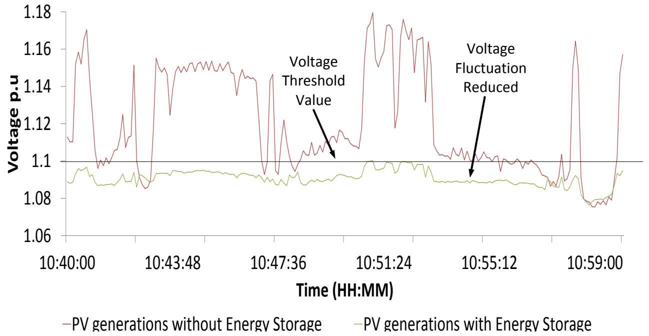

Figure 8: Voltage rise reduction by energy storage at time 10:40-11:00, 6th June

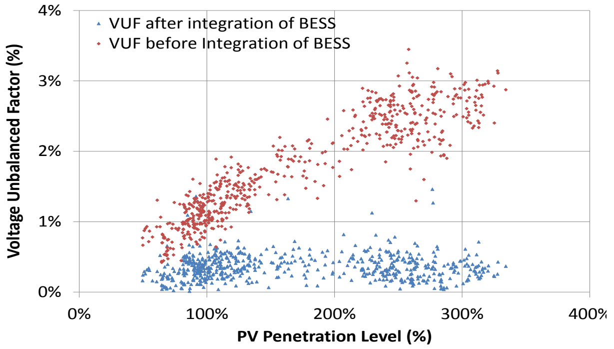

Figure 9: VUF before and after integration of BESS, 10:40-11:00, 6th June

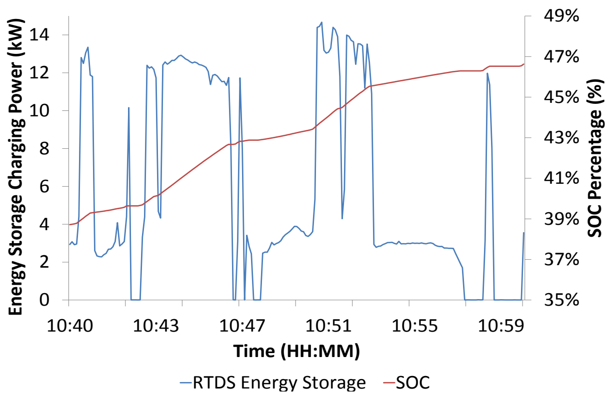

Figure 10: RTDS (Emulated) BESS charging power, 10:40-11:00, 6th June

Critique of Modelling Approach

The use of high resolution generation and demand data in real time allows a detailed study of the condition of the network and battery storage. This approach can be used for evaluating the feasibility of interventions in real networks. However, practical limitations with the approach need to be considered:

- The power available from the smart grid is limited because of the inverter and power amplifier. This means simulated storage may also be needed;
- Real time studies provide high level of detail, but are impractical for studies over long time periods.

CONCLUSIONS AND FUTURE WORK

This paper investigates voltage problems under different solar irradiance profiles and the integration of BESS into LV distribution networks to solve the associated voltage problems. Real network, demand and generation data are used in a real time simulation and the BESS is shown to provide a feasible solution to the problem. Future work will look at how to use storage to solve more transient power quality problems and also will look at the dynamic performance of lab based energy storage.

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