The Use of Second Life Electric Vehicle Batteries for Grid Support

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Abstract---**Matching electrical power supply to customer demand is an on-going problem for electricity distribution network operators and it is increasing with the growth of distributed renewable energy generation at the low voltage (LV) level. A battery energy storage system (BESS) has been suggested which would help the control of voltage levels, optimise renewable generation and supply the evening peak demand. In addition a BESS could offer ancillary support to the network including balancing services as well as deferring network asset upgrade, with ensuing financial advantages. Until now the cost of providing a BESS has been prohibitive except for the most isolated and essential supply. The main contribution of this paper will be to demonstrate that afterlife electric vehicle (EV) batteries can be used in BESS for the provision of such services with particular emphasis on peak shaving and upgrade deferral. The size of the BESS is calculated using a simulation based on a LV load profile and the effect on voltage is modelled and displayed graphically. Considering that the market penetration of EVs has been hampered by high cost of Li-ion batteries and with projections of the first set of used automotive batteries becoming available from 2019 an investigation into the afterlife usage of EV batteries is timely and economic.**

Keywords: storage, second life batteries, grid support, Simulink model

I. INTRODUCTION

Matching power generation and demand is increasingly becoming one of the most challenging areas of the power industry. The inability to store electricity in large quantities has led to utilities constantly trying to match generation with consumption on a real time basis. Forecasting and some demand management goes some way to narrowing the gap, but uncertainty over wind generation and changing consumer profiles still exists.

This variation in consumption presents a problem to utilities as the energy requirements during the peak which lasts just a few hours for the daily cycle and a few months for the annual cycle is substantially higher than the average power requirements of the network. This phenomenon makes it mandatory for utilities to design transmission and distribution systems sized for peak load requirements. This results in the network being under loaded for most of its operational life which is costly and quite wasteful. The use of additional generation with subsequent redundancy of system equipment is required to handle this uncertainty which increases the cost of generation.

The ability to store and utilise significant amounts of energy on demand in power networks can defer system upgrades, increase power quality, buffer variable distributed generation and provide flexibility to utilities. There are many energy storage technologies for power systems. The most popular of these are pumped hydro storage, flywheel storage and battery energy storage systems (BESS). Of these technologies, the BESS stands out because of its power capacity and quick response time (20 milliseconds in some batteries) [1]. The main drawback to more widespread use of BESS is the cost. If cost issues can be overcome, energy storage systems will have multiple benefits which include deferral of system upgrade, optimisation of renewables and improving power quality [2].

Typically, lead acid batteries have been the major players in the power industry because of the maturity of the technology and ease of maintenance. However, most modern battery systems use lithium based batteries because of their higher energy density and very high storage efficiencies [3]. The most widespread use of lithium based batteries is in portable devices and electric vehicles (EVs). However, the high cost of these batteries prevents their use in BESS and is also a major impediment to the widespread take-up of EVs. A 2nd life use for the car battery after degradation had deemed its capacity to be too low for driving, could make the overall cost of the EV more acceptable to the consumer. This has the added benefit of providing ancillary services to the grid to support a future market that will require cost effective energy storage to facilitate flexible generation and demand. [4].

Studies by Kempton & Tomi´c [5] have shown that ancillary services account for 5-10% of the cost of electricity. BESS can play a significant role in the provision of these ancillary services [3]. Another important role that BESS can play is in the deferral of upgrades to transformers and other transmission and distribution (T&D) assets as the peak demand can be shaved by meeting it with power which has been stored during times of lower demand or high renewable generation.

The concept of peak shaving entails storing cheap baseload energy at off peak hours (in the troughs) and releasing it into the network during peak hours. Thus, the load profile of the network, storage efficiency of the storage medium and the tariff structure are the most important considerations in peak shaving. In a study by Pandiaraj et al [6], it is stated that optimal economic operation can only be achieved if reliable storage components that are reasonably priced are selected. These components must be designed such that they satisfy the issues for the network profile under consideration.

Considering that the market penetration of EVs has been hampered by high cost of Li-Ion batteries and with projections of the first set of used automotive batteries becoming available from 2019 [1], an investigation into the afterlife usage of EV batteries is worthwhile for the EV purchaser and the Distribution Network Operator (DNO).

II. NETWORK SUPPORT

A. The Issues

1) Peak shaving: Oudalov et al [7] state that power peak is a relative term and as such, it requires a reference value. Any value above the reference is referred to as a load peak. Using the maximum power to be shaved and the duration of this peak value which is the discharge time, the BESS capacity can be determined using the formula below.

$$B_{cap} = \int B_{pw}\, dt \tag{1}$$

Where B_{cap} = BESS capacity (Wh),
B_{pw}= Power (W) to be shaved
t = Time (hrs)

The use of BESS for peak shaving has an effect on the system voltage. This is especially true on the LV side of the network where there is a higher resistance than reactance and as such, real power has a greater effect on voltage regulation than reactive power. It can also have an effect on the system frequency.

2) Voltage Control in Power Systems: Power utilities are mandated to provide electricity to customers within a fixed voltage range. Within the UK, this level is +10%/-6% of the nominal voltage on the LV network [8]. At present, most voltage control is carried out at high voltages (33kV and higher) by OLTC (On Load Tap Changing) transformers and devices that produce reactive power such as shunt capacitors and reactors, synchronous condensers, static VAR compensators (SVC) and static synchronous compensators (STATCOM). This is due to the widespread use of induction machines for electricity generation which always absorb reactive power even when generating real power on transmission lines.

To calculate the voltage at the end of the feeder:

$$S = P + jQ \text{ and } S = V_R I^* \tag{2}$$

Where: S = Apparent Power (VA),
P = Active Power (W),
Q = Reactive Power,
V_R = Receiving end Voltage

It can be derived that

$$V_S = V_R + \frac{RP+XQ}{V_R} + j\frac{XP-RQ}{V_R} \tag{3}$$

Generally,

$$XP - RQ \ll RP + XQ \tag{4}$$

So voltage drop is

$$\Delta V = \frac{RP+XQ}{V_R} \tag{5}$$

And phase angle is

$$\partial V = \frac{XP-RQ}{V_R} \tag{6}$$

Where V_S = Sending end Voltage,
R = Line Resistance,
X = Line Reactance,
ΔV = Voltage Drop,
∂V = Angular Shift

In transmission systems, the X/R ratio is normally high and thus, the effect of line resistance may be ignored and voltage regulation is determined largely by reactive power control [9]. In distribution circuits such as the network being considered here, the effect of line resistance is higher than line reactance. As such, the effect of active power on the voltage is significant.

One of the problems presented by the rise in penetration of DG into conventional power systems is due to the increase in active power injected into the network by these sources. This may cause the voltage at the point of common coupling (PCC) to rise above the allowable upper limit [10], [11]. Additionally, intermittent generation from the DG will cause a fluctuation in voltage that needs to be addressed in a timely manner. The effects on voltage of peak shaving using BESS may give an insight into how energy storage can be applied to support voltage in distribution circuits.

3) Ancillary services: Energy storage can be integrated into the National Grid to provide a number of services as discussed below.

Ribeiro et al [12] highlighted rapid spinning reserve as a service that can be provided by energy storage systems thus substituting thermal units and combustion turbines that would have been operating in reserve mode. This will reduce fuel consumption – spinning reserve can use 10% of full power – along with wear of generators, turbines and associated equipment.

Reserves for frequency response are another possible application of electrical energy supply (EES) as stated by Parker [13]. Frequency responsive reserves counter-balance fluctuations that exceed limitations in the system thus providing frequency regulation.

In a study by Mohd et al [14] by utilizing energy surpluses from off peak generation, peak demand can be supplied by the EES at higher rates which provide added profits for utilities. This short term operating reserve (STOR) is a service which can be tendered for and payments received from the national grid.

System instability which results from a lack of synchronism of generators due to a phase difference between generation and demand may cause system collapse. These are usually caused by load disturbances. EES can be used to smooth the load demand thereby ensuring synchronous network operation.

Voltage regulation is usually provided by injection of reactive power into the grid. Capacitors are conventionally used to provide this service; however with the addition of power electronics, BESS can be used to provide reactive power during all periods of operation (Charging, discharging and standby mode).

Upgrade deferral is a major application area for EES. T&D upgrades arise due to the inability of existing infrastructure to cater to peak demand conditions. Energy storage can be placed at suitable points on the network in order to shave peak demand and thus defer such upgrades.

Harmonic distortions, voltage sags and spikes cause numerous problems to electronic equipment. Customers can protect such equipment by utilizing EES. Reliability can also be improved by using EES to provide bridging power (UPS) for customers in order to ride through a power disruption

4) Renewable Energy: Integration of renewable energy into the power grid gives rise to a number of difficulties due to the fluctuating nature of most renewable sources. EES coupled with renewable generation can help mitigate most of these issues. The simulation shows how placing BESS at the same voltage level as the distributed generation can counteract issues such as voltage and frequency problems before they cause problems outside the immediate vicinity.

B. The Battery Energy Storage System (BESS)

1) Location of the BESS in the network: It is expected that there will be storage at every voltage level within electricity networks in the future. The pictorial representation of a possible future network is shown in Fig. 1

BESS is expected to play a significant role in these future networks. These will consist of the BESS and a PCS connected in parallel to a load. The BESS placed at the LV can participate in peak shaving and help prevent power flow into the transmission system from renewables.This is shown in Fig. 2.

In order to appropriately install BESS within a particular network, certain parameters need to be considered. These include ratings for the components on the network in order to size the particular BESS, possible impact of BESS on system parameters such as load factor & diversity factor and opportunities for T&D upgrade deferral.

2) Effect of location of BESS on load factor, diversity factor and upgrade deferral: The load factor is a ratio of average demand to theoretical maximum demand over a period of time. The average demand is usually the power consumed by a customer. This is given by:

Average demand

$$\frac{1}{t}\int_0^t Demand\ (t)dt = \frac{1}{t}\int_0^t P(t)dt \qquad (7)$$

∴ Load factor

$$= \frac{Average\ demand}{Peak\ demand} = \frac{\int_0^t P(t)dt}{P_{max}\cdot t} \qquad (8)$$

Sclabbach & Rofolski [15] give typical load factors for different voltage levels as below:

TABLE I
TYPICAL LOAD FACTORS

Voltage level	**Load factor**
132kV	0.75 - 0.82
11kV & other MV systems	0.61 - 0.76
LV systems	0.50 - 0.77

Networks are usually designed to have high load factors indicating that a group of loads operates near its peak most of the time. This can however constitute a problem with constantly expanding networks as the network can easily be stretched beyond its limits prompting expensive T&D upgrades. Strategic placement of BESS can defer such upgrades for a significant amount of time. As can be seen from table I, the LV network has less diversity and so a higher variation of load factor than higher voltage levels. As such, placement of the BESS at that level will ensure stable supply and allow the batteries sufficient time to recharge during low load conditions. Additionally, the effects of a system which supplements the load or provides regulation from the LV end of the network will reduce demand on the MV and HV side as well.

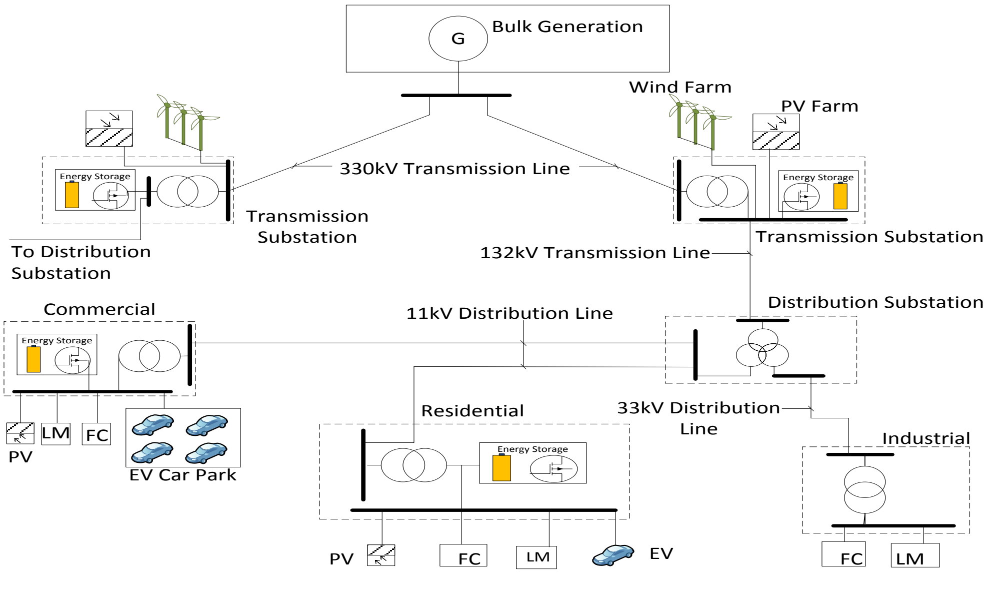

Fig. 1: A vision of future distribution networks

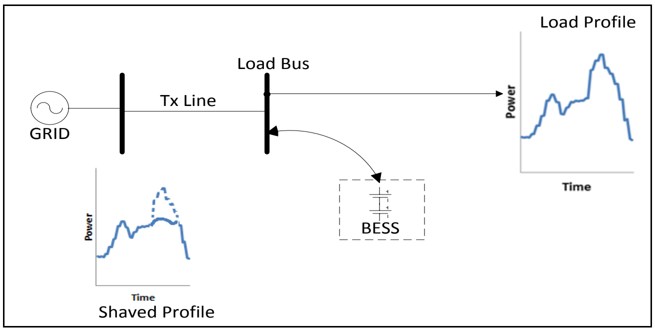

Fig. 2 overview of network with optimum location of BESS

Diversity factor on the other hand is a ratio of the sum of individual non-coincident maximum demands of various subdivisions of the system to the maximum demand of the complete system. It is given by:

$$Diversity\ factor = \frac{\sum Individual\ demands}{Peak\ system\ demand} \tag{9}$$

Increasing load diversity reduces system peak load and results in higher reliability. Thus installing the BESS on the LV reduces loading on the LV transformers. As such, there will be more diversity and hence greater smoothing on the HV section. Smart grids containing renewable energy sources will incorporate DG from the LV side of the network. Placing a BESS at the LV side ensures minimal losses in the storage of unused power from such sources and reduces reverse power flow. There is also a higher strain on LV transformers whenever there is peak load. This can be mitigated by siting the BESS on the LV side thereby displacing energy that would have been provided by the transformer thus prolonging transformer life.

3) Battery Lifetime: The BESS utilizes Li-ion batteries. As they are after-life batteries, they are at an initial SOH of 80%. This implies that they only have 80% of their nominal capacity left. Ideally, the BESS will further consist of an inverter, a power conditioning system and a control system. These components have not been modelled; however, a control system that will regulate the charge/discharge rate within the allowable limits will be required for practical operation. This will ensure that internal resistance build up is minimal during charging and discharging. As shown by Marra et al [16] this extends battery cycle life considerably.

The BESS is modelled to have one charge/discharge cycle per day. It has been sized with an anticipated cycle life of 1600 cycles during which projections extrapolated from the works of Neubauer & Pesaran [1] predict a state of health (SOH) of 50%. . Work by M Francesco [16] has shown that the capacity of the batteries drops from 80% to 50% in approximately 1600 cycles (about 4.5 years) under favourable conditions. Additionally, in studies by NREL [17], utilizing the batteries from 80% to 60% SOH takes about 5 years.

As such, the BoL (Beginning of Life) battery capacity has been sized such that at the EoL (End of Life), the remaining battery capacity can adequately cater to the service being provided.

4) Load profile: The daily load demand curves for the network were generated using data from UKGDS [18] for domestic loads. This was given in half hourly intervals. This is depicted in Fig. 3:

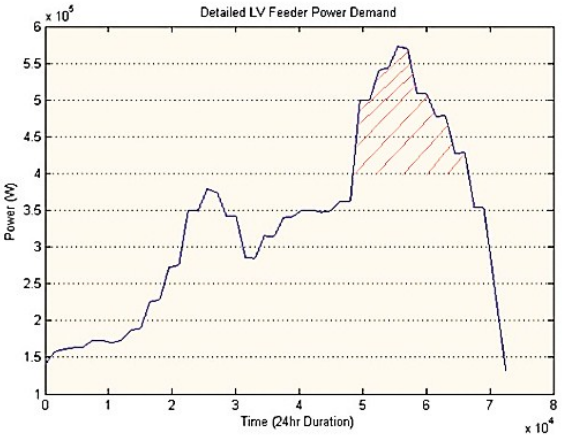

Fig. 3: Power Supplied to Detailed LV Feeder from the Grid

The peak load occurs for a period of about four hours and during this time, the demand exceeds the transformer capacity. As can be seen from above, there is a significant difference between the peak load and the minimum load. The feeder peak load is in excess of 550kW. This is about 150kW (35%) above the transformer capacity of 400kW with the duration of this excess over transformer capacity being four hours. This presents a problem for the network as it puts considerable strain on the transformer. Using energy storage, power can be stored during low load periods and be used to shave the peaks produced by high demand. As such, shaving of this peak will not only save on energy costs, it will defer on upgrade of the distribution transformer.

5) Determination of BESS capacity: In order to appropriately size the BESS, the specific application which it will be used for must be taken into consideration. The BESS in this paper will be used for peak shaving. The effect of this on the network voltage will also be examined. As such, the charge and discharge strategy is designed to accommodate this function.

From table II, the BESS needs to be able to provide 493kWh over a four hour period. This means the batteries have to be sized to be sufficient for providing the required energy at the end of their 2nd life. The model assumes that the batteries must be kept above 20% depth of discharge (DOD) for optimum battery cycle life.

TABLE II
DETAILED LV FEEDER CHARACTERISTICS

Load Profile Characteristics	
Peak Duration	4hrs
Peak Load	552kW
Maximum Load to be Supplied by Grid	400kW
Average Load	333kW
Load Factor	0.6p.u
Peak to be Shaved	493kWh
Load Factor after Peak Shaving	0.83p.u

Using these considerations, the required battery capacity is obtained as shown below.

Energy required to be supplied by BESS = 493 kWh for a duration of 4 hours. The batteries at the end of the 2nd life will have 50% of nominal capacity so nominal capacity must be double that for end of life. In addition the batteries can only discharge to 20%, meaning available capacity is 80%

$$\therefore\ C = \frac{493}{0.5} = 986\ kWh:\ \frac{986}{0.8} = 1{,}232.5\ kWh \qquad (11)$$

Using the 2nd life Nissan LEAF batteries as an example, with a nominal capacity when new of 24kWh, this gives the number of batteries as

$$Number\ of\ batteries = \frac{1232.5}{24} = 52 \qquad (12)$$

The charge discharge profile showing the matching load/storage area is shown in Fig. 4.

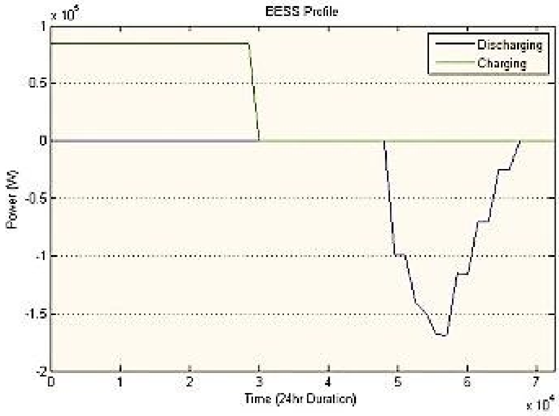

Fig. 4: Charge/discharge profile of BESS

III. A SIMULINK MODEL OF A LV ELECTRICITY NETWORK

A. Build a Simulink model of the network

A Simulink® [18] representation of a detailed network was built using data from an existing system and profiles from UKGDS [19]. This is outlined in Fig. 5. Even though only one LV feeder will be used for the scenarios, the network was constructed from the 33kV down to the LV feeder in order to see the effect of other branches of the network.

Include an afterlife EV Li-Ion BESS within the network and determine the optimum location and size

Simulate and analyse the network performance with and without Distributed Generators (DG).

Simulate and analyse the network performance with the BESS used for peak shaving (with and without DG).

B. Evaluate the results obtained for an application of second life Electric Vehicle batteries for grid support.

Four scenarios were modeled using the network and the results for power demand and voltage variation within the network were observed. The first scenario modeled the network without any additions. The second scenario used the BESS for peak shaving in the network. The third scenario introduced Distributed Generators (DG); 100kW PV array and a 100kW Wind Energy Conversion System (WECS) on the detailed LV feeder. And finally, the fourth scenario looks at the effect of using the BESS and DG on the network at the same time.

A comparison of the four different scenarios was carried out to determine to what extent the BESS will provide the network support which has been identified.

Results from simulation of the network are presented below. The variation of voltage on Bus B1 (Close to the transformer) &Bus B6 (at the far end of the line) is examined. This is shown in fig 6.

It can be seen that the voltage on the bus B1 fluctuates from above 1.05p.u to 0.95p.u during the course of the day while at bus B6, the fluctuation is from 1.05p.u to 0.92p.u. This is very close to the boundaries of the allowable limits of +10% to -6% of rated voltage for bus B1 while the lower limit is violated during peak demand for bus B6.

Fig 7 shows the power supplied by the grid under the four different scenarios. When BESS is used in the original network, peak shaving is achieved and the trough at night rises due to the charging action of the battery. This seems to address the immediate problem facing the network. The transformer is no longer overloaded and thus, an upgrade will not be required. However, networks are bound to change in the near future. As such, any solution proffered may soon become obsolete. For this reason, the network is modelled to include DG.

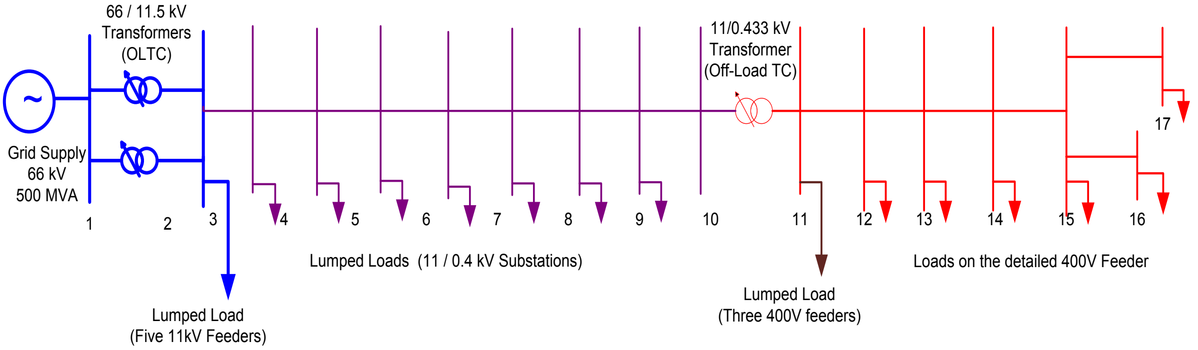

Fig 5: Single line diagram of network considered

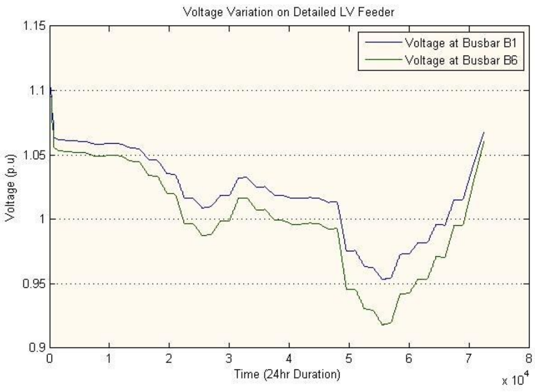

Fig. 6: Voltage Variation on Detailed LV Feeder

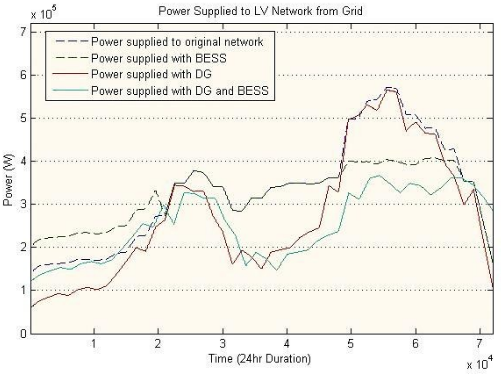

Fig. 7: Comparison of Power Supplied to LV Feeder from the Grid for Different Scenarios

It is evident that the most significant reduction in power supplied to the network when only DG is used occurs at a point in time when this is least required. At other times, the generation is only a fraction of the network demand. Due to the intermittent nature of DG, an effective solution is to use the BESS for renewable energy storage.

Fig 8 shows the voltage variation on Bus B6. From this, it can be seen that only the profiles for the scenario with BESS and the scenario with DG & BESS have voltages within the limit. The other two scenarios violate the lower limit.

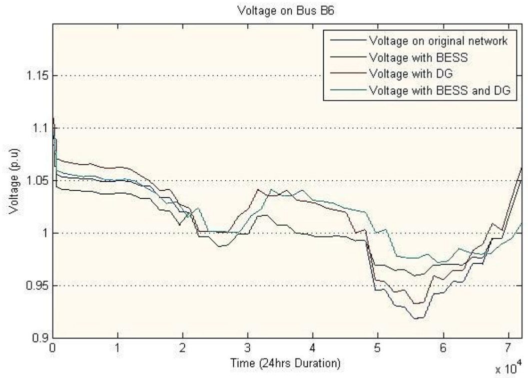

Fig. 8: Comparison of Voltage Variation on Bus B6 for Different Scenarios

It can be seen that integrating DG & BESS into the network not only provides peak shaving, it also supports the voltage profile. This can be especially useful to future networks. This will however need the BESS to be sized for renewable energy storage so that it can charge using power generated from the DG. In such a case, an increase or decrease in voltage outside allowable limits will trigger operation of the storage to provide or consume power thus stabilizing the voltage.

IV. CONCLUSIONS

Utilization of BESS for grid support offers diverse benefits to different parties in the electric power system. The technical and market barriers to the mass deployment of BESS are steadily declining but cost competiveness has still not been achieved as compared to conventional technologies. This may be achieved by using afterlife EV batteries in BESS.

The use of a BESS utilizing afterlife EV batteries has been found to have a positive impact on a detailed LV feeder on the network considered in this project. This can be repeated on the entire network wherever it is required and the cumulative effect will be substantial.

It has been shown that the location of a BESS has a significant impact on the network. Using a network with present day residential load characteristics, it was shown that the load factor is improved and overloading of a transformer can be avoided using a BESS. Additionally, it has been demonstrated that the SOH and allowable DOD are important factors in determining the required battery capacity.

Utilizing a BESS for peak shaving has been shown to have an impact on the system voltage. As such, under the right configuration, voltage support can be provided by a BESS used for peak shaving. Future electricity networks are expected to have a large penetration of DG. It has been demonstrated that operation of such a network without storage can lead to wastage of energy and can have a detrimental effect on system voltage.

BESS location, size and operation characteristics are dependent on the function to be performed. Using afterlife EV batteries has the potential of providing flexibility to operators at affordable rates. However, as demonstrated by various studies, it may be more economically viable to perform more than one ancillary service with any particular BESS.

This paper focuses on using afterlife EV BESS for peak shaving and the consequent effect it has on the system voltage. Further research can be carried out on using the BESS for peak shaving at a different voltage level and controlling the voltage using reactive power compensation.

Another possibility for future work is utilizing the BESS for frequency control at the 11kV or 400V end of the network. This has the potential of reducing the cost of operation by the grid operator.

Analysing the costs avoided on T&D upgrade deferral due to utilization of this BESS for peak shaving is also another interesting possibility for future work. This will give an insight into the real costs of business as usual and can be used as a yardstick against the proposed BESS installations.

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