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Control and Co-ordination of Flexibilities for Active Network Management in Smart Grids – Li-ion BESS Fast Charging Case

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Abstract*— Fast charging of Lithium-ion battery energy storage systems (Li-ion BESSs) when utilized in the medium voltage (MV) distribution networks may introduce its own stress on the network under certain operating modes, especially when combined with intermittent renewable power generation. In such situations, active network management (ANM) schemes by managing available flexibilities in the MV network is a possible solution to maintain operation limits defined by grid codes. The studies in this paper are related to the utilization ANM schemes for MV distribution network in Sundom Smart Grid, Vaasa, Finland. The aim of this study is to capture the stresses induced by fast charging of Li-ion BESSs during low wind power generation and utilization of ANM schemes to mitigate those arising issues. The effect of such ANM schemes on integration of Li-ion BESS, i.e. control of its grid-side converter (considering operation states and characteristics of the Li-ion BESS) and their coordination with the grid side controllers to enforce network ANM schemes have been analyzed in detail. Particularly, the effect of AC load on the DC characteristics of Li-ion BESSs has been evaluated in this simulation study.

***Index Terms*-- Active Network Management; Battery Energy Storage Systems; Lithium ion battery; Equivalent Circuit Model; Power Electronics Converter Controls;**

I. INTRODUCTION

Battery energy storage systems (BESS) play a major role as flexible energy sources (FES) in active network management (ANM) schemes by bridging gaps between non-concurrent renewable energy sources (RES)-based power generation and demand in the medium-voltage (MV) and low-voltage (LV) distribution networks. Ability of the BESS to provide both active power and reactive power flexibility services, makes them a multipurpose FES for ANM needs [1], [2]. With current technological maturity, Li-ion BESSs are capable of acting as a cost-efficient FESs and provide multiple technical ancillary/flexibility services like frequency control by controlling active power injection and voltage control by reactive power management [3], [4].

However, Li-ion BESSs will act as system load when they are being charged. The charging load shall induce stresses on the distribution system (typical at the BESS integration location), especially when they are being charged at a higher current rate (i.e. fast charging). The effects of Li-ion BESSs charging load on the distribution network might be severe, if there is a request to fast charge batteries at an instance of lower renewable power generation at the distribution levels. The negative impact to the distribution grid in such instance shall lead to increase in the overall peak load of the network, there by leading to adverse voltage fluctuations causing detrimental effects on the distribution transformers [5], [6]. Therefore, innovative grid solutions such as ANM schemes are utilised to mitigate such arising network issues.

Reactive power flow from the distributed energy resources (DERs) between the TSO/DSO interface has been defined by the reactive power window (RPW) provided by Finnish TSO, Fingrid, and ENTSO-E network codes [7]. The reactive power flow between TSO/DSO interfaces have to comply within the RPW limits to avoid being penalised. Hence, maintenance of voltage and RPW limits defined by the grid code provides a strong case for implementation of ANM schemes to administer technical ancillary services by effectively managing active and reactive power flows from the available FESs in the distribution network.

In [8]–[10], extensive research on various ANM schemes to maintain system voltage level as well as manage the reactive power flow from the DERs within the RPW provided by the Finnish TSO, Fingrid and ENTSO-E network code [7] have been studied and validated in a local smart grid pilot, Sundom Smart grid (SSG). From previous results, the reactive power control of wind turbine generator (WTG) was sufficient in order to satisfy RPW requirements on an hourly average data obtained from the SSG MV distribution network. However, it was recommended to study multi-use capabilities of BESSs in multi-objective ANM schemes by controlling flexibilities in

RESs, BESSs and on-load tap changing transformers (OLTCs) [11] on a smaller time-step in order to design ANM controllers and services effectively.

Primary role of Li-ion BESSs i.e. their slow dynamics (control of voltages and active power characteristics) over an extended time period was previously studied [12], where the authors tend to support and complement active power generation of WTG on a day-to day basis.

Design and methodology for integration of Li-ion BESS in the MV distribution system, which are capable to capture and study the fast transient dynamics by means of electromagnetic transient (EMT) simulations (i.e. smaller time step system simulation) has been presented in [13]. Therefore, in this paper, the developed Li-ion BESS integration design is subjected to an extreme network event, i.e. fast charging of the batteries under low renewable power generation. Under this condition, the voltages and the RPW window limits are expected to be under duress. Hence, an ANM scheme has been designed to provide ancillary services addressing the network issues. The ability of the developed ANM scheme to provide required ancillary services and the stability of Li-ion BESS integration (i.e. adjoining power electronic controller performance) under extreme conditions are validated by EMT simulation studies in Matlab/Simulink (SimPowerSystems).

II. GRID COMPONENTS AND MODELLING

Sundom Smart Grid (SSG) is shown in Fig. 1, which is a pilot living lab jointly created by ABB, Vaasan Sähköverkko (DSO), Elisa (communications) and University of Vaasa [10]. Measurements of active and reactive power, frequency, RMS voltages and currents are received by GOOSE messages from all the MV feeders. SSG is modelled accurately with available data and grid structure, i.e. distribution network structure, measured loads, generation units etc. obtained from the local DSO Vaasan Sähköverkko. WTG in SSG is rated at 3.6 MW and its modelling details are explained in [13].

Li-ion BESS dynamic characteristics were modelled accurately by considering the influence of parameters such as temperature, depth of discharge and C-rate (charge/discharge) by means of second order equivalent circuit cell model [13]. Li-ion BESS has been connected to the power system by means of power electronic interfaces. Detailed Li-ion BESS integration and its power electronics converter control design has been explained in [13].

III. ANM CONTROL METHODOLOGY

ANM schemes provide improved ways to manage available flexibilities from the inverter-based energy sources in the distribution grid. Hence, in this study the ANM scheme has been developed to effectively manage the available flexibilities at MV distribution grid of SSG, i.e. WTG reactive power (Q_{wind}), active and reactive power of Li-ion BESS, (P_{BESS} and Q_{BESS}) and tap positions in OLTC transformers, thereby providing ancillary services to the system. Active power, reactive power and OLTC controllers explained below will aid in providing the ancillary services, which include,

1. Voltage regulation within the threshold in the MV distribution system, mainly in all the MV feeders,
2. Maintaining reactive power flow within the RPW limits defined by Fingrid

A. Reactive Power Control

Aim of the reactive power controller is the manage voltage regulation by means of QU- control and regulate TSO/DSO reactive power flows within the threshold defined by RPW limits defined by Finnish TSO, Fingrid (Fig .2). According to the grid codes, all the MV feeder voltages must stay within 0.95 to 1.05 pu.

The maximum controllable reactive power from the WTG is calculated by (1). $Q_{\mathrm{wind,min}}$ and $Q_{\mathrm{wind,max}}$ are the minimum and maximum reactive power output from the WTG respectively. The reactive power control of BESS is defined by the phasor relationship between the battery inverter operating parameters. As the output, P_{BESS}, approaches apparent BESS power (S_{BESS}), the range of available Q_{BESS} decreases to zero, as shown in (2). $Q_{\mathrm{BESS,min}}$ and $Q_{\mathrm{BESS,max}}$ are the minimum and maximum reactive power output from the Li-ion BESS. Positive symbol of the reactive powers means it is capacitive and of negative value shows it's inductive in nature.

Q_{flex} is meant to control U_{SUL} because it has been under maximum stress during the defined use cases. Q_{flex}, the flexible reactive power allotted for QU- control is based on (3), whose values are in turn dependant on RPW limits defined in Fig. 2. Based on Fig. 2, $Q_{\mathrm{rpw,max}}$ is defined as the maximum allowed reactive power that can be consumed by the HV/MV transformer (denoted by positive sign) and $Q_{\mathrm{rpw,min}}$ provides set-points minimum allowed limits for reactive power export by the HV/MV transformer (denoted by negative sign). The reactive power control from both Q_{BESS} and Q_{wind} constitutes the overall Q_{flex}. The controller is designed in such a way that the Q_{flex} allocated shall control the reactive power flow in the TSO/DSO interface within $Q_{\mathrm{rpw,min}}$ and $Q_{\mathrm{rpw,max}}$ and

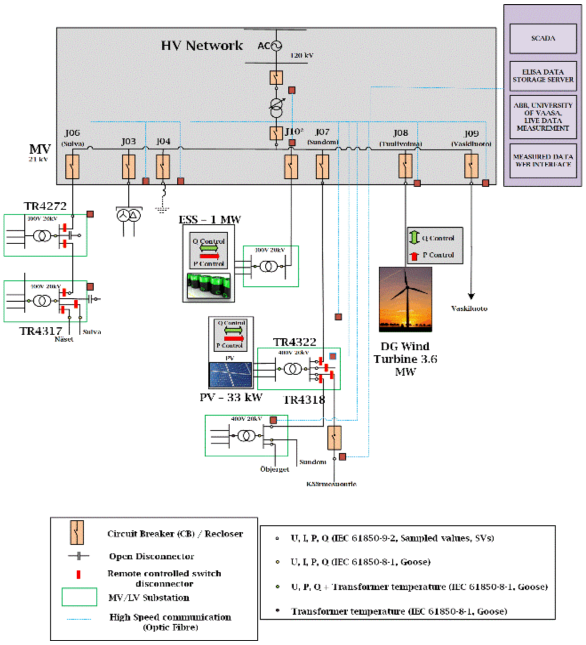

Figure 1. Sundom Smart Grid single line diagram

$$Q_{wind,min} \leq Q_{wind} \leq Q_{wind,max} \tag{1}$$

$$where, \begin{cases} Q_{wind,min} = -\sqrt{{S_{wind}}^2 - {P_{Wind}}^2} \\ Q_{wind,max} = \sqrt{{S_{wind}}^2 - {P_{Wind}}^2} \end{cases}$$

$$Q_{BESS,min} \leq Q_{BESS} \leq Q_{BESS,max} \tag{2}$$

$$where, \begin{cases} Q_{BESS,min} = -\sqrt{{S_{BESS}}^2 - {P_{BESS}}^2} \\ Q_{BESS,max} = \sqrt{{S_{BESS}}^2 - {P_{BESS}}^2} \end{cases}$$

$$Q_{flex} = \begin{cases} Q_{wind,max} + Q_{BESS,max}\,; (if\ U_{SUL} < 0.95\ PU\ and\ Q_{rpw,min} < Q_{MV} < Q_{rpw,max} \\ -(Q_{wind,max} + Q_{BESS,max}); (if\ U_{SUL} > 1\ pu\ and\ Q_{rpw,min} < Q_{MV} < Q_{rpw,max} \\ 0;\ (if(0.95\ pu < U_{SUL} < 1\ PU) \end{cases} \tag{3}$$

$$P_{dis} = \begin{cases} P_{Load} - P_{Wind};\ (if((P_{Load} - P_{Wind}) < 1\ MW) \\ 1C;\ (if\ SOC > SOC_{min}) \\ 0;\ (if\ (SOC) < SOC_{min})\ and\ P_{dis} > 1\ MW \end{cases} \tag{4}$$

$$P_{chg} = \begin{cases} 0;\ if\ SOC > SOC_{max} \\ P_{chg};\ if\ (SOC_{min} < SOC < SOC_{max}) \end{cases} \tag{5}$$

manage voltage at Sulva feeder, U_{SUL} which is considered as the reference MV voltage since it has been under maximum stress during the defined use cases. U_{SUL} is considered as the reference point for voltage control as it tends to have the highest voltage drop in base case simulation (explained in detail in section IV).

B. *Active Power Control*

Li-ion BESS discharge power (P_{dis}) is defined by logical conditions stated in (4), where it is designed to discharge power when the load requirement (P_{Load}) is higher in magnitude than P_{wind}. According to the first condition in the equation, the magnitude of P_{dis} is calculated as the difference between P_{Load} and P_{wind}, and this active power output is expected from Li-ion BESS, if ($P_{\mathrm{Load}} - P_{\mathrm{wind}}$) is less than 1MW. If ($P_{\mathrm{Load}} - P_{\mathrm{wind}}$) is higher than 1 MW, then P_{dis} magnitude is fixed at 1C rate, i.e. 1 MW, given the Li-ion BESSs state of charge (*SOC)* is higher than its minimum, SOC_{min}. If none of the two conditions is met, P_{dis} is set to 0 MW.

Li-ion BESS charging (P_{chg}) is defined by (5). P_{chg} is regulated by Li-ion BESS's *SOC,* which has to be regulated within the maximum *SOC,* SOC_{max}. According to the first condition in (5), Li-ion BESS must stop charging if the *SOC* reaches SOC_{max}. Charging operations are always undertaken if the ANM scheme requires it to do, when the *SOC is* between SOC_{max} and SOC_{min}.

C. *OLTC Tap Controllers*

In the developed ANM scheme, OLTC's are activated to regulate voltages when both active and reactive power controllers fail to provide the required voltage regulation defined by the grid codes in the MV distribution system. OLTC controller receives initial tap position, U_{MV} and U_{REF} as inputs. In order to maintain the MV feeder voltages within the grid codes, U_{REF} of 1pu is given as input, i.e. U_{MV} is meant to be controlled at 1pu. Based on U_{REF} and U_{MV}, required tap changes are calculated and executed by regulating the voltage at the MV side of the HV/MV transformer.

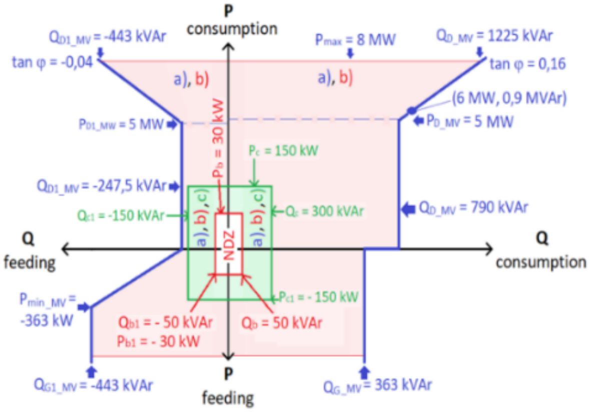

Figure 2. Reactive Power Window at HV/MV substation of SSG

IV. CASE STUDIES: FAST CHARGING OF BESS

Li-ion BESS characteristics used in the study is shown in Table I. In this use case, Li-ion BESS is charged at a rate of 2C, equivalent to 2 MW charge power, which is considered as fast charging method for a 1MW nominal power Li-ion BESS, during low renewable energy generation. The effects of charging at 2C during low wind power generation has been observed and then addressed by the ANM schemes to mitigate their detrimental effects. Two sub-cases are defined, where the first one shows the strain of charging power on the MV distribution network without any ANM schemes and the second sub-case shows effect of ANM principles on the MV network stability.

Table I. Li-ion BESS characteristics

Lithium Ion Battery Characteristics	
Nominal DC Voltage	311 V
Peak Voltage	353 V
Cut-off Voltage	235 V
Discharge Power (1C)	1 MW
Nominal Discharge current (1C)	2832 A
Peak Discharge current (3C)	8496 A
Inverter Size	2.5 MVA

A. *Without ANM*

Fig 3(a) shows P_{BESS} and Q_{BESS} characteristics of the Li-ion BESS from its MV feeder (J10). BESS is charged with 2 MW power (positive symbol denotes battery charging) and its reactive power control has been deactivated. P_{wind} is shown in Fig 3(b) and the Q_{wind} contribution from wind turbine has been unused in the base case evaluation. Fig 4(a) depicts the active power characteristics at the MV side of the HV/MV transformer. Negative symbol states that the active power is consumed by the MV distribution system. Reactive power characteristics are shown in Fig 4(b). It is observed that the Q_{MV} is higher than the threshold defined by the RPW limits set by FINGRID.

Fig. 5 represents the voltages (pu) at various MV feeders in the MV distribution system of SSG. It is observed that the MV voltages are well within the threshold defined by the grid codes, except the voltages at the Sulva and Sundom feeders. U_{SUL} and U_{SU} was seen to be lower than 0.95 pu throughout the simulation period in the base case evaluation. Hence, both MV feeder voltages and RPW limits were distorted in the use case without ANM schemes.

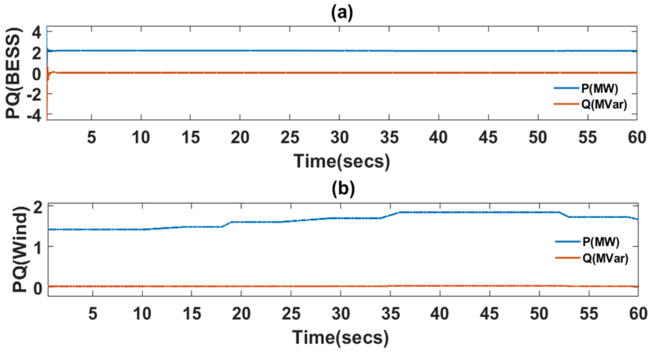

Figure 3. Simulation results (Without ANM): (a) BESS Active and reactive power characteristics (b) Wind Active and reactive power characteristics

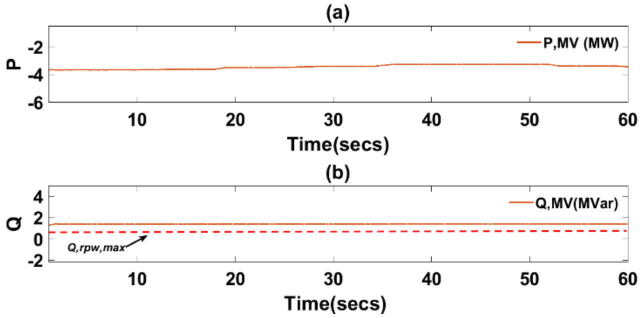

Figure 4. Simulation results (Without ANM): (a) MV bus Active power (b) MV bus reactive power

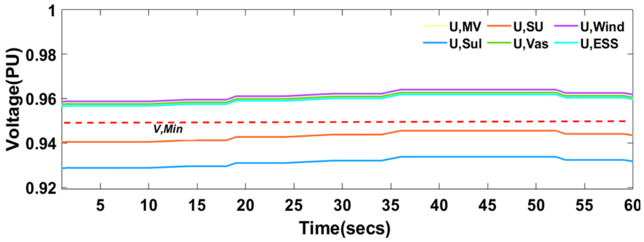

Figure 5. Simulation results (Without ANM): MV bus voltages

B. *With ANM*

Fig 6(a) shows the active P_{BESS} and Q_{BESS} characteristics of the Li-ion BESS from its MV feeder (J10). BESS is charged with 2 MW power and its maximum reactive power allocation have been activated according to the ANM schemes. Allocation from the Q_{BESS} has been designed as per (2). P_{WIND} is shown in Fig 6(b) and Q_{wind} contribution from the wind turbine has been utilized to maximum, as designated by (1), to stabilise MV feeder voltages. Fig 7(a) depicts the active power characteristics at the MV side of the HV/MV transformer. Reactive power characteristics are shown in Fig 7(b). It is observed that the Q_{MV} has been reduced in magnitude and currently well within the threshold defined by the RPW limits from FINGRID.

Fig. 8 represents the voltages in pu at various MV feeders in the MV distribution system of SSG. With the reactive power control alone, it is evident that the voltage at U_{SU} had been improved within the grid code requirements after Q_{flex} has been allocated as per first condition in (3). However, U_{SUL} still has a magnitude less than 0.95 pu, and hence the tap position changes in the OLTC transformer after 5 seconds into simulation, thereby regulating all MV feeder voltages within limits.

Fig. 9 explains DC characteristics of the Li-ion BESS and its adjoining power electronic converters for MV grid integration. BESS charge/discharge current characteristics are shown in Fig 9(a), where magnitude of defined BESS current, in this case the BESS charge current. Fig 9(b) depicts the changes in BESS operational voltage. Overall, BESS DC charge power is shown in 9(c), BESS *SOC* behaviour is presented in Fig 9(d). DC- bus voltage is constantly maintained at 600V, despite frequent variation of BESS voltage and current rate to the DC/AC- converter stage as shown in Fig. 9(e), thereby, reinforcing robust BESS model and adjoining converter controller design for 2 MW charge power at low

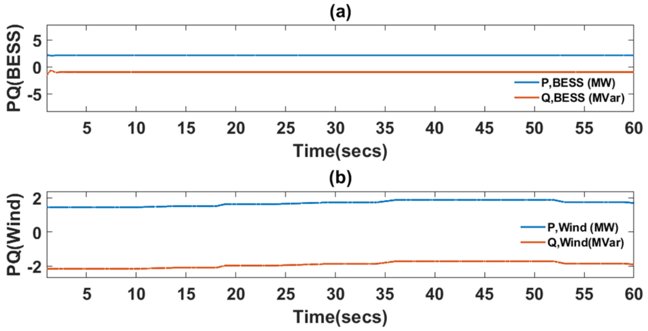

Figure 6. Simulation results (With ANM): (a) BESS Active and reactive power characteristics (b) Wind Active and reactive power characteristics

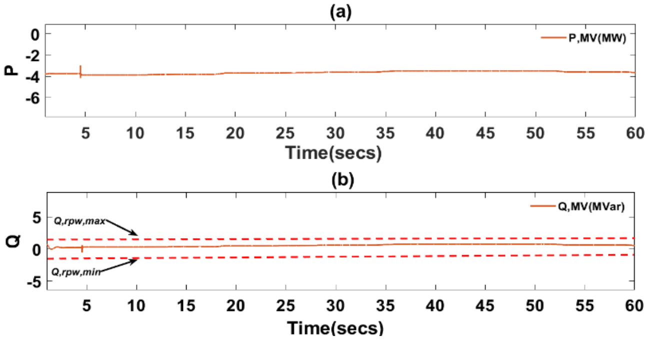

Figure 7. Simulation results (With ANM): (a) MV bus Active power (b) MV bus reactive power

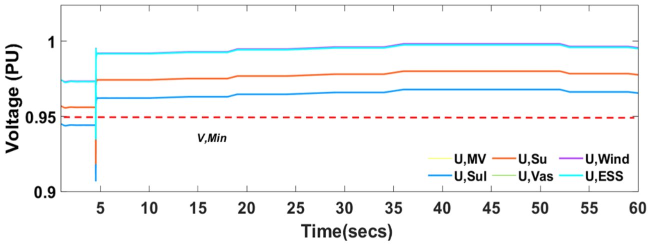

Figure 8. Simulation results (With ANM): MV bus voltages

WTG output. The ambient temperature of battery operations is assumed to be 25 ^{o}C which is represented in Fig 9(f). Recorded field temperature measurements will be introduced in the future studies. Accurate Li-ion BESS and its integration modelling was important to understand the effects of AC loadrequirements on the DC characteristics of the battery, especially to regulate their operation within safe limits while maintaining DC bus voltage stable.

V. CONCLUSION

Role of Li-ion BESSs as flexible energy sources in such distribution networks are multi-faceted considering their participation in both active and reactive power related flexibility services. The use case of fast charging of Li-ion BESSs, especially during low renewable power generation induces its own strain in the distribution system in the form of voltage distortions and reactive power flows barring the RPW limits of the SSG. In such cases, active network management schemes provide a basis to mitigate arising network stability issues by actively managing available flexibilities in the MV distribution network of the SSG, where penetration of inverter based flexible energy sources are increasing at a faster pace.

In this study, the ANM schemes were modelled to utilise the entire range of reactive power control possibility, due to the extremeness of the use case. Table II provides a summary of the simulation results and an indication on how the flexibility indices have been utilised based on the equations, (1)-(5) which forms the basis of ANM control schemes. Q_{wind} and Q_{BESS} were allocated based on their maximum limits defined in (1) and (2) respectively. From the results, it is indicative that the Q_{flex} based on (3), was instrumental in keeping the reactive power flow, Q_{MV} between HV/MV grids, within the limits specified by the RPW. Since, this case was investigating the effects of fast charging, (4) which provides set-points for discharging were unutilized. With respect to the results of

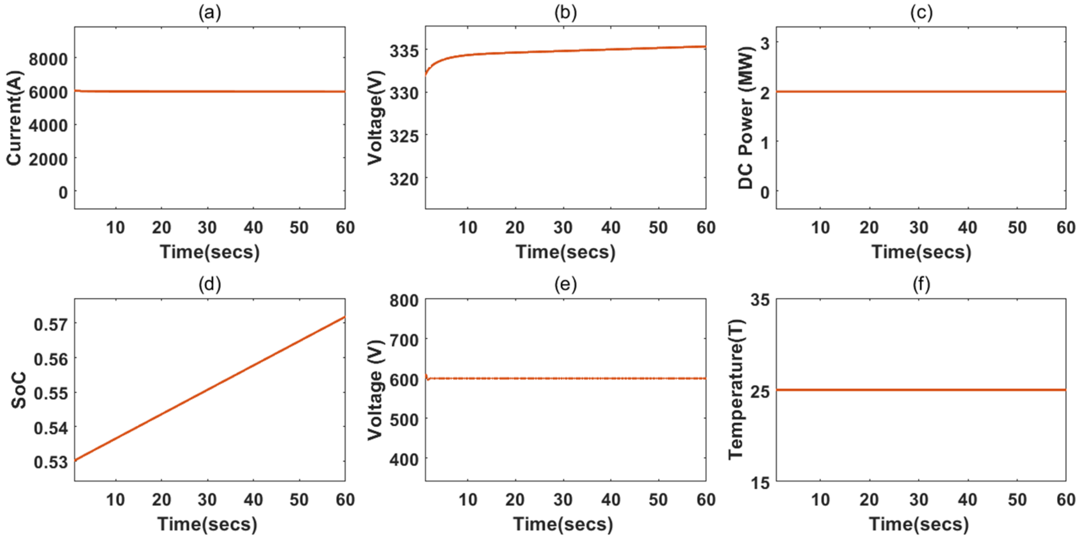

Figure 9. (a) BESS Current (b) BESS Voltage (c) BESS DC Power (d) BESS *SOC* (e) DC Bus voltage (f) Ambient operational temperature

Table II. Simulation Result Summary

Simulation Step	**5 Secs**		**10 Secs**		**20 Secs**		**30 Secs**		**40 Secs**		**50 Secs**		**60 Secs**	
Flexibility Indices	**No ANM**	**ANM**	**No ANM**	**ANM**	**No ANM**	**ANM**	**No ANM**	**ANM**	**No ANM**	**ANM**	**No ANM**	**ANM**	**No ANM**	**ANM**
Q_{BESS} **(Mvar)**	0	0,5	0	0,5	0	0,5	0	0,5	0	0,5	0	0,5	0	0,5
Q_{wind} **Mvar)**	0	2,05	0	2,05	0	1,96	0	1,92	0	1,88	0	1,88	0	1,94
Q_{flex} **(Mvar)**	0	2,55	0	2,55	0	2,46	0	2,42	0	2,38	0	2,38	0	2,44
Q_{MV} **(pu)**	**1,8**	**0,43**	**1,8**	**0,44**	**1,8**	**0,45**	**1,8**	**0,44**	**1,8**	**0,46**	**1,8**	**0,46**	**1,8**	**0,45**
U_{SUL} ***(pu)***	**0,924**	**0,938**	**0,924**	**0,96**	**0,93**	**0,962**	**0,932**	**0,963**	**0,934**	**0,965**	**0,934**	**0,965**	**0,933**	**0,963**
U_{SU} ***(pu)***	**0,94**	**0,955**	**0,94**	**0,975**	**0,942**	**0,976**	**0,943**	**0,976**	**0,945**	**0,978**	**0,945**	**0,978**	**0,944**	**0,977**

voltage limits at various MV feeders, it has been evident that the voltages at Sulva and Sundom feeders were below 0.95 pu without any ANM schemes operational. However, with the allocation of Q_{flex}, voltage at the Sundom feeder improved, but Sulva was still barring the MV voltage limits. Hence, at about 5 seconds into simulation, OLTC were activated, thereby improving the voltage at Sulva feeder. Therefore, the designed ANM scheme, acted as required to provide RPW and voltage regulation. In future, more adaptive and accurate ANM schemes will be designed and modelled for real-time simulations to optimise the control of flexible energy sources in the MV distribution systems.

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