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***Abstract*— This paper presents an investigation and design of a unified control framework of a battery energy storage system (BESS) for the electrification of different Distributed Energy Resources (DER) assets. The preliminary challenge is that BESS should operate in both grid-connected and standalone modes while ensuring a seamless transition between the two modes and efficient power distribution between the load, the battery, and the grid. So, having a unified controller scheme deployed in suitable compliant controller hardware is highly desired. Additionally, it is vital for suitable integration and operation of BESS into different grid and load conditions. This approach is different from the conventional methods found in literature, which use a different individual controller for each of the modes. Instead, in this work, a single unified controller is proposed. The unified controller framework is evaluated in the simulation of different case studies. The results disclosed that the proposed control scheme gives good dynamic responses to grid power events and load variations.**

Keywords— Energy storage, Grid-forming, Grid-connected inverter, Virtual Synchronous Generator (VSG), Control methods for electrical systems.

I. INTRODUCTION

Power systems are going through the evolution from a substantial share of conventional power generation to massive renewable resources interfaced by power electronics. The growth of DER, such as solar and wind power, presents both challenges and opportunities for different stakeholders like utilities, integrators, and Independent Power Producers (IPP). When effectively managed, DER can help different stakeholders reduce peak power consumption, avoid costly system upgrades, and improve the flexibility of the grid. Left unmanaged, DER can disrupt utility operations and unbalance the grid, but integration presents a major challenge for utilities due to cost, regulatory, and operational challenges [1]. DER can be owned and controlled by utilities, third parties or end consumers, creating complexities that further hinder DER integration [2]. As universally acknowledged, a large deployment of inverter-based generation is foreseen that governs lower grid inertia levels and the identification of assets capable to maintain the power balance [1]. Various power systems are already facing this control challenge. In this context, converter-interfaced BESS is promoted as a possible answer for grid frequency regulation (e.g., [3]) due to their large ramping rates, high round-trip efficiency, and commercial availability [4]). Effective management of DER requires BESS solutions that address these complications, accommodating two-way energy flows on the system, avoiding renewables from overcapacity of the system, and providing consumers the data and congruent tools to contribute entirely to power quality improvement activities. Recently installed large BESS, like the 100 MW/129 MWh unit of the Hornsdale Power Reserve (HPR) in Australia and

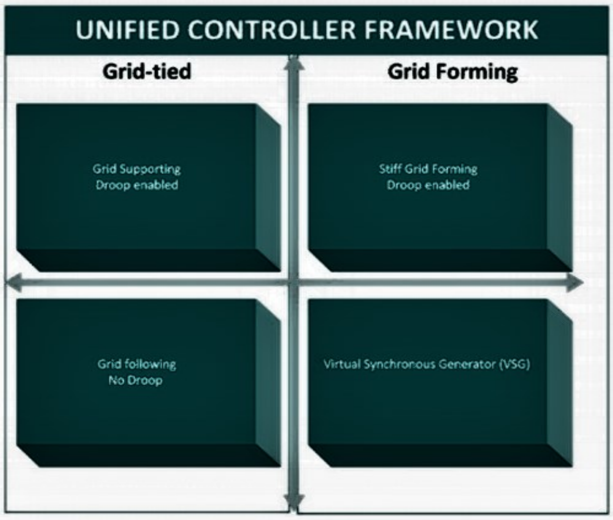

Fig. 1 Structure of Unified Controller Framework

the 300 MW/1200 MWh unit at Moss Landing in California), have revealed the pertinence of this technology in real-world contexts. As BESS can provide substantial worth to multifunctional facilities (both frequency containment and restoration services), quantitatively assessing their performance is of essential importance [2]. Outside autonomous islanded systems, energy storage brings considerable benefits in numerous applications including residential, industrial and commercial facilities [3].In [4], the proposed automated generation control (AGC) scheme assigns BESS capacity to secondary frequency regulation. Moreover, Technoeconomic control is correspondingly presented in the literature [5] showing different behaviour patterns [6] of battery systems.

Considering the standardization [7] aspect, IEEE Standard 1547 [8] outlines the inverter's primary control useful foundations that can be primarily grouped in two operative provisions: (i) Grid-Following Operation or Grid Support Mode (GSM) and (ii) Grid-Forming Operation. In GSM, the inverter is controlled as a current source in which the main control goals are to supply the load (linked to the microgrid) and to contribute to frequency and voltage support [9]; due to these motives, GSM is the typical configuration in a grid-tied state.

Through the high penetration of inverter-interfaced resources there is a reduction of total inertia as well as damping since most of the anticipated control methods for grid-forming inverters, e.g., droop control methods [10], provide hardly any inertia or damping support for the microgrid. That's why, one of the most performing primary control techniques for grid-forming inverters is the VSG mode [11] where the control operates on the inverter to imitate the

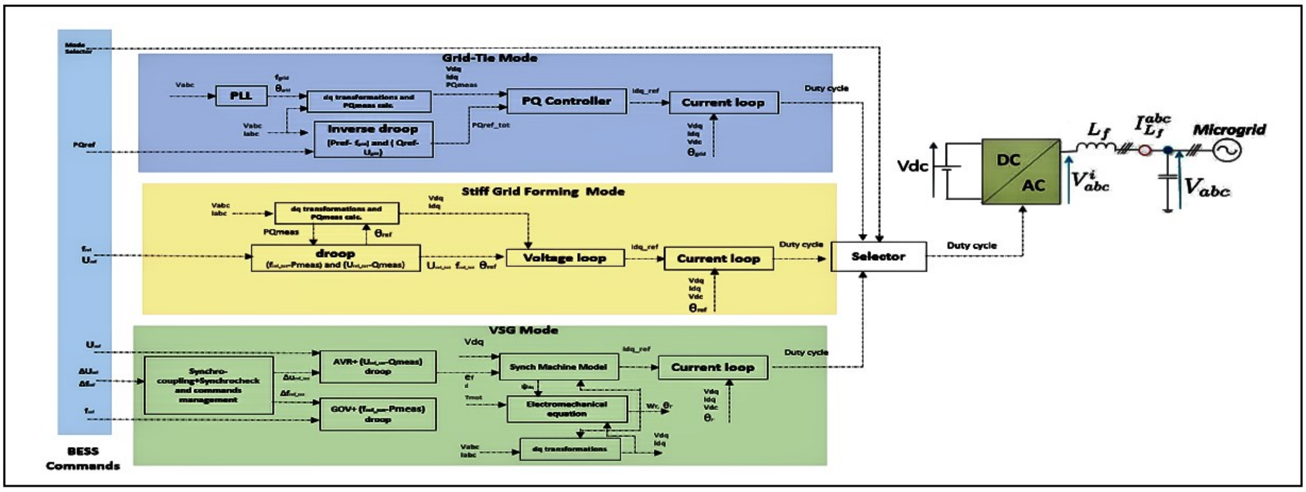

Fig. 2 BESS Unified Controller Architecture

[12, 13] effectively adding inertia and frequency damping to the system's dynamical behaviour of a conventional synchronous generator and consequently, improving microgrid stability, because inertia response is the consequence of rotating heavy mass and it is proportional to the rotor speed, the VSG concept can also directly improve the frequency response [14].

The main distinguishing feature of the unified controller is defined by the ability to guarantee:

- Accurate active and reactive power-sharing in parallel with other DER

-Fast control actions in grid-tied mode to allow providing frequency and voltage support (GSM) as well as power control following the reference signals from the secondary level control (for instance Power Management System).

- Synchronization and linking of the BESS to the external main grid or other DERs in islanded mode with minimum transients.

The rest of the paper is structured as follows. Section II presents the Unified Simulation Framework. Section III illustrates the result and discussion through study cases and simulation results as well as associated discussion, finally Section IV concludes the paper.

II. Unified Simulation Framework

The structure of the Unified Controller Framework is shown in Fig.1. and the architecture of the BESS Unified Controller is presented in Fig.2. BESS encompasses a DC/AC inverter, and DC/DC converter that interfaces BESS to the DC bus. The BESS is required for the following reasons: to accumulate the energy essential for inertia emulation, to uncouple the DERs from the AC microgrid by smoothing out the renewables power disparities, and to deliver some spinning reserve (in case of VSG) inverter that remains working appropriately throughout the time required to initiate another DER for example real genset when there is a higher level of reduction in renewables production. The control embedded in the DC/DC DSP (Digital Signal Processor), controlling the DC/DC converter, is not addressed in this paper because of the lack of space. The model has been developed and simulated using Matlab/Simulink® environment and evaluated under grid-tied and grid-forming

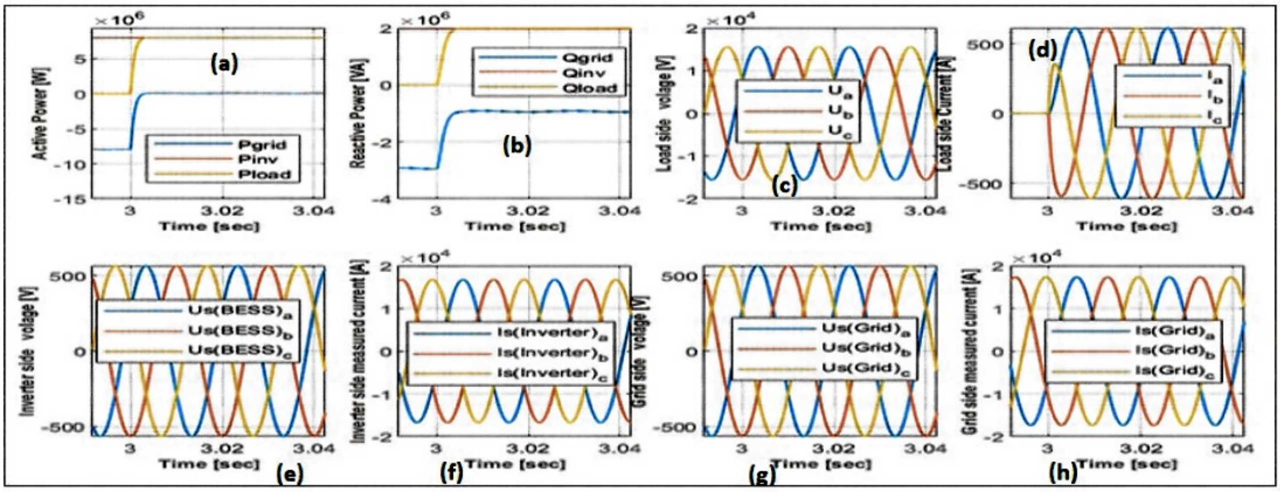

Fig.3 Subsequent response within Grid following mode active power reference value of 8 MW and reactive reference value of 2MVar.Complete response is shown in (a) Active Power, (b) Reactive Power (c) Load Side Voltage, (d) Load Side current (e) Inverter Side Voltage, (f) Load Side current (g) Grid Side Voltage, (h) Grid Side current.

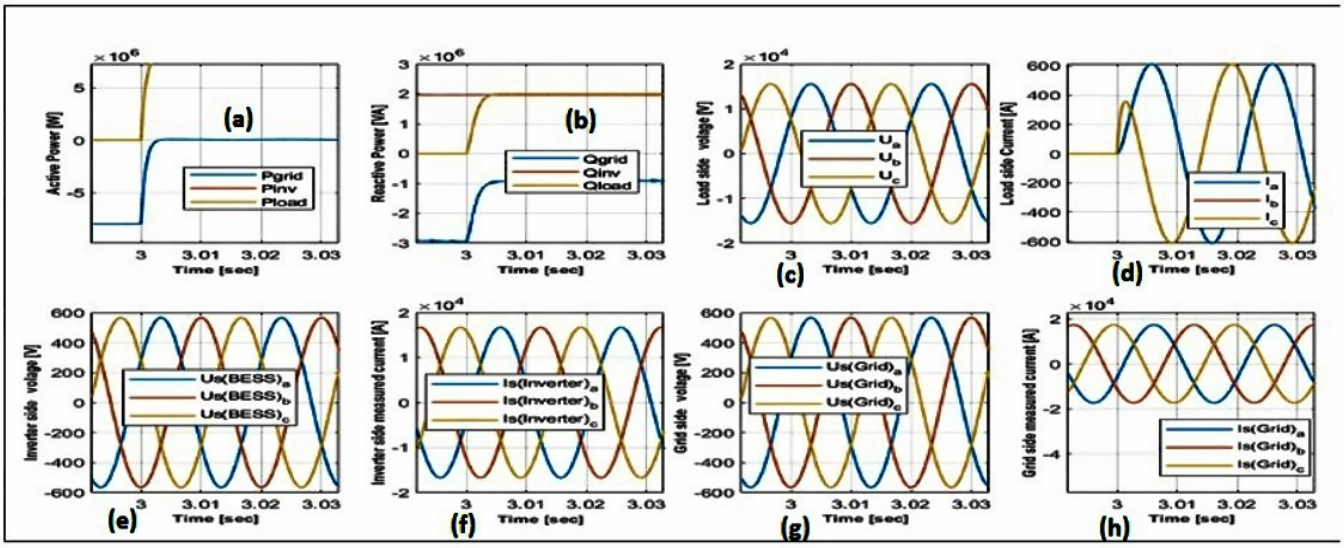

Fig.4 Subsequent response within Grid-supporting mode following active power reference value of 8 MW and reactive reference value 2MVar.response following Transition. (a) Active Power, (b) Reactive Power (c) Load Side Voltage, (d) Load Side current (e) Inverter Side Voltage, (f) Load Side current (g) Grid Side Voltage, (h) Grid Side current.

operation modes. The controller schemes and their brief mechanisms are described in the following sections.

III. Results and Discussions

In this section, the simulation outcomes for several practical use cases are presented and remarked on. These results highlight the dynamic performances of the presented unified BESS control framework under different transient conditions. The BESS inverter can work both in grid-tied and in grid-forming mode ensuring the possibility to work in parallel with other DERs or an external main grid (refer to Fig.2).

A. Pass/Fail Criteria

How the system responds to a sudden perturbance is vital because large and probably fast deviations from the long-term steady-state may cause extreme effects on the system itself and other portions of the overall system reliant on that. Furthermore, the overall system cannot act until the BESS component's output settles down to the approximate vicinity of its final state, delaying the overall system response. Recognising the response of a dynamical system gives evidence of the stability of such a system, and its ability to reach one stationary state when starting from another [9].

Overshoot is an additional reference to the transient values of any parametric measurement that exceeds its steady-state or final value through its evolution from one value to another. Besides, in terms of the application of the term overshoot, is the time elapsed from the application of an ideal instantaneous step input to the time at which the output has entered and remained within a specified error band according to the grid code [8].

A significant feature of grid-connected power generating facilities is the Fault Ride-Through (FRT) or Low Voltage Ride-Through (LVRT) capability, which indicates the capability of the generation unit remaining coupled to the grid in the exposure of grid fault, and of delivering active power directly after clearing the fault, consequently, stabilizes the grid. The voltage dip is stipulated that the generating unit in France must remain connected during voltage dips down to a minimum of 0% and resume back to 50% of nominal voltage in 150ms.

To validate its performance and demonstrate its advantages, the proposed framework is simulated with different regulatory control approaches.

B. Grid-tied operation

Grid-following controlled inverters depend on externally generated voltages by synchronous machines to function, which is mainly composed of phase-locked loop (PLL) (utilised to guess the instantaneous angle of the measured inverter terminal voltage, which delivers the angular reference of the current commands and conveys the grid-following actions) and a current-control loop to adjust the AC part of the current inserted into the grid. Like this, the grid-following AC terminals mimic a current source tracking the reference of real and reactive output. For fixed power commands, an inverter acts as a constant *PQ* source [9]. A change in the system frequency will immediately be tracked by a change in the droop curve position on the power axis. The droop curve oscillates up or down subject to the system frequency adjustment to maintain the output power constant. Thus, given the entire system, the grid-following element just provides predefined power at the output and has no standalone capabilities. In a grid-following inverter, the current introduced by the inverter is regulated with a specific phase displacement from the grid voltage at the point of common coupling (PCC) [8]. Consequently, the information of the fundamental frequency phasor of the grid voltage is required at any time for the accurate calculation of the inverter's reference current, whose amplitude and angle regarding the grid voltage phasor are appropriately adapted by outer control loops to inject the essential quantity of active and reactive power or control the RMS voltage [9].

Grid-Following Mode

The results are shown in Fig. 3 and the corresponding results are tabulated in TABLE I.

Grid Supporting Mode

The results are presented in Fig. 4 and the corresponding results are organised in TABLE II.

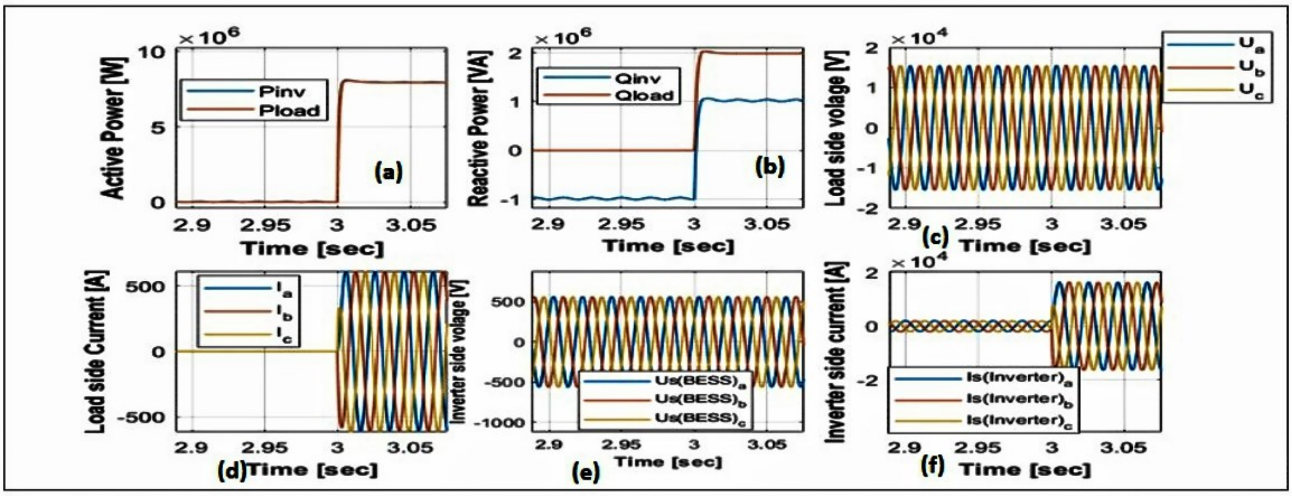

Fig.5 Stiff Grid forming operation under load impact of 8 MW active and reactive power of 2 MVar. Response following Transition is shown in (a) Active Power, (b) Reactive Power (c) Load Side Voltage, (d) Load Side current (e) Inverter Side Voltage, (f) Inverter Side current.

TABLE I. RESULTS OF UNIFIED BESS CONTROL FRAMEWORK IN GRID-FOLLOWING MODE

Grid-tie mode: Droop Disabled (Grid-following)				
Test condition	***Setpoint***		***Test Step***	Qualitative check ***(Pass/Fail)***
	P_{ref} *MW*	Q_{ref} *Var*		
Charging (Load 10 *MW*)	10	0	Basic BESS charge functionality with 10 *MW* load	Pass
Discharging (Load 10 *MW*)	10	0	Basic BESS discharge functionality with 10 *MW* load	Pass
Check positive reactive power capability	8	4	Check BESS reaction with positive reactive power	Pass
Check negative reactive power capability	8	-4	Check BESS reaction with negative reactive power	Pass

The voltage undershoots in all cases conform with the grid code and resume back to no less than 50% in 150ms after the grid event.

C. GRID-FORMING OPERATION

Grid-forming operations are initiated by inverter controller which adapts instantaneous terminal voltages and can coexist with other inverters and synchronous generators in the same system.

Stiff grid-forming mode

The grid-forming inverters perform as voltage sources that output tracks droop laws that are referred to as the stationary droop characteristics of the *P-ω* (real power-frequency) as well as *Q-V* (reactive power-voltage) relationships. Mutually frequency and voltage references are sent as constant setpoints. An alteration in the system frequency affects the inverter power output change. Grid-forming controllers do not encompass a PLL, moreover, in VSG case, it can emulate the kinetic energy and the self-synchronization characteristics of synchronous machines through robust control of voltage and frequency. Grid-forming inverters can assist in load sharing/ drooping, black-start, inertial response, and hierarchical frequency/voltage regulation.

Droop controllers display a linear trade-off between frequency and voltage versus real and reactive power, the same as a distinctive synchronous machine does in a steady state. Droop control permits controlling properties as follows [10]: System-wide synchronization (All units reach the same frequency), Power-sharing (Each unit provides power in proportion to its capacity or its programmable droop slope).

TABLE II. RESULTS OF UNIFIED BESS CONTROL FRAMEWORK IN GRID SUPPORTING MODE

Grid-tie mode: Droop Enabled (Grid Supporting)				
Test condition	***Setpoint***		***Test Step***	Qualitative check ***(Pass/Fail)***
	P_{ref} *MW*	Q_{ref} *Var*		
Charging	10	0	Basic BESS charge functionality with 10 *MW* load	Pass
Charging (Load 10*MW*)	10	0	Basic BESS discharge functionality with 10 *MW* load	Pass
Check positive reactive power capability	8	4	BESS positive reactive power functionality with 10 *MW* load	Pass
Check negative reactive power capability	8	-4	BESS negative reactive power functionality with 10 *MW* load	Pass

In the case of a grid-forming element, the magnitude and angle of the voltage at the PCC are controlled. Consequently, the information of the fundamental frequency phasor of the grid voltage at the point of connection is not firmly essential. Depending on the features of the network with that the inverter is associated, whether it is an isolated system or a

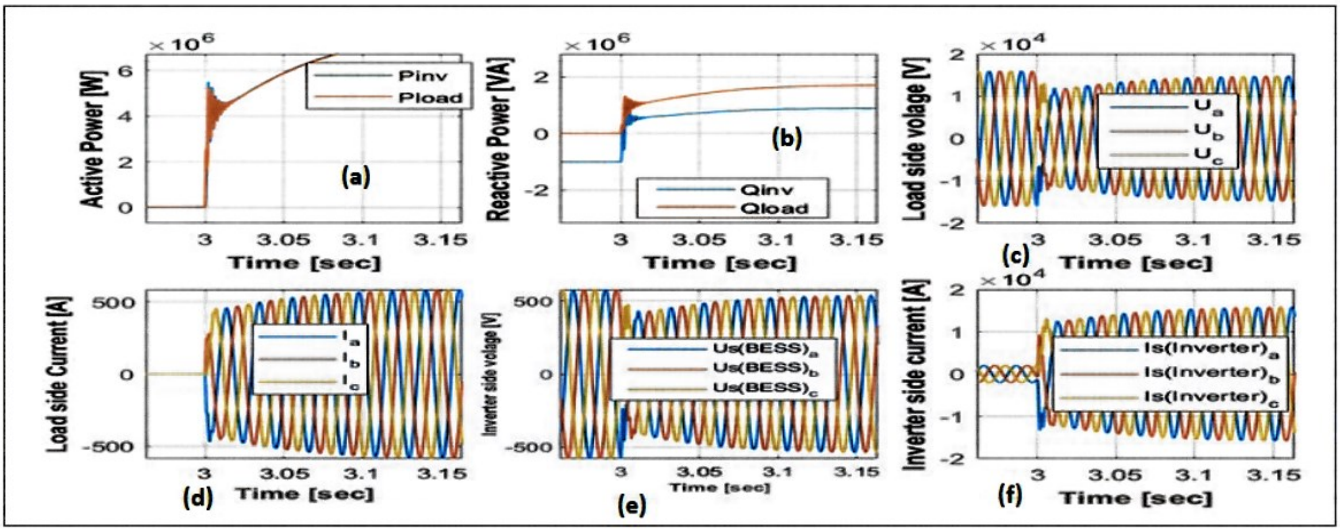

Fig.6 VSG behaviour under load impact. Complete response is shown in Response following Transition is shown in (a) Active Power, (b) Reactive Power c) Load Side Voltage, (d) Load Side current, (e) Inverter Side Voltage, (f) Inverter Side current.

slack bus, it is probable exploiting additional outer loops to adapt the injected instantaneous active and reactive power. Consequently, it assists to provide voltage and frequency support. In the case of an isolated system, a grid-forming unit could perform itself like a slack bus [10]. Once linked with other power sources, within an inductive line, the grid-forming inverter is directing the active power by the adjustment of the angle. The voltage magnitude is self-regulating by the active power control [10]. The results are presented in Fig. 5 and the corresponding results are organised in TABLE III.

TABLE III. RESULTS OF UNIFIED BESS CONTROL FRAMEWORK IN STIFF GRID-FORMING MODE

Stiff grid-forming mode			
Test condition	***Setpoint***	***Test Step***	Qualitative check ***(Pass/Fail)***
No Load test	The load is commented out	Basic BESS functionality with No Load	Pass
Resistive load impacts	Active Power=10 MW Reactive Power=0 MVar	BESS functionality with 10 MW Resistive loads	Pass
inductive load impacts	Inductive Power=8e6 MVar	BESS functionality with 8MVar inductive load	Pass
resistive and inductive load impacts	Active Power=8 MW Reactive Power=4 MVar	BESS functionality with 10 MW Resistive loads and 4MVar inductive load	Pass

VSG mode

The virtual synchronous machines are established on the emulation of a synchronous machine within the controls of inverter realisations that capture the dynamics of an emulated rotor and its steady-state P-ω droop [10]. The realised model has been described thoroughly in [15]. The results are presented in Fig. 6 and the corresponding results are organised in TABLE IV.Fig.6 shows the transient behaviour of a VSG inverter under a resistive and inductive load impact. The curves of the phase-to-phase voltages (See Fig.6), current and frequency are characteristic of a real genset of the equivalent power. During the first milliseconds following the load impact, the sub transient and transient reactances of the VSG impose the dynamics of the output voltages and currents, then after approximately 100-200 ms, the effect of the Automatic Voltage Regulator (AVR) on voltage regulation appears since the RMS output voltage progressively converges towards its setpoint.

TABLE IV. RESULTS OF UNIFIED BESS CONTROL FRAMEWORK IN VSG MODE

VSG mode			
Test condition	***Setpoint***	***Test Step***	Qualitative check ***(Pass/Fail)***
No Load test	Check no-load impact	Basic BESS functionality with No Load	Pass
R load impacts	Active Power=10 *MW*	BESS functionality with 10 *MW* Resistive loads	Pass
Try to see inductive load impacts	Inductive Power=8 *MVar*	BESS functionality with 8*MVar* inductive load	Pass
Try to see resistive and inductive load impacts	Active Power=8e6 *MW* Positive Reactive Power=4 *MVar*	BESS functionality with 10 *MW* Resistive loads and 4*MVar* inductive load	Pass

D. Discussion

This research study only evaluates the post-disturbance performance of BESS under a single system action point. The likely effects of different inverter controls are considered. In this framework, this paper contributes to the current state of the art by explicitly modelling the BESS dynamics and comparing grid-forming and grid-following control approaches. Building upon current research on BESS contribution to secondary regulation, this paper provides a comprehensive solution in the time scale of seconds to minutes. An essential difference from other arrangements presented in the literature, the shown framework is simple, scalable, and easy to apply in real-life systems, its tuning is undemanding, and it is compatible with different market and regulatory environments. However, the BESS is modelled as an ideal power source and falls short of capturing the dynamic interactions between the converter and the grid. In this work, the state of charge (SoC) regulation method [16] is not taken into consideration the effect that BESS setpoint variations may have on system reserves.

IV. Conclusion

In this paper, the unified controller framework of the power grid has been modelled and simulated to assess the performance of grid-forming and grid-following inverter-interfaced with BESS for enhancing power quality. Simulations demonstrate that this unified BESS controller is capable of significantly improving the system voltage and frequency containment i.e., improving the power quality of the grid. The results are quantitatively verified, employing suitably defined metrics, that the grid-forming control strategy outperforms the grid-following one achieving better power quality and offering greater flexibility for integration. In grid-forming mode, BESS can synchronize and connect BESS inverter to the external main grid or other DERs with minimum transients and guarantee proper active/reactive power-sharing among other DERs. Moreover, simulations showed that the proposed unified control can provide fast control actions also in grid-connected mode to allow providing frequency and voltage support (GFM-*fV*) as well as power control following the reference signals from the secondary level control (Grid supporting-*PQ*). Future works will be focused on the transitions between the two operating modes to provide system stability during planned or unplanned islanding or during the reconnection of the main grid.

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