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HESS Management for Virtual Inertia, Frequency, And Voltage Support Through Off-Board Ev Bidirectional Chargers

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Abstract:

The massive integration of renewable energies into the grid using fast- response converters without inertia generates issues such as inertia reduction, temporary voltage violations, and power quality reduction. The system inertia reduction is a critical problem that could lead to grid frequency exceeding the acceptable range, resulting in undesirable load-shedding or even large-scale blackouts. To overcome these issues, the use of electric vehicle bidirectional chargers (EVBCs) implementing functionalities such as distributed virtual inertia (VI), long-term frequency support, voltage support by reactive power, and harmonics compensation, has been proposed as a possible solution. This article proposes a novel control strategy to manage a hybrid energy storage system (HESS) composed of dc-link capacitors and battery, through an isolated two-stage ac–dc converter (composed of a dual active bridge resonant type dc–dc converter cascaded to a voltage source inverter), intended for off-board EVBCs. The HESS management allows decoupling of the active power dynamic response since dc-link capacitors supply the fast dynamic response for VI support whereas the battery supplies the slower dynamic response for long-term frequency support, respectively. Hence, the VI support does not affect the battery lifetime. Simulations and experimental results are presented for a 2.5 kW prototype to validate VI, frequency-voltage support along with harmonics compensation.

INDEX TERMS: **Electric vehicles, off-board, bidirectional chargers, virtual inertia (VI), hybrid energy storage system (HESS), frequency support, reactive support, harmonics compensation**

1.INTRODUCTION

Electric vehicles bidirectional chargers implementing vehicle-to-grid (V2G) functionalities have been proposed as a possible solution to compensate voltage and frequency variations in distribution grids having a high integration of renewable energies. Mostrenewable energy systems are connected to the grid through inertialess power electronics converters, leading to a decrease in the overall system inertia and consequently to deviations of frequency beyond the acceptable range, resulting in undesirable load-shedding or even large- scale blackouts. These frequency variations can be quantified by two parameters: the time derivative of the frequency, known as rate- of-change-of-frequency (RoCoF), and the minimum value of the frequency during the transient period, known as frequency nadir which are shown in Fig. 1. To overcome this problem, researchers have proposed the concept of virtual inertia (VI) which consists of the integration of an energy storage system (ESS) into the grid to emulate the synchronous generator behavior by grid-connected converters (GCCs), commonly called grid forming converters (GFM)However, since GCCs with GF control strategies are controlled as a voltage source, the direct control of the ac voltage without an inner current control loop may lead to difficulties in dealing with voltage drop faults, generating over currents and stability problems, making these solutions challenging to integrate into distribution grids. Furthermore, most of the GFM strategies are intended for generation systems that consider large ESSs. The situation is quite different at the distribution level where the total cost is an important constraint. As an alternative, the distributed virtual inertia (DVI) concept was proposed in, which is based on several small contributions from individual GCCs through stored energy in dc bus capacitors. Since most GCCs at the distribution level are current-controlled converters, also known as grid following converters (GFL), the GFL VI approach appears more suitable to supply DVI in distribution grids. However, since stored energy in dc- link capacitors is limited, the full frequency support including long- term frequency support requires an ESS with higher energy density. Batteries have higher energy density compared to capacitors. Hence, since electric vehicles (EVs) remain plugged into the grid most of the day, EV batteries along with their bidirectional chargers (EVBCs) present a high potential to supply both VI and long-term frequency support. However, according to the state-of-the-art review, very few studies have been carried out to integrate VI support in EVBCs. Moreover, the fast-dynamic response of active power required for VI implementation would decrease the battery lifetime. To overcome this limitation, in a hybrid energy storage system (HESS) is proposed. The dc-link capacitors supply the faster dynamic response for VI support, whereas the battery supplies the slower dynamic response for long-term frequency support. Moreover, the HESS is controlled through a non isolated two-stage ac–dc converter composed of a bidirectional boost dc–dc converter cascaded to a voltage source inverter (VSI) implementing a GFM control strategy. Nevertheless, since typical EVBCs implement GFL control strategies and its power structure is based on a dual active bridge (DAB) dc–dc for galvanic isolation novel control strategies along with different procedures to size the dc-link capacitors should be developed to implement VI and long- term frequency support.

In this context, this article introduces a novel design and control approach for an isolated two-stage ac–dc converter intended for EVBCs, having the capability of managing a HESS to supply both, VI (fast response) and long-term frequency support (slow response). However, since dc-link capacitance could be increased to implement VI, the volume of the ac–dc converter could be increased also. Hence, the proposed control strategy is intended for off-board EVBCs or for stationary batteries grid-connected where the reduced volume is not a critical parameter. Therefore, the main contributions of this work are as follows. 1) An enhanced GFL VI for practical implementation is introduced. In the proposed method, the dc-link capacitor is sized considering the maximum allowed extra power to deliver VI support, and the overshoot in estimated frequency by the phase-locked loop (PLL) is minimized. 2) A novel control strategy to manage a HESS through an isolated two-stage ac–dc converter is proposed, where dc- link capacitors supply the fast-active power response for VI, whereas EV battery covers the long-term frequency support with slower dynamics. Moreover, reactive power support and harmonics compensation are also implemented to cover full V2G support. The rest of this article is organized as follows: Section II briefly explains the traditional GFL VI approach. Section III presents the practical limitations to implementing VI in two stage ac–dc converters. Section IV presents the proposed control strategy to manage the HESS for frequency and voltage support. Section V presents the design of a reduced-scale 2.5 kW prototype.

2. LITERATURE SURVEY

Jhonatan D. Paucara, José Carlos U. Peña, and Damian Sal y Rosas (2024) This paper proposes a novel control strategy to manage a HESS composed of DC-link capacitors and batteries through an isolated two-stage AC–DC converter in off-board EV bidirectional chargers. The strategy allows decoupling of active power dynamic response, with DC-link capacitors providing fast dynamics for virtual inertia support and batteries supplying slower dynamics for long-term frequency support, thereby enhancing grid stability without compromising battery lifespan.

R. P. Yadav, R. Reddy (2024) Introduced a framework that integrates HESS and bidirectional EV chargers to provide frequency and voltage support in smart grids, with an emphasis on real-time optimization techniques.

P. Bhardwaj, A. Gupta (2023) Presented the importance of HESS in providing virtual inertia for grid-connected EVs. Discussed the role of frequency and voltage control through bidirectional charging in facilitating grid-EV.

Y. Zhang (2023) Proposed an advanced Hess management strategy for virtual inertia and frequency support in power systems with high renewable energy penetration.

D. Aliprantis, E. O'Brien (2022) Focused on the dual benefits of HESS in supporting power system frequency and voltage through EV bidirectional charging, especially under high demand and renewable variability.

T. Lee (2021) Proposed optimal control methods for HESS and bidirectional EV chargers, aiming to balance virtual inertia, voltage, and frequency requirements.

H. Li, X. Li, Z. Zhang (2021) Discussed the design and operation of HESS incorporating EVs for frequency regulation, exploring charging/discharging strategies that maximize grid stability.

L. S. Simoes, A. A. G. Lopes (2020) Investigated advanced control algorithms for coordinated operation of off-board EVs and HESS, optimizing the provision of grid services like virtual inertia, frequency, and voltage support.

L. G. A. F. M. de Castro (2019) Investigated the feasibility of off- board EV bidirectional chargers to provide ancillary services like frequency regulation and voltage stability in power systems.

A. D. Lopes, C. L. Moreira (2018) Focused on the concept of virtual inertia provided by EVs integrated into HESS, offering insights into enhancing grid stability and supporting the transition to renewable energy.

3. PROPOSED METHODOLOGY

The block diagram of the proposed control strategy along with the scheme of the power stage are shown in Fig.5.1. Note that a two-stage ac–dc topology is adopted which is composed of a three-phase VSI to interface with the grid, and a dual active bridge series resonant dc–dc converter to interface EV battery. In the proposed control strategy, different V2G functionalities are implemented through managing an HESS. For this purpose, six controllers are designed: the ac current controller, the dc bus voltage controller, the dc current controller, the VI controller, the PQ controllers (active power P and reactive power Q controllers), and the droop controllers to compensate for frequency and voltage variations. In addition, a computational block to calculate active and reactive power (PQ block), a PLL, and transformation blocks complete the control strategy. The management of HESS allows to decouple the dynamics responses of active power as shown in Fig.

Note that in front of a frequency variation increment fPLL, the power delivered by the converter (Pg) is given by the following:

$$Pg = Pc + PEV$$

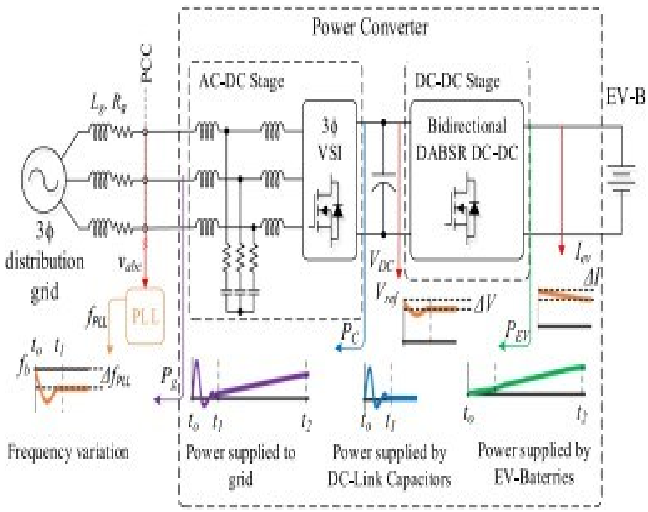

Figure 1: Block diagram of the proposed HESS management.

where Pc and PEV are active powers supplied by the dc link capacitors and the EV battery, respectively. The power Pc has a faster dynamic response compared to PEV, and it is intended for VI support unlike PEV which is focused on long-term frequency support. For simplicity, no power losses are considered. Moreover, in the proposed control strategy, the controllers are classified according to timescale as fast, medium, and slow response . A fast response is required for the inner ac current controller on the ac–dc stage, with a timescale of around a few milliseconds. The medium response is related to dc-link voltage, VI, and dc current control, with a timescale of several milliseconds.

Finally, the slow response corresponds to the PQ and droop controller with a timescale of several seconds. Since special care must be taken in choosing the bandwidth of medium response controllers to ensure system stability, the transfer functions, and controllers design are explained as follows.

3.1 FAST RESPONSE CONTROL: THE AC CURRENT

CONTROLLER

For ac current, proportional + resonant controllers in the stationary αβ frame are adopted. The TF from VSI voltage to ac current is given by where L1, L2, Cf , and Rd are respectively the VSI side inductance, grid side inductance, filter capacitance, and damping resistance.The transfer function of the PR controllers with selective harmonic GPR(s) is defined where K pc is the proportional gain, Krj (j=13,57,9) are the gains for resonant components, the term ξ is the damping factor which defines the bandwidth of the resonant components and the gain at each resonance frequency.

3.2 MEDIUM RESPONSE CONTROL

3.2.1 DC-LINK VOLTAGE CONTROLLER

The dc-link voltage controller is designed to provide the reference (Id ref) for ac current controller according to the following equation, where m is the modulation index Gvi (s) = vDC (s) id (s) ≈ m 1 CDCs.

Moreover, since the reference for the dc-link voltage V ∗ DC is provided by the VI controller, the dynamics of VI controller should be slower to ensure the system stability.

3.2.2 ENHANCED GFL VI CONTROLLER

As explained in Section III, the traditional GFL VI approach generates an overshoot of 7% in the frequency estimation by the PLL. To reduce the overshoot, the estimated frequency fPLL is filtered by a first-order low-pass filter (LPF), as shown in Fig. 6. The LPF must be tuned with a cutoff frequency lower than the dc-link voltage dynamic response to ensure stability. To evaluate the effectiveness on the resulting overshoot, the PLL response was evaluated with three different configurations: a PLL tuned at 10 Hz bandwidth without LPF, a PLL tuned at 60 Hz bandwidth without LPF, and a PLL tuned at 60 Hz bandwidth with a LPF tuned at 10 Hz. The transient responses are depicted in Fig. 8. Note that PLL with LPF filter achieves an overshoot of just 0.4%.

This value can be obtained by evaluating the PLL TF Gf (s), given by (9), including the LPF TF, leading to the following: RoCoF (s) = ωbws
+ 0.1ωbw 2 s2 + ωbws + 0.1ωbw2 1 s ωbw 6 s + ωbw 6. With cutoff frequency of ωbw/6 for the LPF, following the procedure detailed Section III-B, a maximum RoCoF of 1.004 Hz/s is calculated. Hence, the overshoot in the estimated frequency has been considerably decreased, which leads lower transient peak deviation for both dc bus voltage and supplied power for VI.

3.2.3 DC- AC CONVERTER (INVERTER)

An inverter is an electrical device that converts direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits.
Solid-state inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers, to large electric utility high-voltage direct current applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar panels or batteries.
There are two main types of inverter. The output of a modified sine wave inverter is similar to a square wave output except that the output goes to zero volts for a time before switching positive or negative. It is simple and low cost (~$0.10USD/Watt) and is compatible with most electronic devices, except for sensitive or specialized equipment, for example certain laser printers.
A pure sine wave inverter produces a nearly perfect sine wave output (<3% total harmonic distortion) that is essentially the same as utility-supplied grid power. Thus it is compatible with all AC electronic devices. This is the type used in grid-tie inverters. Its design is more complex, and costs 5 or 10 times more per unit power (~$0.50 to $1.00USD/Watt).
The electrical inverter is a high-power electronic oscillator. It is so named because early mechanical AC to DC converters was made to work in reverse, and thus was "inverted", to convert DC to AC. The inverter performs the opposite function of a rectifier.

4.SYSTEM DESIGN

To validate the proposed control strategy, a 2.5 kW EVBC based on the parameters listed in Table 1 was evaluated. For practical implementation, VDC max is limited to ensure lineal modulation [9], whereas the dc-link capacitance is sized considering the maximum allowed extra power Pmax to VI support. Therefore, PDC, given by must be limited to Pmax, according to the following equation.
Then the maximum allowable dc capacitance is calculated by the following: CDC ≤ fbPmax KωV 2 re f RoCoFmax . Since RoCoFmax is a priori known value defined by grid codes, the gain Kω, given by, is calculated as Kω = 17.65 from parameters of Table 1. Then, replacing values in (28), CDC ≤3.13 mF is calculated. With this consideration, CDC = 2.9 mF is adopted. Bandwidths for the Controllers

Finally, droop controllers are tuned through gains KdP and KdQ, according to the following equations:
HV ≈1.85 is obtained; thus, according to, the converter can provide VI in front of frequency variations up to 3 Hz/s without exceeding its limits. On the other side, according to constraints detailed in Section IV, the chosen controller's bandwidths are listed in Table 2. Note in Table 2 that the controllers are classified according to the dynamic response. The ac current controller is the fastest, whereas the active and reactive controllers(P&Q) are the slowest. Moreover, among the medium dynamic responses controllers, the PLL is tuned considering a bandwidth equal to the grid frequency [9] whereas, the DC-Link voltage controller has a bandwidth higher than the battery current and the LPF cascaded to the PLL, which allows to ensure the stability system.
The PLL, dc-link voltage, and ac-current controller's parameters are tuned following the methodology of a grid connected converter [29].The battery current and P&Q controllers' parameters are calculated according the first-order systems given respectively, and the desired bandwidth given in Table 3. Finally, the droop gains KdP and KdQ are calculated considering power deviations of Pref
=400 W and Qref =400 VAR for frequency and voltage variations of

0.2 Hz and 17 V, respectively [31]. The bode plot of the loop gain for current controller Ti(s), given by (19), is shown in Fig. 10. Note that the crossover frequency (fc) is much lower than the cutoff frequency (fLC) of the LoCo filter. Hence, the resonance peak of Gi(s), given by (18), is attenuated in −53 db.

5. SIMULATION RESULTS

Simulation Waveforms

HARMONIC COMPENSATION To test this functionality, the converter was connected to an ac grid with THDv = 3.19%. The corresponding voltage harmonic spectrum is presented in Fig. 9.1(a). The test was performed considering a load of 1.6 kW (64% of the rated power). The resulting ac is presented in Fig. 9.2(b). Note that the main harmonics components of grid voltage have been suppressed and the obtained THD is only 1.46%.

The dynamic response of the estimated frequency for a frequency step of 0.2 Hz is shown in Fig. Two cases are analyzed to estimate the grid frequency: using only a PLL and using a PLL cascaded to a first-order LPF. The bandwidth of the PLL is 60 Hz, whereas for the LPF is 10 Hz respectively. Note that, filtering the estimated frequency by a LPF allows to decrease considerably the overshoot which validates the analytic and simulation results of the proposed method shown in Fig.1

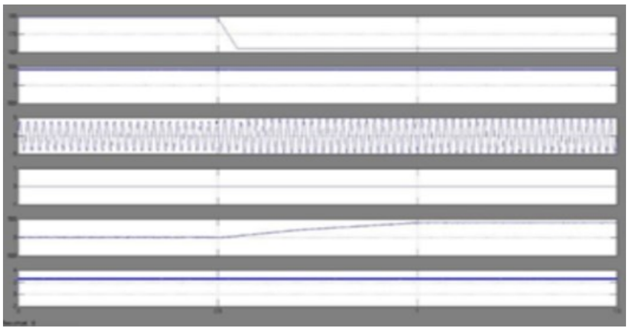

Figure 2: System response for a step of +0.2 Hz Main waveforms

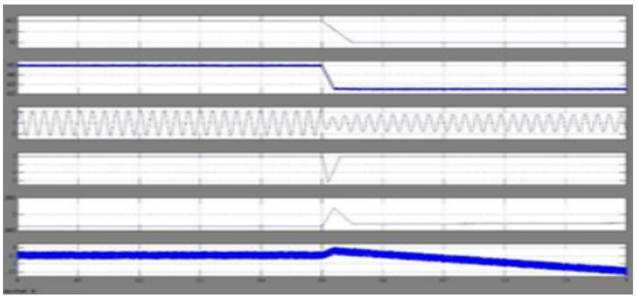

Figure 3: System response for a step of +0.2 Hz waveforms Ac currents

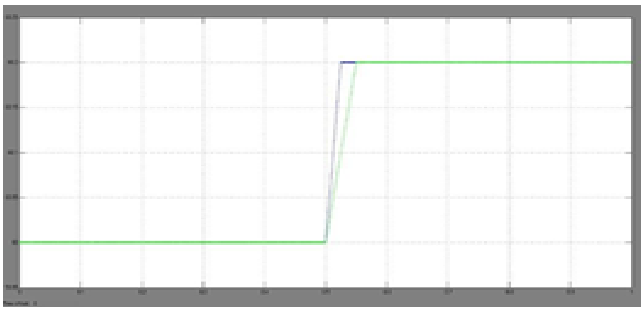

Figure 4 :Dynamic response of estimated frequency

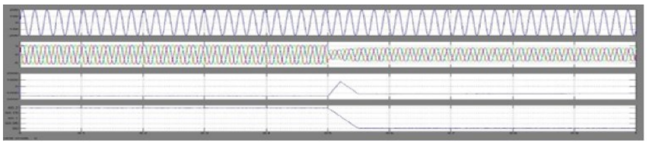

Figure 5: Waveforms of grid voltages and currents for a frequency variations of +0.2 Hz

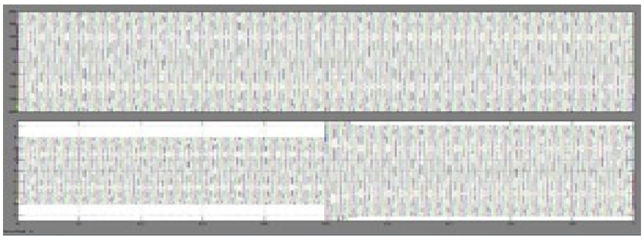

Figure 6: Waveforms of grid voltages and currents for a frequency variations of +0.2 Hz

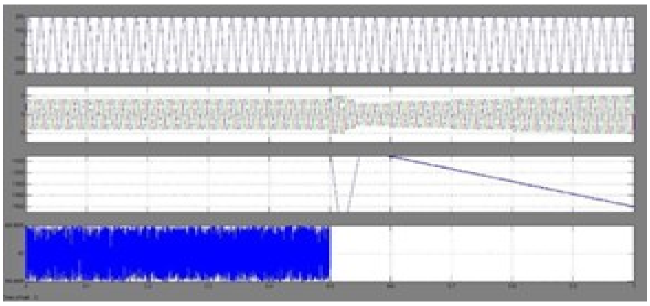

Figure 7: Waveforms of grid voltages and currents for a frequency variation of +0.2

APPLICATIONS

Virtual Inertia Provision:

HESS management enables rapid responses to frequency fluctuations. Supercapacitors or DC- link capacitors can provide fast-acting virtual inertia to counteract rapid frequency changes. The capacitors handle the immediate response , while the battery provides sustained support.

Frequency Regulation:

EV batteries, managed by HESS control systems, can inject or absorb power to stabilize grid frequency. This is especially important with the increasing penetration of intermittent renewable energy source.

Voltage Stabilization:

Bidirectional charges can provide reactive power support to maintain voltage levels. HESS management optimizes the flow of reactive power to address voltage fluctuations.

Grid Stability Enhancement:

By providing virtual inertia, frequency and voltage support, EV bidirectional charges and HESS contribute to overall grid stability, reducing the risk of blackouts and power quality issues.

ADVANTAGES

The advantages of HESS (Hybrid Energy Storage System) management for virtual inertia, frequency, and voltage support through off-board EV bidirectional chargers are substantial, particularly in the context of modernizing power grids. Here's a breakdown of the key benefits:

1.Enhanced Grid Stability:

Improved Frequency Regulation:

HESS allows for rapid responses to frequency fluctuations. The fast-acting components (like capacitors) handle sudden changes, while batteries provide sustained support. This leads to a more stable grid frequency.

Effective Voltage Support:

By managing reactive power flow, HESS helps maintain voltage levels within acceptable ranges, preventing voltage sags or swells.

2.Optimized Battery Lifespan:

Increased Battery Longevity:

By minimizing stress, HESS management contributes to a longer battery lifespan, making EV bidirectional charging a more sustainable and cost-effective solution.

Reduced Battery Stress:

HESS management allows for the separation of fast and slow power responses. This means that the battery is shielded from rapid, high-power fluctuations, which can degrade its lifespan. By having the fast changes handled by the capacitors, the batteries are reserved for the slower more sustained frequency support.

3.Economic Benefits:

By providing grid support, EVs can reduce the need for costly grid upgrades.

6. CONCLUSION

This work presents a novel control strategy that allows the operation of a two-stage AC-DC as a fully controllable HESS able to supply voltage and frequency support while ensuring high-quality in a grid current. The proposed strategy ensure that the fast dynamic response of active power is supplied by the DC link capacitor.where as the battery provides long term frequency support with a slower dynamic response. Hence the VI implementation as no negative impact on the battery lifetime. Additional contributions are the practical cosiderations to GFL VI implementation and the minimization of the overshoot in frequency estimation by PLL. The proposed strategy can be implemented in existing AC-DC converters with only a firmware upgrade, being ideal for off board EVBCs but also for stationary batteries incase frequency support is required to work permanently. Future works will be focused on implementing the full V2G functionalities but considering unbalanced grid voltages and weak grids.

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