Voltage Unbalance Mitigation by Novel Control of BESS Single–phase Inverters

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***Abstract*—In this paper, voltage unbalance compensation in a three–phase power distribution system by means of single–phase connected battery energy storage systems (BESSs) is proposed. A novel control strategy based on orthogonal signal generation is presented to regulate active and reactive power injection from the BESS inverter. A modified version of the 'IEEE 13 node' benchmark system is built in MATLAB / Simulink and three case studies are illustrated to verify the effectiveness of the proposed compensation method.**

***Index Terms*—BESS, unbalance compensation, symmetrical components, voltage unbalance factor, single–phase inverter, orthogonal signal generator, power quality**

I. INTRODUCTION

In light of the increasing penetration of single–phase loads and generation in the power system, voltage unbalance issues are expected to exacerbate. Most prominently, single–phase PVs can cause unequal three–phase power flows, resulting in unbalanced grid currents and voltages [1]. In addition, the random charging behaviour of Plug–in Hybrid Electric Vehicles (PHEVs), usually equipped with a single–phase on–board charger, is expected to further contribute to voltage unbalance rise as their number grows [1], [2]. If voltage unbalance increases to unacceptable levels, it may have adverse effects on power system operation and the equipment connected to it [3].

Generally, voltage unbalance mitigation techniques are divided into passive (e.g. corrective actions implemented by the utilities) and active [4] (e.g. use of power electronic equipment controlled to inject active and reactive power to compensate for voltage unbalance). Active compensation equipment includes: series–parallel compensators, unified power quality conditioner (UPQC), static synchronous compensators (STATCOMs) and distributed generation (DG) inverters [3].

The majority of the literature studies [5], [6] refers to control strategies implemented in three–phase voltage source converters (VSCs) or current source converters (CSCs), whereas the unbalance compensation by single–phase devices is addressed in only a few references.

In [7], single–phase and three–phase PV inverters are managed by a central controller to mitigate voltage unbalance by generating the required amounts of active and reactive power. In [4], the unbalance mitigation is achieved by controlling the reactive power provided by single–phase PHEV chargers. In [1], single–phase DG inverters are controlled without modifying their active power production. The reactive power references are the outcome of an optimization function that minimizes the negative and zero current sequence components. In [8], a control strategy is deployed in a single–phase BESS connected to a low voltage distribution network that integrates PVs and unbalanced loads distribution.

Based on the limited number of references found on the subject, there is still room for further application of single-phase BESSs for unbalance compensation. This paper contributes to this research area by providing a novel control strategy that allows coordinating three BESS inverters to compensate voltage unbalance, by injecting both active and reactive power into the distribution system.

Section II elaborates on the single–phase inverter control system and introduces the unbalance compensation strategy. In Section III, the network for the simulation studies is presented. In Section IV, the simulation results for three case studies are presented, while Section V draws the concluding remarks.

II. INVERTER CONTROL

This section presents the control strategy employed to regulate each single–phase BESS inverter and the unbalance compensation strategy.

A. Control based on the single–phase PQ theory

Fig. 1 gives an overview of the implemented control system. The BESS is modelled by a constant dc voltage source (V_{dc}), while R_f, L_f, C_f are the parameters of the inverter output LC filter and Z_{tr} is the transformer impedance.

Conventional control schemes of single–phase grid–connected systems include an outer voltage loop and an inner current loop, normally operating at unity power factor [9]. In this paper, the BESS inverters are controlled to generate both the active and reactive power to mitigate the voltage unbalance, thus unity power factor is not a constraint.

Active and reactive power are calculated based on the instantaneous power theory as [10]:

$$p = (v_{g\alpha} i_{g\alpha} + v_{g\beta} i_{g\beta}) \times 1/2 \tag{1}$$

$$q = (v_{g\beta} i_{g\alpha} - v_{g\alpha} i_{g\beta}) \times 1/2 \tag{2}$$

where $v_{g\alpha}$, $v_{g\beta}$, $i_{g\alpha}$, $i_{g\beta}$ are the "α" and "β" grid voltage and current components in the $\alpha\beta$–stationary reference frame.

Under the absence of harmonic distortion, active and reactive power are dc quantities in steady–state and they can be regulated by PI controllers. The current reference is [9]:

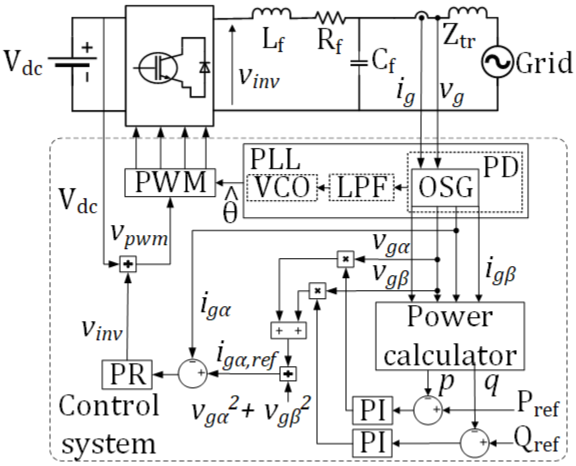


Fig. 1: Control structure of the single–phase grid connected inverter based on the single–phase PQ theory.

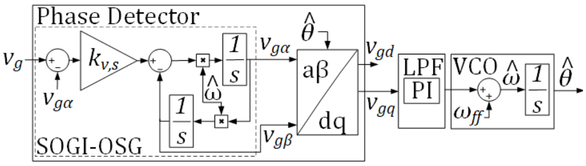


Fig. 2: General structure of a SOGI–OSG based PLL.

$$\begin{bmatrix} i_{g\alpha,ref} \\ i_{g\beta,ref} \end{bmatrix} = \frac{1}{v_{g\alpha}^2 + v_{g\beta}^2} \begin{bmatrix} v_{g\alpha} & v_{g\beta} \\ v_{g\beta} & -v_{g\alpha} \end{bmatrix} \begin{bmatrix} H_p(s)(P - P_{ref}) \\ H_q(s)(Q - Q_{ref}) \end{bmatrix} \tag{3}$$

where $H_p(s)$, $H_q(s)$, P_{ref}, Q_{ref} are the PI controller transfer functions, active and reactive power references respectively.

A proportional–resonant (PR) controller is adopted to regulate the current, since ist reference is sinusoidal. Essentially, the controller introduces an infinite gain to remove the steady–state error at the selected resonant frequency [11].

To obtain the needed voltage and current components for power calculation, an orthogonal signal generator (OSG) system is used. Among the several methods found in the literature, the system based on second order generalized integrator (SOGI–OSG) is used here. The single–phase PLL based on this structure has been implemented, as shown in Fig. 2. As shown in [12], this configuration achieves: orthogonal voltage system generation, filtering without delay and frequency independence. The choice of $k_{v,s}$ is a trade–off between the bandpass and the system's dynamic response [12].

B. Proposed voltage unbalance compensation strategy

Voltage unbalance is quantified by the negative or zero voltage unbalance factor (k_{v2} or k_{v0}), that are defined as the ratio of the negative– or zero–sequence voltage component to the positive sequence voltage component, respectively [13]:

$$k_{v2} = \frac{|\boldsymbol{V_2}|}{|\boldsymbol{V_1}|} \times 100\% \quad k_{v0} = \frac{|\boldsymbol{V_0}|}{|\boldsymbol{V_1}|} \times 100\% \tag{4}$$

According to IEC 61000-2-2, the limit for k_{v2} is 2%. Since the standards provide limits for the negative unbalance factor only, k_{v2} is chosen as the metric to quantify the effectiveness of the proposed control strategy.

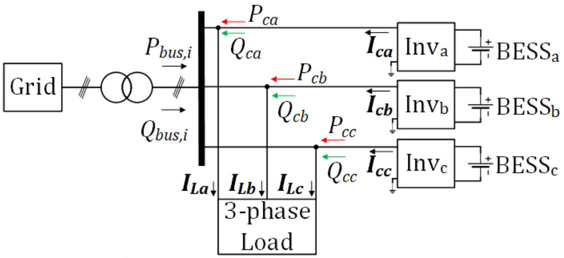


Fig. 3: Block diagram of single–phase connected BESS inverters used for unbalance compensation.

To compensate voltage unbalance, a possible solution consists in controlling the single–phase BESS inverters to inject negative– and zero–sequence current components to be equal in magnitude and 180^o out of phase compared to the sequence components measured at the downstream branch [7].

The concept is shown in Fig. 3, where three BESS units are connected to the distribution system via three single–phase inverters. The aim of the method is to equalize the three–phase power flows at the bus ($P_{bus,i}, Q_{bus,i}$) by injecting the proper current phasors [$\boldsymbol{I_{ca}}$, $\boldsymbol{I_{cb}}$, $\boldsymbol{I_{cc}}$] from each inverter to counteract the negative– and zero–sequence current components of the downstream branch [$\boldsymbol{I_{La}}$, $\boldsymbol{I_{Lb}}$, $\boldsymbol{I_{Lc}}$].

The symmetrical components of the downstream currents are obtained by applying the Fortescue transformation [7]:

$$\begin{bmatrix} \boldsymbol{I_{L1}} \\ \boldsymbol{I_{L2}} \\ \boldsymbol{I_{L0}} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \boldsymbol{\alpha} & \boldsymbol{\alpha^2} \\ 1 & \boldsymbol{\alpha^2} & \boldsymbol{\alpha} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{I_{La}} \\ \boldsymbol{I_{Lb}} \\ \boldsymbol{I_{Lc}} \end{bmatrix} \tag{5}$$

where the phasors [$\boldsymbol{I_{L1}}$, $\boldsymbol{I_{L2}}$, $\boldsymbol{I_{L0}}$] represent the positive, negative and zero sequence components respectively, while [$\boldsymbol{I_{La}}$, $\boldsymbol{I_{Lb}}$, $\boldsymbol{I_{Lc}}$] are the fundamental frequency phasors of the measured downstream currents.

Unbalance compensation can thus be achieved through the injection of a set of compensating currents calculated as:

$$\begin{bmatrix} \boldsymbol{I_{ca}} \\ \boldsymbol{I_{cb}} \\ \boldsymbol{I_{cc}} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \boldsymbol{\alpha^2} & \boldsymbol{\alpha} & 1 \\ \boldsymbol{\alpha} & \boldsymbol{\alpha^2} & 1 \end{bmatrix} \begin{bmatrix} 0 \\ -\boldsymbol{I_{L2}} \\ -\boldsymbol{I_{L0}} \end{bmatrix} \tag{6}$$

where [$\boldsymbol{I_{ca}}$, $\boldsymbol{I_{cb}}$, $\boldsymbol{I_{cc}}$] are the phasors of the currents required by the BESS inverters.

The compensating current signals are transformed into power signals by multiplication with the fundamental frequency voltage phasors [$\boldsymbol{V_{ga}}, \boldsymbol{V_{gb}}, \boldsymbol{V_{gc}}$] :

$$\boldsymbol{S_{ci}} = \boldsymbol{V_{gi}} \boldsymbol{I_{ci}^*} = P_{ci} + jQ_{ci} \tag{7}$$

where * is the complex conjugate and $i = a, b, c$. Equation (7) gives the required amount of active and reactive power (P_{ci}, Q_{ci}) injected by the single–phase inverters. A saturation block is used to limit the power signal values, since the total generated apparent power from each inverter should not exceed its nominal rating. The unbalance compensation strategy described above is summarized in Fig. 4.

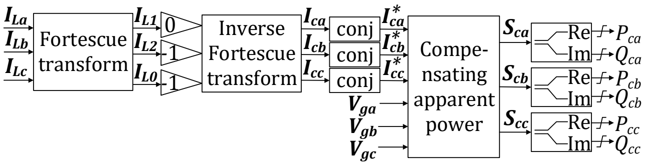


Fig. 4: Unbalance compensation strategy.

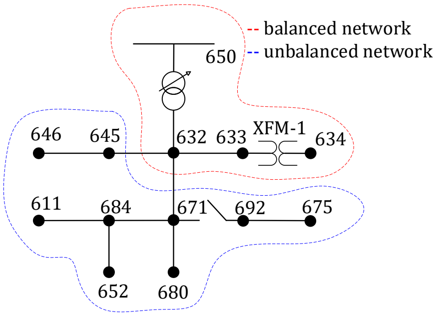


Fig. 5: Configuration of the IEEE 13–node system.

III. System configuration

To evaluate the proposed unbalance compensation strategy, the 'IEEE 13 node test feeder' benchmark system (Fig. 5) is used [14]. This system is unbalanced and therefore provides a good benchmark for the proposed method. The sources of the system unbalance include the unbalanced supply voltage (bus 650), non–symmetrical lines, and the presence of single–phase, two–phase and unbalanced three–phase loads.

The test system was undergone the following modifications to conduct three case studies:

- Case 1: Only the feeder consisting of nodes 650–632–633–634 (termed as 'balanced network') is considered. Its parameters are modified to balance the supply voltage; the overhead line 632–633 and the three–phase loads connected at buses 632 and 634 are made symmetrical. The load 634 is turned to unbalanced and three single–phase BESS inverters are connected at the same bus to compensate the unbalance.
- Case 2 and Case 3: The network consisting of nodes 646–645–611–684–652–680–671–692–675 (termed as 'unbalanced network' here) is included, thus allowing to evaluate the unbalance due to these components.

TABLE I: Simulation parameters

Parameters	**Values**
Grid frequency	$\omega_n = 2\pi \times 60$ rad/s
LC filter parameters	$L_f = 3.6$ mH , $R_f = 0.135\ \Omega$, $C_f = 8\ \mu$F
Switching frequency	$f_{sw} = 10$ kHz
BESS rated dc voltage	$V_{dc} = 500$ V
PI based power controller	$k_{pp} = k_{pq} = 0.1$, $k_{ip} = k_{iq} = 10$
PR current controller	$kpi = 20$, $kri = 150$
Saturation limits	$S_{limit} = \pm 12$ kVA

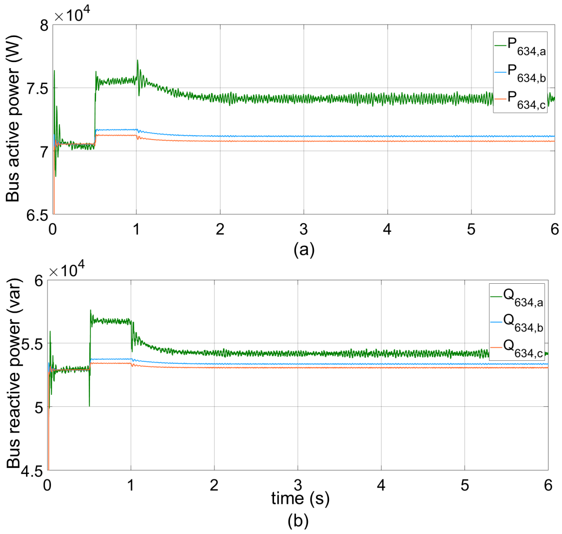


Fig. 6: Case 1 - (a) Active and (b) reactive power at bus 634.

IV. Simulation results

To verify the effectiveness of the proposed method, simulations for the system of Section III were performed in MATLAB/Simulink. Table I gives the system parameters.

For all cases, a balanced load of nominal power P_L = [120 120 120] kW, Q_L = [90 90 90] kvar at bus 634 is assumed initially. At $t_1 = 0.5$ s, the load becomes unbalanced and at $t_2 = 1$ s, the compensating reference signals ($P_{ci,ref}, Q_{ci,ref}$) are fed to the controller in order to compensate for the voltage unbalance at bus 634. The controls are not activated from the start of the simulation to illustrate the effectiveness of the proposed strategy, and to compare the results without and with unbalance compensation.

A. Case 1: Single–phase unbalanced load

In this case, only the balanced network is considered. A load unbalance is introduced on phase 'a'. The measured load power is P_L = [75.6 71.7 71.3] kW, Q_L = [56.8 53.8 53.4] kvar. Only phase–a inverter is controlled to compensate for the unbalance.

Figures 6a and 6b present the three–phase active and reactive power at bus 634. Initially, a balanced power flow is observed, i.e. $P_{L,i}$ =70.5 kW and $Q_{L,i}$ = 53 kvar, where $i = a, b, c$. At $t_1 = 0.5$ s, when load unbalance is introduced, a significant deviation in phase–a active and reactive power is observed.

Figure 7 shows the compensating active and reactive power reference signals. During the time period 0–t_1, under balanced load conditions, $P_{ca} = Q_{ca} = 0$. At $t_1 = 0.5$ s, the required amount of generated active and reactive power is calculated by the unbalance correction strategy. At $t_2 = 1$ s, unbalance compensation is activated and the generated active and reactive power by the inverter settle to $P_{ca} = 9.8$ kW and $Q_{ca} = 8.8$ kvar. The effect of compensation is observed in Figures 6a and 6b, since after $t_2 = 1$ s, $P_{634,a}$ and $Q_{634,a}$ start to converge to the active and reactive power values of the other two phases.

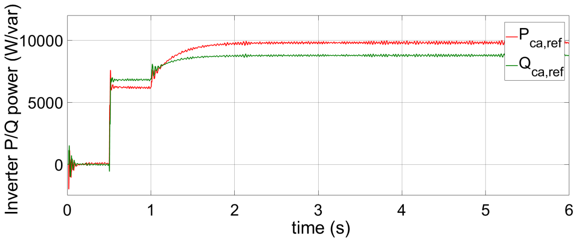


Fig. 7: Case 1 - Compensating (a) active and (b) reactive power reference signals of phase–a connected inverter.

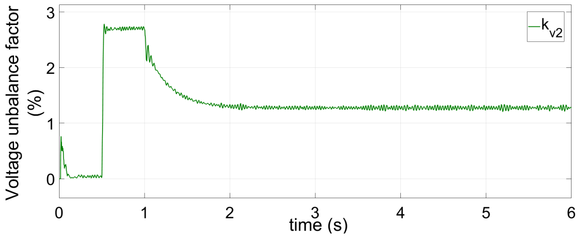


Fig. 8: Case 1 - Negative–sequence voltage unbalance factor.

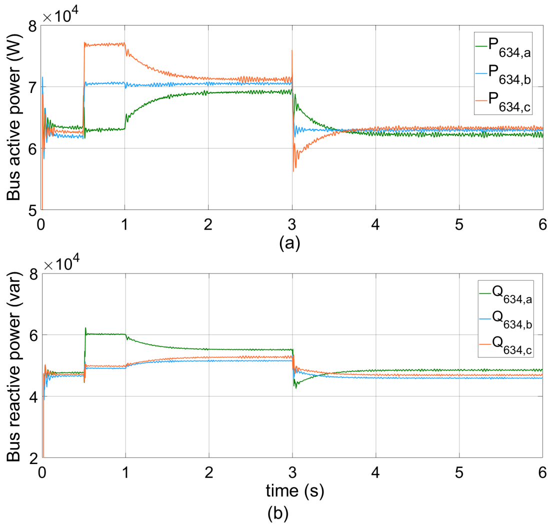
Finally, Fig. 8 presents the calculation of k_{v2}. The compensating action of phase–a inverter reduces k_{v2} almost by half, i.e. its value drops from 2.7% to 1.28%, thus making the system compliant with the requirement of IEC 61000-2-2. Though a considerable unbalance reduction is achieved, voltage unbalance is not completely eliminated by using a single inverter. To further mitigate it, all three BESS inverters must inject active and reactive power. If all BESS inverters are controlled, k_{v2} will be reduced to 0.2%. The results for this case are omitted here for brevity reasons.

B. Case 2: Three–phase unbalanced load

Simulations are performed considering the complete 13–bus system. A three–phase load unbalance is introduced and the measured load power is $P_L = [63\ 70.6\ 77]$ kW, $Q_L = [60\ 49\ 50]$ kvar. All three BESS inverters are controlled. The load is switched back to balanced at $t_3 = 3$ s.

Figures 9a and 9b present active and reactive power at bus 634 for each phase. Compared to Case 1, these two quantities are not balanced between 0–t_1 due to the presence of the unbalanced network. At $t_1 = 0.5$ s, the load unbalance is introduced and, as a consequence, the difference between power measurements increases, with $P_{634,c} > P_{634,b} > P_{634,a}$. Since phase 'c' draws the largest amount of active power, the BESS connected at that phase must inject active power (discharge), while the BESSs connected at phases 'a' and 'b' must absorb active power (charge), such that the active power flows at bus 634 converge and thus the desired voltage unbalance mitigation is achieved.

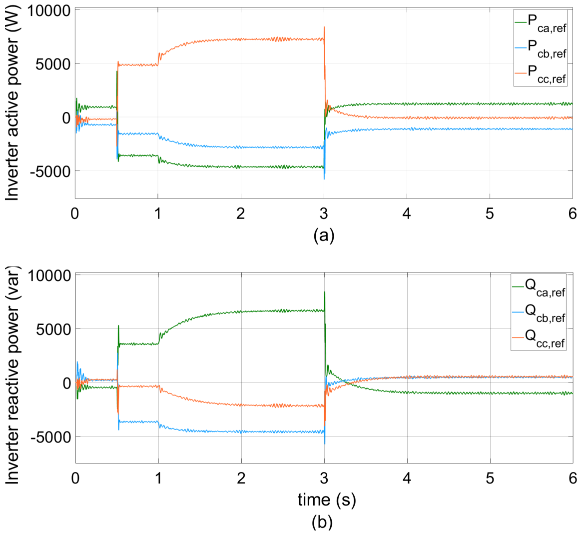
This behavior can be observed in Fig. 10a, where the compensating active power reference signals calculated by the unbalance compensation strategy block for each inverter are plotted. It can be observed that $P_{cc,ref} > 0$, while $P_{ac,ref} < 0$ and $P_{bc,ref} < 0$. Fig. 10b presents the reactive power commands for each inverter. In general, the pattern of reactive power injection is not correlated to active power.



(a)

(b)

Fig. 9: Case 2 - (a) Active and (b) reactive power at bus 634.



(a)

(b)

Fig. 10: Case 2 - Compensating (a) active and (b) reactive power reference signals of three inverters.

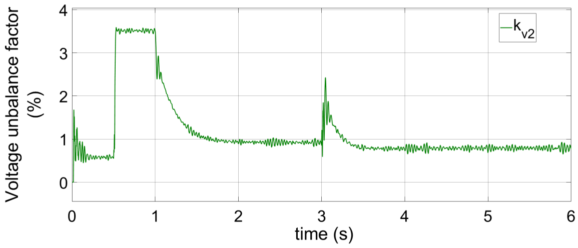


Fig. 11: Case 2 - Negative-sequence voltage unbalance factor.

Fig. 11 shows the voltage unbalance factor waveform. From 0–t_1, $k_{v2} = 0.57\%$ due to the unbalance caused by the net-

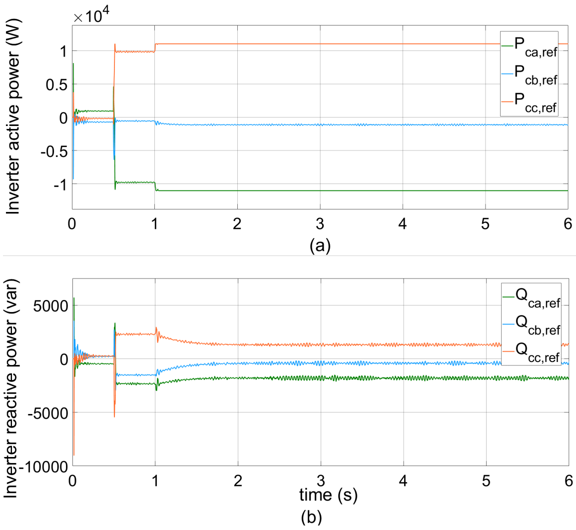


Fig. 12: Case 3 - Compensating (a) active and (b) reactive power reference signals of three inverters.

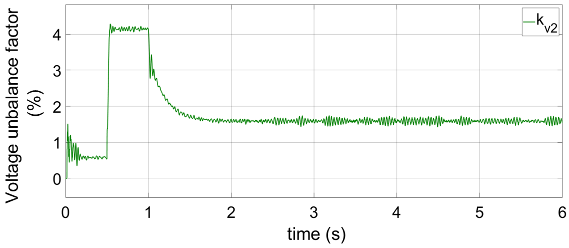


Fig. 13: Case 3 - Negative sequence voltage unbalance factor.

work. When the unbalanced load is introduced, $k_{v2} = 3.52\%$. After the unbalance compensation is activated, the voltage unbalance factor is reduced to $k_{v2} = 0.95\%$. At $t = t_3$, the load returns to balanced and $k_{v2} = 0.8\%$.

C. Case 3 - Three–phase unbalanced load with saturation

Compared to Case 2, the load unbalance is further exacerbated. The measured load power is P_L = [52.2 60.5 73.4] kW, Q_L = [52 45.5 43.8] kvar, thus increasing the amount of power required from each BESS inverter to compensate the unbalance. This condition leads to the saturation of the reference power signal sent to the controller. As a result of the above, active power reference signals for phase–a and phase–c inverters are saturated at -12 and 12 kW respectively, as Fig. 12a depicts, while the reactive power reference signals are far from the saturation limits (Fig. 12b). Due to saturation, the voltage unbalance factor cannot be fully mitigated, i.e. k_{v2} is reduced from 4.1% to 1.5% (Fig. 13). However, this value is below the limit indicated in IEC 61000-2-2. Further mitigation requires the connection of additional BESS units.

V. CONCLUSIONS

In this paper, an unbalance compensation strategy was proposed making use of single–phase BESS inverters. The performance and effectiveness of this approach was verified by simulations on a modified version of the ’13 node test feeder’ benchmark system.

In case of load unbalance in a single phase, the inverter connected to the same phase was able to partially mitigate voltage unbalance, while further reduction would require the contribution of the inverters of the other two phases.

The three BESS inverters were controlled to reduce the voltage unbalance factor under the presence of a three–phase load unbalance, showing satisfactory mitigating performance. When a higher load unbalance was introduced, the inverters were not able to fully mitigate voltage unbalance due to their power rating limitations.

The results demonstrate that the proposed strategy may provide a substantial reduction of the network voltage unbalance, thus rendering the single–phase BESS units a promising candidate for mitigating unbalance conditions and improving power quality in highly unbalanced networks.

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