

Unbalance and Harmonic Mitigation Using Battery Inverters

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Abstract—Slight unbalance in voltage in a distribution system can result in high unbalance in currents due to induction machine loads. Further, a wide spectrum of harmonic components will be generated in currents due to uncontrolled power electronic loads employing diode-bridge rectifiers. Power quality becomes a critical issue for a microgrid if both induction machine loads and rectifier loads exist. Mitigation of unbalanced and harmonic currents without additional investments is of interest of utility companies. With energy storage systems such as batteries installed for peak shaping and valley filling, power quality improvement through voltage source converter (VSC) based battery inverters is proposed in this paper. This paper develops a Unbalanced Current (UC) and Harmonic Current (HC) controller for battery inverters based on the structure of Proportional-Resonance (PR) controller. Real-Time simulations carried out in RT-LAB demonstrate the grid current can be successfully improved to meet the IEEE standard when the negative sequence component of grid voltage is lower than 4% for the study system in this paper.

Index Terms—Unbalance, harmonics, Proportional-Resonance (PR), Voltage Source Converter, Battery.

I. INTRODUCTION

MICROGRID is a promising technology to integrate distributed energy resources (DERs) [1–3] such as wind turbines and solar photovoltaic panels. A common characteristic of those renewable energy resources is the intermittency on power output. Therefore, in order to compensate the intermittency and improve the power output profile, energy storage devices are always required such as batteries [4–6].

Induction motor loads in a microgrid occupy a large portion of loads. Such loads are vulnerable to grid voltage unbalance. [7, 8] demonstrate the effect of voltage unbalance. For high power induction machine, even very low level of grid voltage unbalance may lead to very high percentage of unbalanced currents if the slip is small [9]. In order to prevent unbalanced currents flowing into a utility grid, [10–12] proposed to use a shunt connected Voltage Source Converter (VSC) to inject compensation currents with controllers designed in a dq synchronous frame. Other than compensating unbalanced currents, STATCOM and D-STATCOM have been widely used to compensate the unbalanced voltage at the Point of Common Coupling (PCC) [13–18].

Unbalance in grid voltage can also cause low order harmonic currents due to power electronic interfaced loads. In [9], an example case study shows that a diode rectifier electric

drive causes increase in 3rd harmonics due to unbalanced grid voltage. Active filter is a solution to mitigate the harmonic currents [19–22]. The current control strategies (linear current control, digital deadbeat control, and hysteresis control) are discussed and compared in [23]. In the linear current control scheme, multiple dq rotating frames are utilized to convert harmonic and negative sequence current components to dc variables. Proportional-integral (PI) controllers, effective for dc variable controls, are then applied to regulate currents. An alternative control scheme developed in [24, 25] is called Proportional-Resonant (PR) controller. PR controllers can regulate sinusoidal signals. With PR control, the complexity of harmonic current control system can be reduced.

Unbalanced and harmonic current mitigation needs the installation of VSCs, such as active filters. For microgrids equipped with energy storage systems such as VSC interfaced batteries, the batteries can be used not only for peak shaping but also for power quality improvement.

The objective of this paper is to explore battery inverters' capability in power quality improvement, specifically in unbalance and harmonic current mitigation. A control strategy for the inverter of a battery will be developed to compensate unbalanced and harmonic currents under various grid voltage conditions. In the sections following, the paper first describes the system configuration of a microgrid with a battery, a PV station, an induction machine load and a rectifier interfaced load. In Section III, the mechanism and the block diagram of the controller based on PR control scheme are presented. Results of real-time digital simulation carried out in RT-LAB are presented in Section IV. Section V concludes the paper.

II. SYSTEM CONFIGURATION

The microgrid studied for this paper consists of a PV station and a battery as the distribution generation and storage devices respectively. An induction machine and a diode rectifier interfaced RL load are chosen as the customer loads. The microgrid is connected with the main grid via a transformer. Fig. 1 shows the topology of the study system. The parameters are listed in Table I. The battery system consists of two groups connected in series. Each group has an equivalent open circuit dc voltage at 4.1 kV. The maximum active power capability of which is 1 MW for each group, and the energy capacity is 1 MWh, which means the whole battery station could inject 2 MW active power to the microgrid for 1 hour.

The PV array consisted of many small PV panels, which could build up an open circuit dc voltage to 2 kV for the whole

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array. The short circuit dc current under nominal insolation level is set to 1 kA. The PV array is connected to a dc/dc converter, which is controlled by Maximum Power Point Tracking (MPPT) algorithm. A dc/ac inverter which utilizes IGBTs connects the dc/dc converter to the microgrid.

The induction machine is used to simulate traditional customer load. A simple RL load connected with a rectifier is a representation of uncontrollable rectifier interfaced loads.

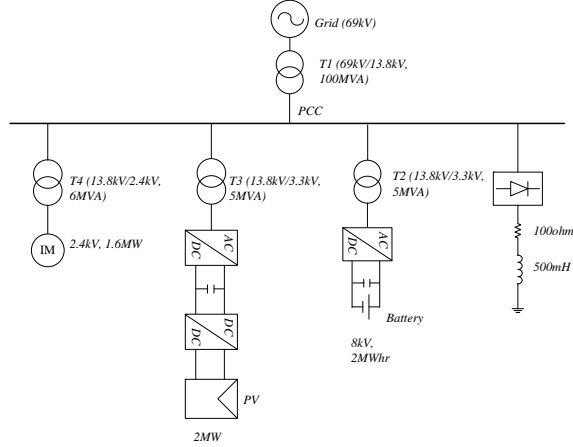


Fig. 1. System topology of a microgrid.

TABLE I
SIMULATION SYSTEM PARAMETERS

Quantity	Value
ac grid voltage	69kV (L-L RMS)
Transformer 1	69kV/13.8kV, 100MVA, leakage 8%pu
Transformer 2	13.8kV/3.3kV, 5MVA, leakage 10%pu
Transformer 3	13.8kV/3.3kV, 5MVA, leakage 10%pu
Transformer 4	13.8kV/2.4kV, 6MVA, leakage 10%pu
Induction machine ratings	2.4kV, 1.6MW
Battery ratings	8.2kV, 2MWhr
PV ratings	2kV, 2MVA
Load ratings	100ohm+500mH

A. Consequence of unbalance in motor loads

The positive and negative sequence currents can be written as (1) and (2).

$$I_{ps} = \frac{V_p}{\sqrt{(R_s + \frac{R_r}{s})^2 + (X_{ls} + X_{lr})^2}} \quad (1)$$

$$I_{ns} = \frac{V_n}{\sqrt{(R_s + \frac{R_r}{2-s})^2 + (X_{ls} + X_{lr})^2}} \quad (2)$$

where R_s and X_{ls} are stator resistance and leakage reactance respectively, R_r and X_{lr} are rotor resistance and leakage reactance referred to stator side respectively. X_m is the magnetizing reactance. V_p and V_n represent the positive and negative sequences of voltage, while I_{ps} , I_{pr} and I_{ns} , I_{nr} are the corresponding currents. For example, if $R_s = 0.3$, $R_r = 0.1$, $X_{ls} = 0.5$, $X_{lr} = 0.2$, $s = 0.01$, $V_p = 1.0$, and V_n is only 2% of V_p , the resulting negative sequence current is $I_{ns} = 0.0256$, whereas, the positive sequence current is $I_{ps} = 0.0969$. The

negative sequence current is 26.42% of positive sequence current although the negative sequence voltage is only 2%. Therefore, when there is a small percentage of unbalance in the PCC voltage, the induction machine will inject significant unbalanced currents to the system.

The consequence of unbalanced voltage applied in motor loads is demonstrated in Fig. 2, which shows the induction machine currents. The system voltage contains a 2% negative sequence. The unbalance degree in current reaches 26%. Such high magnitude negative sequence currents may cause severe problems to the end users, since it may cause vibrations on the machine torque, unstable rotating speed and noise. The power factor and efficiency of machine may get worsen as well. The worst case would be shut down of the machine. For sensitive industry customers, such system performance is not acceptable.

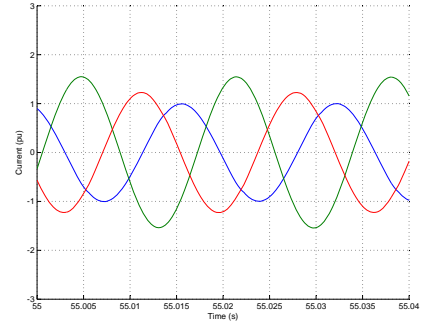


Fig. 2. Induction machine current under 2% unbalanced grid voltage.

B. Consequence of unbalance in rectifier loads

For a diode rectifier, if the ac side is subject to unbalance, the instantaneous power will contain a dc component and a harmonic of double line frequency. Ignore the switching loss, this instantaneous power equals the dc side instantaneous power. Therefore, the dc current will contain second harmonic component. At ac side, there will be a 3rd harmonics.

The consequence of unbalanced voltage applied in rectifier loads is presented in Fig. 3. The system voltage has 2% negative sequence component. The rectifier phase A current is presented in Fig. 3. Under balanced grid voltage, the main harmonic components in currents are 5th and 7th order. At the unbalance case, the largest harmonic shifts to 3rd order as shown in in Fig. 3. The grid current injected into main grid is critical to power quality. The current harmonics limits for a power system can be found in IEEE standard [26], which is 4% for harmonic order of 9 and less, and 2% for harmonic order of 15 and less. Fig. 5 depicts the FFT analysis of grid current under 2% unbalanced grid voltage. The red bar is the magnitude percentage corresponding to fundamental current for various odd harmonic orders, while the green bar is the limit specified by the standard for different odd harmonic order currents. Based on the system parameters and short circuit calculation, the THD limit of grid current for the model is 8% [26]. However, the actual THD of the current for this case is 15.86%, which is almost 2 times of the limit.

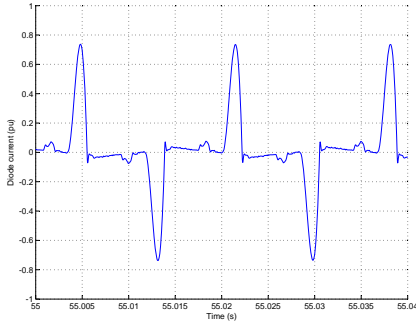


Fig. 3. Rectifier current under 2% unbalanced grid voltage.

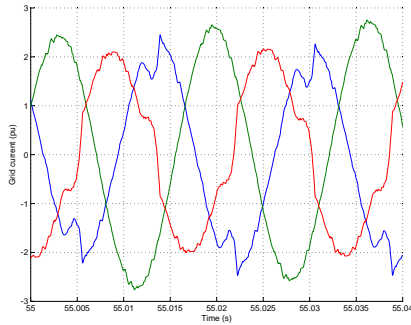


Fig. 4. Grid current under 2% unbalanced grid voltage.

III. CONTROLLER DESIGN

Since the battery is connected with the microgrid via a VSC, it is possible to design a proper control strategy to have the VSC to compensate both negative sequence and harmonic currents injected into the grid. The reason that we do not use the PV's VSC to perform the compensation is that the VSC of PV has to control the dc voltage for the PV panel's dc/dc converter. The battery has a relatively stable dc voltage. So its VSC has more freedom to implement sophisticated controls.

In Fig. 6, the microgrid is simplified with each component's current labeled. Since the major negative sequence and harmonic currents are contributed by induction machine and rectifier, the PV station is ignored in Fig. 6. Assuming the PCC voltage is unbalanced, the induction machine current i_m can

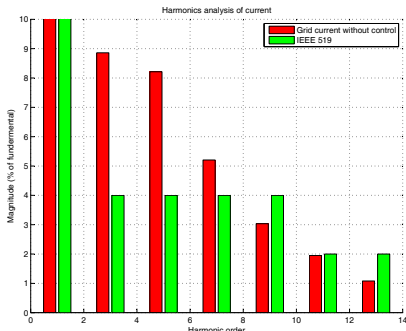


Fig. 5. FFT analysis of grid current under 2% unbalanced grid voltage.

be written as $i_m = i_{mp} + i_{mn}$, where i_{mp} and i_{mn} represent the positive and negative sequence current. The rectifier load current i_r also can be written as $i_r = \sum_{k=1} (i_{rp_k} + i_{rn_k})$, where $k = 1, 2, 3, \dots$ is the harmonic order and the subscript rp and rn represent positive and negative sequences. Apparently, the current i_g injected into the grid would contain various harmonic currents and negative sequences, which is not acceptable in terms of power quality.

One solution for this problem is to design a proper control strategy for the battery's VSC and make it inject specific currents to the grid for compensation. For instance, let the battery $i_b = i_{b0} - i_{mn} - \sum_{k=2} i_{rp_k} - \sum_{k=1} i_{rn_k}$, where i_{b0} is the battery's own current order. So the total grid current i_g will only have positive sequence and the negative sequence and harmonic currents will be canceled out.

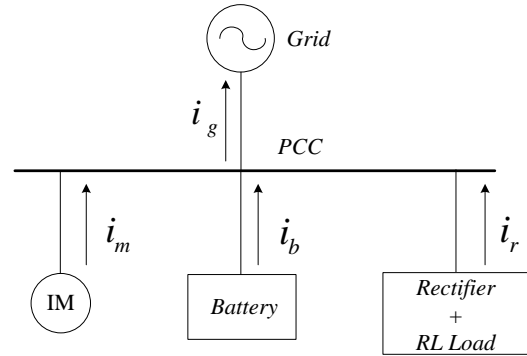


Fig. 6. Simplified system topology.

The conventional control scheme for VSC is dq decoupled control algorithm, which is shown in Fig. 7. θ is the system voltage angle at nominal frequency of 60Hz. For a balanced system, the currents i_d and i_q are both dc quantities, and the PI controllers are able to regulate them in order to track the respective references. However, under unbalanced case, the dq currents are no longer dc quantities but contain ac time varying currents at frequency of 120Hz. Since PI controllers can not track ac signals, two low pass filters are needed to get rid of the 120Hz components. Similarly, in order to control the negative sequence current, a negative sequence dq transformation is needed and two low pass filters are required to filter out the 120Hz positive sequence part. Moreover, this control structure is specific for nominal frequency, for each harmonic order, a complete set of the controller shown in Fig. 7 is needed. The difference is the angle θ will be the corresponding angle at each harmonic order. Obviously, the complexity of the overall controller is very high and the calculation burden will cost much resources for a real controller.

Instead of the conventional dq controller, a Proportional-Resonance (PR) controller is more suitable for such kind of application. The transfer function of a PR controller is shown in (3), where K_p is the proportional gain and K_{ih} is the resonance gain for each harmonic order. The control structure is also shown in Fig. 8, where only first order and second order controller are drawn. The current regulated by PR controller has to be ac current as it has very limited

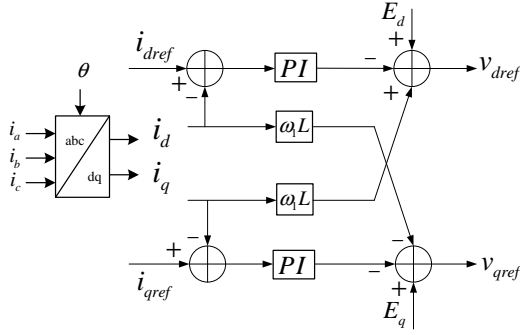


Fig. 7. Conventional dq control strategy for VSC.

response for dc signals. Another advantage of PR controller is for each order of current, the controller can regulate both positive and negative sequence as long as the frequency is the same with the controller's harmonic order [27, 28]. Hence, the overall controller would be much more easier to implement. Since the controller needs ac current signals, instead of dq transformation, the abc currents will be transformed into $\alpha\beta$ frame. The current reference of the battery shown above will also be transformed into $\alpha\beta$. Obviously, in order to get a proper current reference for battery, a signal conditioning unit which can correctly extract the negative sequence and harmonic currents of i_m and i_r is needed.

$$G_h(s) = K_p + \sum_{h=2,3,4,\dots} K_{ih} \frac{s}{s^2 + (\omega \cdot h)^2} \quad (3)$$

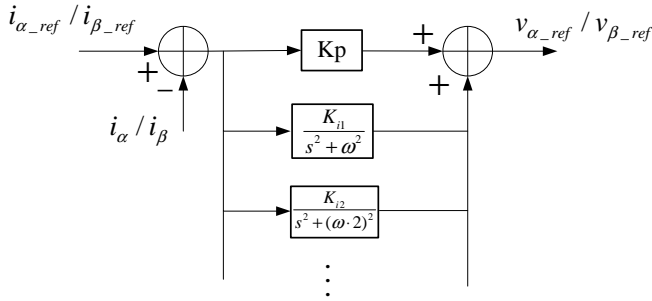


Fig. 8. A PR controller structure.

In order to extract the negative sequence and harmonic order components of induction machine and rectifier currents, one method is to obtain the positive sequence component and subtracted from the total current. Fig. 9 depicts the signal conditioning block to extract the negative and harmonic currents components. For example, the three-phase induction machine currents i_{m_a} , i_{m_b} , and i_{m_c} are sent to a abc/dq transformation block at fundamental frequency to calculate the currents in dq frame, which are $i_{m_d}^{+\sim}$ and $i_{m_q}^{+\sim}$ respectively. The subscripts $+$, $-$, and \sim represent positive, negative and harmonic components respectively. Since the currents are measured under unbalanced voltage, the negative sequence current may have a relatively high magnitude. A notch filter tuned at 120Hz is used to filter out the negative sequence current, which

is a 120Hz ac signal in dq frame. The harmonic currents in dq frame are at even higher harmonic order frequencies, for instance, the 3rd harmonic order current in dq frame would be 120Hz and 240Hz ac signals. Therefore, a low pass filter (LPF) is used to get rid of the harmonic components. After that, the dq currents contain only positive sequence which are transformed back to abc quantities and subtracted from the total abc currents. After the subtraction, the currents contain only negative sequence and harmonic order components. A $abc/\alpha\beta$ block will turn the current signals into $\alpha\beta$ frame and will be used by the controllers shown in Fig. 8.

The controller parameters are listed in Table ??, and the respective bandwidth for each harmonic order controller is shown in Table ?? with 1st, 3rd and 5th order controller listed.

IV. VALIDATION

A simulation model of microgrid is built in RT-LAB in order to validate the capability of the battery inverter for negative sequence and harmonics current compensation. RT-LAB is a Real-Time Digital Simulator manufactured by OPAL-RT which can simulate the power system model with detailed power electronic switches in real-time. Therefore, it can provide precise simulation results and take the switching details of IGBTs into account. Moreover, the simulation can run in real time and highly improve simulation efficiency. Fig. ?? shows the setup of RT-Lab simulator and its corresponding oscilloscopes which monitor the simulation signals, such as voltage, current and power.

A three-phase programmable voltage source is selected to emulate the grid. Besides the regular positive sequence voltages, the programmable voltage source can also generate negative sequence voltages and superimpose them onto the positive sequence voltage. Therefore, that feature can be used to simulate the unbalanced voltage cases. Three case studies will be conducted to investigate the current compensation capability of the battery inverter with PR controller under different level of grid voltage unbalance.

A. Case I

The microgrid built in RT-LAB consists of five main components: the main grid, an induction machine, a rectifier interfaced load, a battery and a PV station. The electrical parameters are listed in Table I.

The first case investigates the system performance while the UC controller is enabled. The HC controller is firstly disabled and then enabled to validate the harmonic current compensation capability by battery inverter. The negative sequence of grid voltage is set to 0.5%, which indicates a relatively low unbalanced grid voltage case. Fig. 10 (a) shows the induction machine currents which contain 7% negative sequence component, and Fig. 10 (b) shows the grid currents with both UC and HC controllers enabled. Fig. 11 shows the rectifier phase A current, which has various harmonic components. The 3rd harmonic current is smaller comparing with Fig. 2. Generally, the 3rd harmonic current increase as the voltage contains more negative sequence.

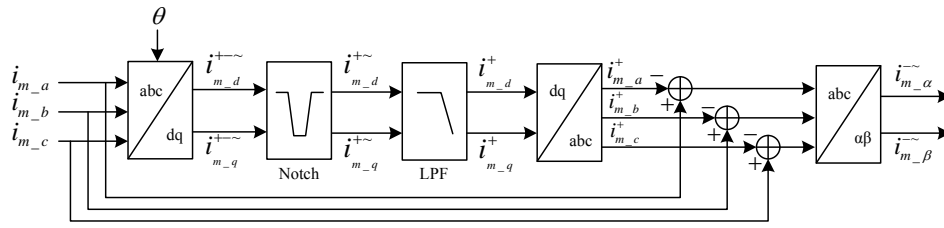


Fig. 9. Signal conditioning.

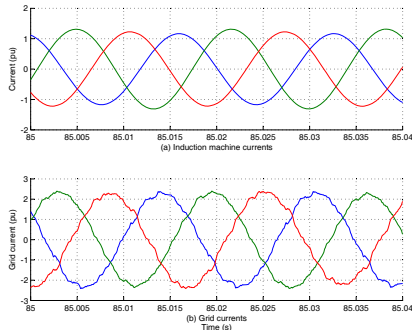


Fig. 10. Induction machine and grid currents under 0.5% unbalanced grid voltage.

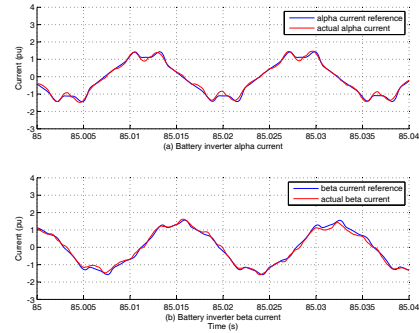


Fig. 12. Battery inverter currents in the stationary frame, $i_{b\alpha}$ and $i_{b\beta}$.

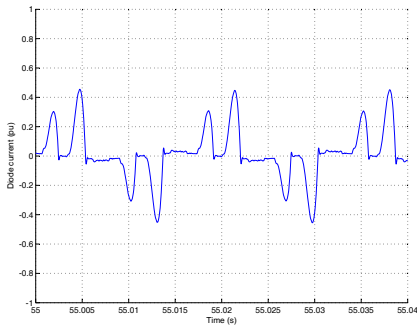


Fig. 11. Rectifier current under 0.5% unbalanced grid voltage.

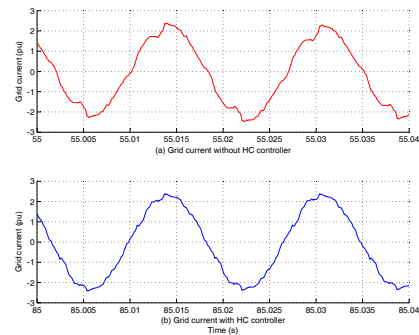


Fig. 13. Grid current under 0.5% unbalanced grid voltage, without and with controller.

Fig. 12 depicts the battery inverter current in stationary frame. The blue trace is the battery inverter α current reference and the red line is the actual α current. Since the battery has to inject harmonic currents to compensate the rectifier current, the reference current is already distorted. Thanks to the UC and HC controllers, the actual current tracks the reference in a precisely manner both on α and β axes. Therefore, the grid phase A current shown in Fig. 13 (b) is improved comparing to Fig. 13 (a) when the HC controller is disabled. The FFT analysis of Case I is included in Fig. 14. Grid current with and without controller enabled are compared with the 5th and 11th order harmonic current are beyond the limits set by [26] when the HC controller is disabled. With the help of HC controller, all odd order harmonic currents are less than the limits. The THD of grid current without HC controller is 11.3% while the THD of grid current decreases to 5.1% with HC controller enabled.

Due to the page limits, the two other case studies are not

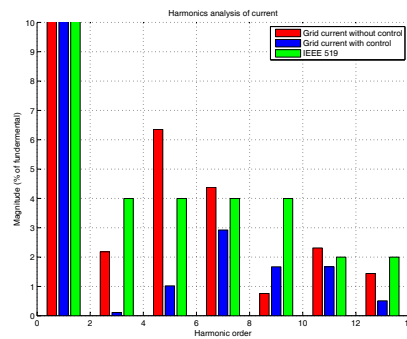


Fig. 14. FFT analysis of grid current under 0.5% unbalanced grid voltage.

presented in this paper. A longer version of this paper is posted at

<http://power.eng.usf.edu>.

V. CONCLUSION

Slight voltage unbalance can lead to high degree of unbalance and harmonics in currents in a microgrid with induction machine and rectifier loads. This paper explores the capability of a battery's inverter in power quality improvement. A PR controller is designed to mitigate unbalanced and harmonic currents. The controller is tested under different level of grid voltage unbalance. The case studied in RT-LAB shows the battery inverter can successfully compensate unbalanced and odd harmonic currents when the grid voltage has 0.5% and 2% negative sequence component. The THD level and profile of harmonic currents meet the requirement of corresponding IEEE standard. However, when the negative sequence component increases to 4%, the 3rd and 5th harmonic currents slightly exceed the limit. This phenomenon implies the battery inverter can improve the grid current profile at the PCC without any additional investment. However, it may need additional solution in order to improve the current distortion if the grid voltage contains high level of unbalanced component.

APPENDIX A

Controller parameters:

$$K_p = 0.02, K_{ih} = 500.$$

Controller bandwidth:

1st order harmonics: 1.036 Hz

3rd order harmonics: 2.914 Hz

5th order harmonics: 4.713 Hz.

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