Voltage Unbalance Compensation for Islanded Microgrids with Hybrid Control Approach

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***Abstract*—Voltage unbalance is one of the challenges of low-voltage microgrids. It is often caused by unbalanced loads connected to the microgrid. Its compensation is required to ensure an efficient microgrid operation. In this paper, a voltage unbalance compensation mechanism based on modifying the control signals is explored. A hybrid control scheme is used to control and regulate the distributed generators (DGs) inverters in an islanded low voltage microgrid. The DGs inverters are either controlled as grid-forming or grid-feeding units. A voltage unbalance compensation mechanism using local measurements is used to reduce the voltage unbalance at the different points throughout the microgrid. This voltage unbalance compensation is performed only by the grid-forming controller which uses local voltage measurements only. The compatibility between the control algorithm and the compensation mechanism is shown through different test scenarios. The simulation results obtained using Matlab/SimscapePowerSystems prove the effective performance of the proposed approach.**

***Index Terms*—AC microgrid, islanded, unbalanced loads, inner-loop control**

I. Introduction

The use of microgrids as a solution to overcome the challenges of rural electrification and the challenges of the transition to renewable energies has been progressively increasing. This is due to their decentralized characteristics and ability to incorporate renewable energy sources. AC microgrids exhibit a similar behavior to the main electrical grid. While this allows transposing techniques used in the main grid, it also means that AC microgrids suffer from similar power quality problems. Along with nonlinear loads, unbalanced loads are one of the two main sources of power quality problems in microgrids [1]. One of the most common sources of unbalance is the connection of single phase loads [2].

Because of the lack of support from the main grid, unbalanced loads can greatly degrade the power quality of microgrids. This type of unbalance can lead to abnormal operation by causing vibrations, over-heating, and over-voltage of equipment [3]. The voltage unbalance caused by the unbalanced loads can also significantly affect the stability of the microgrid. The reason is that when there is a voltage unbalance on the system, the direct d and quadrature q components of signals will not be steady and oscillate. This can degrade the performance of controls that use signals in the $dq-$ synchronous reference frame [4].

The connection of single phase loads can lead to an unbalances that causes either an increase on the negative sequence (NS) or the zero sequence (ZS). This paper focuses on a compensation mechanism dealing with mitigation of the negative sequence. As mentioned in [3], one way to compensate for the unbalance is by using active power filters. However, this is not an economical solution. Approaches such as the one shown in [5], suggests using one inverter for power injection and another one for voltage unbalance compensation. In this paper the possibility of having the controller of the distributed generators (DGs) voltage source inverter (VSI) compensate directly the voltage unbalance without additional elements is explored. In [2], an offline compensation mechanism proportional to the negative sequence of the reactive power is used. It expanded on previous works by proposing the injection of the compensation signal at the input of the voltage controller along with the voltage reference. This was done so that the compensation signal would not be considered as a disturbance by the voltage control loop. Another approach is presented in [6], where the compensation mechanism is proportional to the negative sequence of the voltage and not of the reactive power. The focus of the previously mentioned approach is the compensation of the unbalance at the point of common coupling (PCC) requiring the use of low bandwidth communication links. The voltage unbalance factor (VUF) can be reduced successfully, but the output voltage of the compensating DGs becomes unbalanced.

In this paper, the effectiveness of an voltage unbalance compensation mechanism that uses local measurements in combination with a hybrid inner control loop approach is explored. The voltage unbalance compensation mechanism used is a compensation proportional to the negative sequence of the voltage using local measurements. The proposed method allows to reduce the VUF throughout the microgrid without increasing the VUF at the output of the compensating inverter. The compensation is carried out solely by the grid-forming VSI and is able to reduce the VUF throughout a low voltage islanded microgrid. The paper is organized as follows. Section II describes the hybrid control scheme that manages the microgrid. Afterwards, in section III the voltage unbalance compensation mechanism is described. Section IV shows the different tests performed and the obtained results. Finally, the conclusion is discussed in section V.

II. Microgrid Control Architectures

Fig. 1 gives the architecture of a three-phase microgrid composed of a battery and two photovoltaics (PV) sources. Each DG is connected to the PCC through a voltage source inverter (VSI), an LC filter, and a line impedance. Each LC filter is represented by a resistance R_{fi}, an inductance L_{fi} and a capacitor C_{fi}. The battery inverter is controlled as a grid-forming inverter, while the inverter of the PVs are controlled as grid-following inverters. The line impedance is represented by a resistance R_{linei} and a reactance X_{linei}.

A constant DC voltage is assumed at the inverter input for modeling the primary energy source, thereby decoupling dynamics of the primary source from the AC microgrid. This implies that the microgrid dynamics and stability are imposed by the implemented microgrid control system [7].

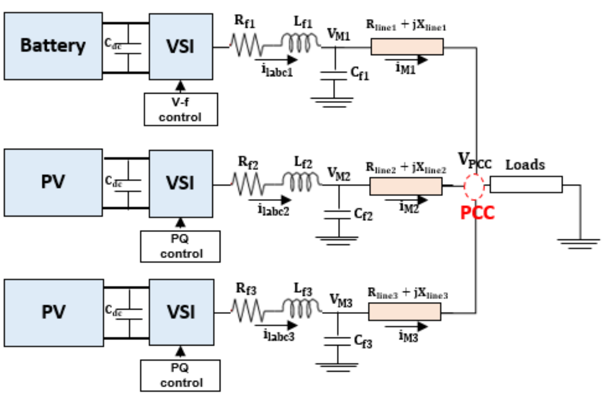

Fig. 1. Microgrid control architecture based on the grid-forming VSI and grid-following VSI

The implemented microgrid control system is performed by a hybrid control based on grid-forming VSI and grid-following VSI [7]. The VSI interfacing the battery is acting as the grid-forming element while the VSI connected to the PVs are the grid-following VSI. The grid-forming VSI controls the voltage magnitude and imposes the microgrid frequency (V-f control). Whereas, the grid-following VSI controls the injected active and reactive currents into the microgrid (P-Q control). These two VSI control systems are achieved in the $dq-$synchronous reference frame as described in Fig. 2 and Fig. 3.

Fig. 2 gives the voltage control structure of the grid-forming VSI [8]. It consists of an inner current and an outer voltage control loop. Proportional integral (PI) controllers are used to control the voltage error signals ($V^*_{Md1} - V_{Md1}$ and $V^*_{Mq1} - V_{Mq1}$) and the current error signals ($i^*_{ld1} - i_{id1}$ and $i^*_{lq1} - i_{iq1}$). Where V^*_{Md1} and V^*_{Mq1} are the set points of the components of the microgrid voltage. V_{Md1} and V_{Mq1} are the measured components of the microgrid voltage. i^*_{ld1} and i^*_{lq1} are the current set points, and i_{ld1} and i_{lq1} are the measured components of the current on the filter inductance. The PI controllers are modeled through a proportional gain K_{Pi} and an integral gain K_{Ii}.

The compensation terms are added at the output of each loop to compensate for the disturbances caused by the physical system. The feed-forward terms V_{Md1} and V_{Mq1}, and the decoupling terms $-\omega L_{f1} i_{lq1}$ and $\omega L_{f1} i_{ld1}$ are added at the output of the current control loop. The feed-forward terms Fi_{Md1} and Fi_{Mq1} along with the decoupling terms $-\omega C_{f1} V_{Mq1}$ and $\omega C_{f1} V_{Md1}$ are added at the output of the voltage control loop. In addition, Fig. 2 shows that the system frequency is imposed through the instantaneous angle θ_1, which is used for the dq to abc transformation.

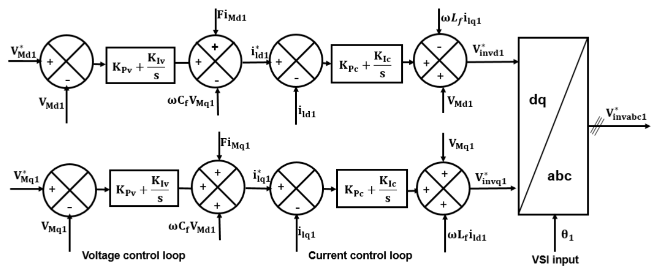

Fig. 2. Control system structure of the grid-forming VSI

Fig. 3 gives the control structure of the current loop in the grid-following VSI. The active and reactive currents are controlled through the direct $i_{ld2(3)}$ and quadrature $i_{lq2(3)}$ components of the current respectively. The phase angle $\theta_{2(3)}$ of the microgrid bus voltage $V_{M2(3)}$ is tracked by using a phase-locked loop (PLL) [7].

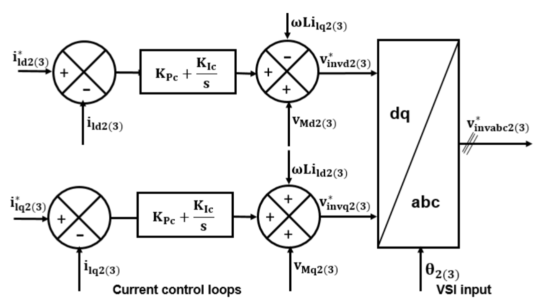

Fig. 3. Control system structure of the grid-following VSI

III. Voltage Unbalance Compensation

A. Unbalance compensation reference

The voltage unbalance is often caused by the connection of single phase loads to the grid. The level of unbalance is assessed through the voltage unbalance factor (VUF). The VUF should be limited to 2% as recommended by the International Electrotechnical Commission (IEC) [6]. According to [9], the true definition of voltage unbalance is the ratio of the negative sequence (NS) voltage over the positive sequence (PS) voltage as shown in (1).

$$\%VUF = \frac{Negative\ sequence\ voltage}{Positive\ sequence\ voltage} * 100 \qquad (1)$$

The positive and negative sequence is obtained through the Notch filtering method. In this approach, the symmetrical component decomposition is done through the usage of the dq transformation along with low pass filters [10]. If the positive rotation frame wt is used for the dq transform, the positive sequence will appear as a DC signal, and the negative sequence as an AC signal. If the negative value of the rotation frame $-wt$ is used, the negative sequence will appear as a DC signal, and the positive sequence as an AC signal. By using low pass filters, it is possible to obtain the positive sequence dq values v_{dq}^{+} and the negative sequence dq values v_{dq}^{-}. The main positive and negative sequence can be calculated as shown in (2) and (3).

$$V_{dq}^{+} = \sqrt{(v_d^{+})^2 + (v_q^{+})^2} \tag{2}$$

$$V_{dq}^{-} = \sqrt{(v_d^{-})^2 + (v_q^{-})^2} \tag{3}$$

Once the positive and negative sequences are obtained, the negative sequence compensation system is implemented as shown in [6]. The VUF of the system is calculated and is compared against a reference VUF*. The difference is fed into a PI controller. The output signal of the PI controller is then multiplied by the negative sequence voltage. The final output is the Unbalance Compensation reference UCR_{dq}. The described process is illustrated in Fig. 4 [6].

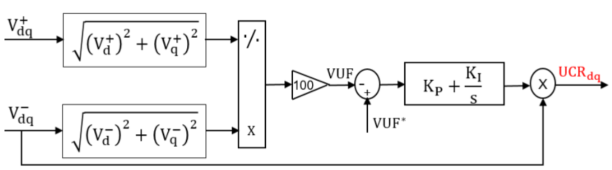

Fig. 4. Unbalance compensation reference generation

B. Application with the hybrid control

The voltage unbalance compensation in the hybrid control system in this paper is done only by the grid-forming VSI. This is because the microgrid control system is composed of only one grid-forming VSI, which maintains the voltage magnitude and imposes the system frequency. The modified voltage control structure is given in Fig. 5. This modification consists of adding the compensation signals UCR_d and UCR_q at the input of external voltage control loops.

The UCR_d and UCR_q signals generated in Fig. 4, are not directly added to the grid-forming VSI. They are first transformed into their $\alpha\beta$ frame equivalent $UCR_{\alpha\beta}$ using the negative rotation frame $-wt$. Then, they are converted back into the dq frame using the positive rotation frame wt. After this, they can be added into the voltage control loops. This is done because the obtained negative sequence compensation signal UCR_{dq} is a negative sequence appearing as a DC signal. However, the inner-loop control is done using the positive rotation frame where the negative sequence will appear as an AC signal. Thus, in order to do the compensation, the signal UCR_{dq} must be added in its equivalent AC signal representation.

The compensation mechanism as described in [6] is a low bandwidth communication system with a focus on improving power quality at the PCC. The low bandwidth communication is used to send the measurements of the voltage unbalance at the PCC to the other controllers that will perform the compensation. In this paper, the compensation mechanism is implemented without communication, and thus uses local measurements. In other words, the voltage unbalanced measured to generate the unbalance compensation reference UCR_{dq} is the one at the output of the grid-forming VSI.

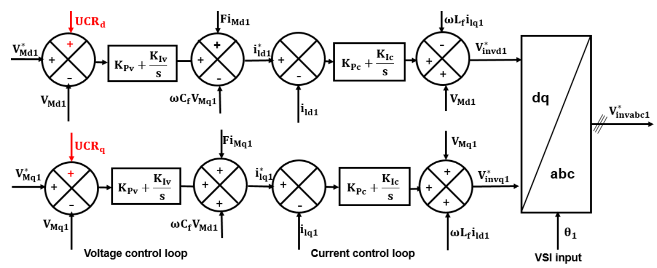

Fig. 5. Unbalance compensation reference applied to the grid-forming VSI

IV. Results

In order to test the compatibility of the control system and the compensation mechanism, the islanded microgrid shown in Fig. 1 is used. A simplified schematic of the islanded microgrid is shown in Fig. 6. The microgrid consists of three different VSI and their corresponding energy sources that are connected to the PCC through cables of different lengths. The energy sources are modeled using an average model. VSI1 is acting as a grid-forming VSI to maintain the voltage magnitude and frequency at 230 V RMS and 50 Hz. Meanwhile, VSI2 and VSI3 are acting as grid-following VSIs that inject 3 kW and 5 kW respectively. The studied microgrid is a low voltage one in which the lines are mainly resistive. The line parameters are detailed in Table I. The PI controller parameters and LC filter parameters are shown in Table II.

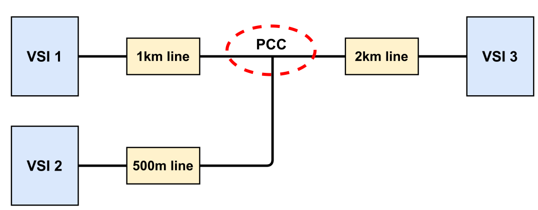

Fig. 6. Test microgrid layout

TABLE I
Typical Line Parameters [11]

Type of line	R' Ω/km	X' Ω/km	I_N A	$\frac{R'}{X'}$
Low voltage line	0.642	0.083	142	7.7
Medium voltage line	0.161	0.190	396	0.85
High voltage line	0.06	0.191	580	0.31

TABLE II
PI CONTROLLER AND LC FILTER PARAMETERS

PI controller and LC filter	K_P	K_I	L_f mH	C_f μF
VSI1: Voltage control loop	1.1	2.8	19.2	11.7
VSI1: Current control loop	120	6000		
VSI1: VUF control loop	0.5	2.5		
VSI2: Current control loop	120	6000	40.6	5.6
VSI3: Current control loop	120	6000	9.6	23.4

In each test, the system will be started with an initial load of 8 kW and 5 kVAR. During its stabilization, the system will first experience a voltage unbalance even if no unbalanced load is connected. As the system reaches its steady state the VUF decreases until it reaches a value close to zero. Fig. 7 shows the previously described behavior during the initialization of the system. In Fig. 7 the VUF before $t = 0.2s$ is not registered as it corresponds to significant high values due to the system start-up. Once the system has stabilized, a single phase load representing 25% of the initial load is connected. This load represents 2 kW and 1.25 kVAR connected between two phases, which causes the unbalance. The compensation mechanism is activated $t = 0.2s$ after the system is started. The activation is done at this time in order to avoid the high unbalance linked to the system start-up transient as shown in Fig. 7. Once it is started, the compensation remains active and reacts accordingly to changes in the VUF.

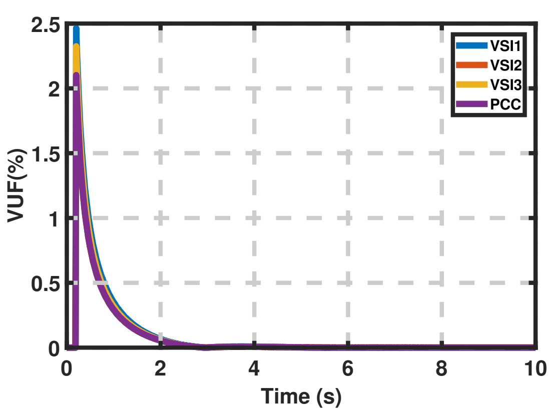

Fig. 7. Voltage unbalance during microgrid initialization

The efficiency of the proposed approach is assessed in different tests. The difference between them is where the unbalanced load is connected in the microgrid. The first test evaluates the effect of having the single phase load connected at the PCC. The subsequent tests examine the connection of the single phase load at the output of the different VSIs.

A. PCC test

First, the connection of the unbalanced load at the PCC is tested without using the compensation. As shown in Fig. 8 and Fig. 9, the grid-following elements inject the power specified. Meanwhile, VSI1 adjusts its active and reactive power output to compensate the connection of the unbalanced load at $t = 2s$.

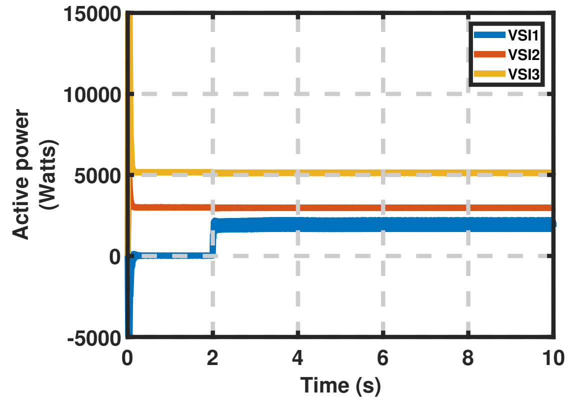

Fig. 8. Active power with an unbalanced load connected to the PCC at $t = 2s$

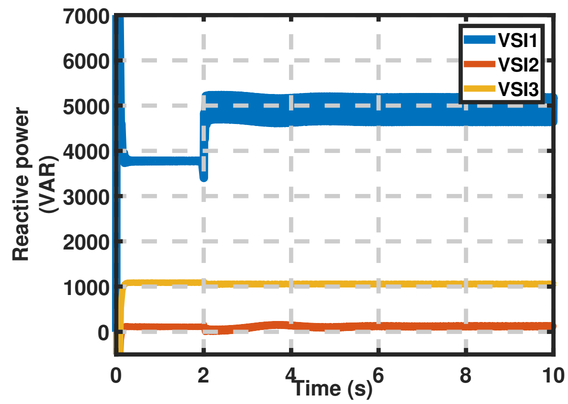

Fig. 9. Reactive power with an unbalanced load connected to the PCC at $t = 2s$

It can be seen in Fig. 10 that the unbalanced load not only causes the VUF to rise at the PCC, but also the VUF at the different VSIs. The resulting VUF is above the recommended limit of 2%, and thus it should be reduced. Conversely, in Fig. 11 and Fig. 12 the unbalanced load is connected again at $t = 2s$, but the voltage unbalance compensation mechanism is active. It can be seen that the VUF initially increases, but it does not reach the limit as before due to the action of the compensation mechanism. The system is able to successfully maintain the VUF below the recommended limit of 2%. The VUF is reduced more for VSI1 than for the other points. This is because the compensation is injected by VSI1 based on its local measurements. Therefore, it is more effective at that point. In the case of the RMS voltage, it is seen that as the VUF is reduced the grid-forming VSI returns to the nominal voltage of 230 V.

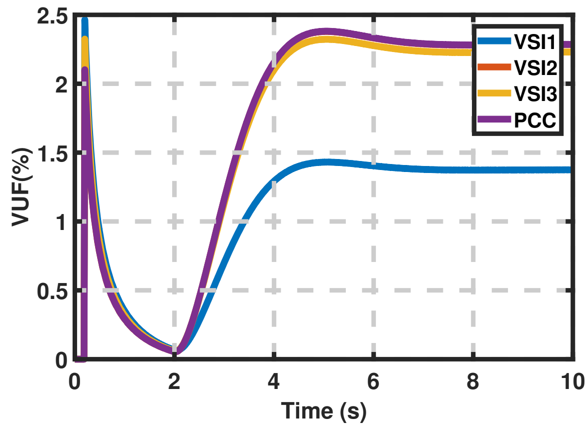

Fig. 10. VUF with an unbalanced load connected to the PCC at $t = 2s$ with no unbalance compensation

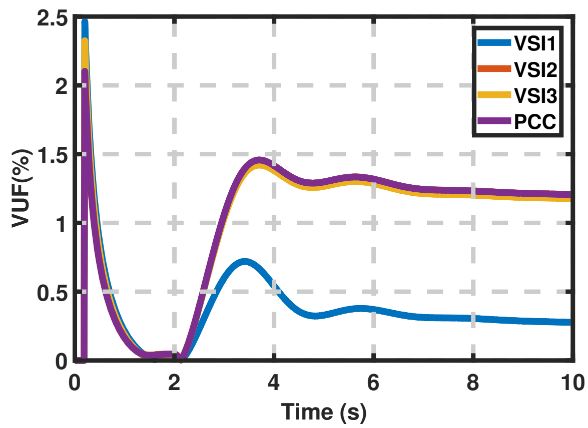

Fig. 11. VUF with an unbalanced load connected to the PCC at $t = 2s$ with unbalance compensation

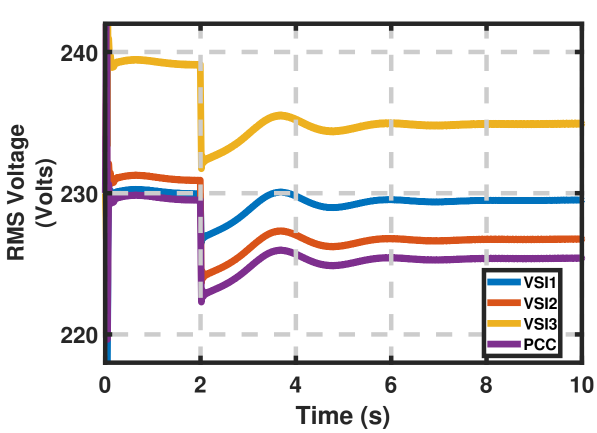

Fig. 12. RMS voltage at the VSI output with an unbalanced load at the PCC with unbalance compensation

B. Non-PCC test

In the following simulations, the effectiveness of the compensation mechanism when the load is connected to locations different to the PCC is evaluated.

1) Unbalanced load at VSI1: Fig. 13 presents the VUF % reached if no compensation is used. It is seen that the VUF increases due to the connection of the unbalanced load. If the voltage unbalance compensation is active, the results shown in Fig. 14 is obtained. As the VUF is rising, the compensation is increased thus reaching a smaller peak compared to the case with no unbalance compensation. The peak of the VUF for the whole microgrid is limited by the grid-forming VSI. As its inner loop control will act to limit the voltage deviations of the unbalance load connected at its output. Equally the compensation will be more significant as the unbalance load is at the point where the local measurements are done.

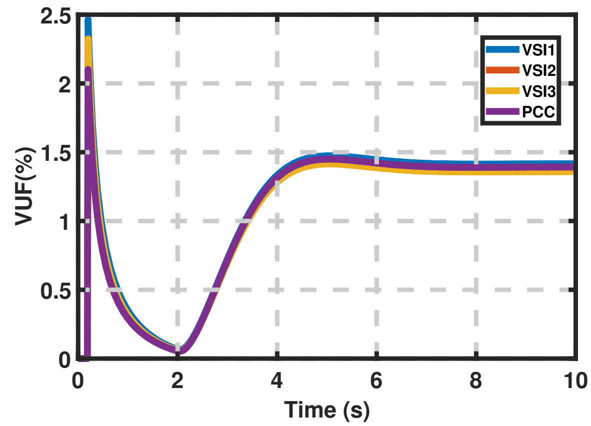

Fig. 13. VUF with an unbalanced load connected to VSI1's output at $t = 2s$ with no unbalance compensation

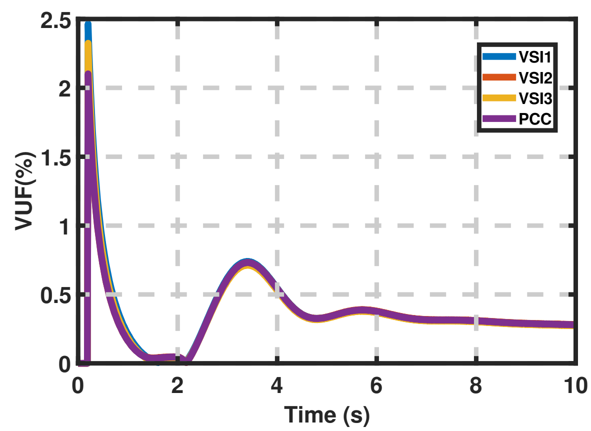

Fig. 14. VUF with an unbalanced load connected to VSI1's output at $t = 2s$ with unbalance compensation

2) Unbalanced load at VSI2: The simulation is once again done, but connecting the unbalanced load at the output of VSI2. Without any compensation, a similar result is obtained. Only VSI1 does not exceed the recommended limit, but the other points do. VSI2 has the highest percentage of voltage unbalance as the unbalanced load is connected at its output. This can be observed in Fig. 15

In Fig. 16, the effectiveness of the unbalance compensation is shown. The VUF is reduced at the different points below the recommended limit. If compared to the compensation done when the unbalanced load is at the PCC in Fig. 11, it is seen that similar results are obtained, except for the VUF of DG2. This is due to the unbalanced load being connected at the output of DG2.

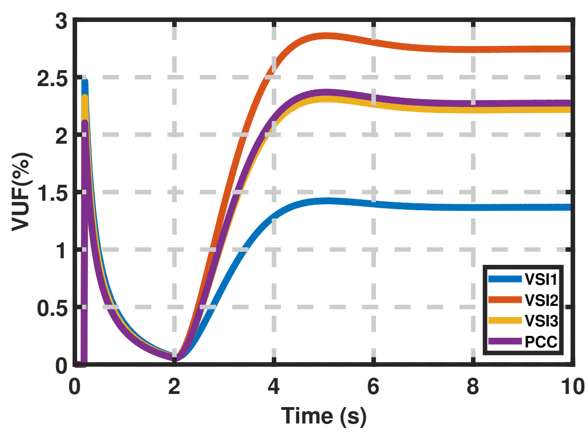

Fig. 15. VUF with an unbalanced load connected to VSI2's output at $t = 2s$ with no unbalance compensation

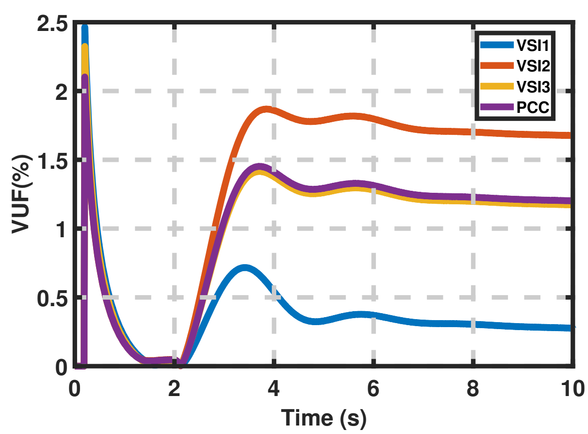

Fig. 16. VUF with an unbalanced load connected to VSI2's output at $t = 2s$ with unbalance compensation

V. Conclusion

The proposed hybrid inner-loop control based on grid-forming VSI and grid-following VSI is implemented along with a voltage unbalance compensation mechanism using local measurements in a low voltage islanded microgrid. The shown results demonstrate that the system is able to reduce the VUF to acceptable levels independently of the position of the load. The VUF reduction is carried out by a single grid-forming VSI without increasing the VUF at its own output. The proposed approach can be used if the unbalanced loads are connected at different points throughout the microgrid. Furthermore, it could also be used to complement a communication based compensation in case of communication failure. The propagation of the voltage unbalance and the compensation as well are dependent on the impedance between the elements of the microgrid. In the case of a microgrid with more connections and longer lines having more compensating VSIs can be envisioned.

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