Unbalanced Load Compensation by Power-Based Control in the Synchronous Reference Frame

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***Abstract*-- Power-based control has proven to be an effective and robust way for having a centralized control scheme in a microgrid. The scheme has a minimal communication requirement, which enables the distributed energy resources (DERs) in the system to share the load proportionally according to their capability. This paper proposes a modification of the conventional power-based control, which is applicable to the synchronous reference frame. The proposed scheme enables unbalanced load compensation, while reducing the necessary communication between the master controller and the local inverter controllers. Finally, the scheme also proposes weighting factors for reducing the voltage unbalance factor of the grid. The proposed scheme is valid for three-phase three-wire systems. The effectiveness of the scheme is shown through numerical simulations.**

***Index Terms*—Master/slave control, microgrid, unbalance compensation.**

I. Introduction

In addition to paving the way for smart grids, microgrids present several advantages such as reduced feeder losses, improved reliability and possibility for delivering ancillary services [1], [2]. However, the microgrid philosophy also leads to challenges. One of the major challenges of microgrids has been to operate properly in both islanded and grid-connected modes.

The two main categories for control schemes in microgrids are centralized and decentralized control. The decentralized control has been widely studied in the literature, and is based on applying droop control [3]. This type of control enables each inverter to regulate the voltage at the terminals it is connected to. The main advantage of the decentralized control strategy is the ability to control the microgrid autonomously, i.e. without a central controller and a fast communication system, thus achieving enhanced reliability. Furthermore, no single generation unit is indispensable, which contributes to the improved reliability. However, the conventional droop scheme suffers from poor reactive power sharing, and poor power quality in the presence of non-linear or unbalanced loads [4].

The other control philosophy is based on having a centralized control, in which a centralized master controller determines the function of the inverters in the system. In a centralized type of control, most inverters are acting as current sources, injecting power according to references given by a master controller. In contrast to the decentralized scheme, the primary control function depends on communication, thereby rendering the centralized scheme less reliable due to the potential failure of either the master controller or the communication system. However, in practical applications of microgrids that are installed today, low-bandwidth communications are included [5]. Hence, it is reasonable to study this type of microgrids as well.

An early proposal for a central power-based control for microgrids is given in [6]. The goal here was to cooperatively compensate grid non-idealities based on the conservative power theory (CPT). The approach consisted in letting static VAR compensators (SVCs) compensate reactive power and unbalances, whereas active power filters (APFs) compensated void terms.

A more recent example of a centralized architecture using power-based control (PBC) is presented in [7]. In this scheme, a centralized controller is acting as a master controller, giving active and reactive power references to all the DER units in the system. The advantage of this approach is fast dynamic response, good stability and good robustness to grid parameter variations [7]. This scheme was only devised for balanced systems, i.e. all DER units only inject positive sequence components.

The distribution network typically contains a large number of single-phase loads, thereby leading to unbalances in the system. Moreover, a large portion of low power DER units are also single-phase. Therefore, it is likely that a real microgrid would be an unbalanced system. An extension of the PBC for enabling unbalance compensation at the microgrid PCC was given in [8]. The proposed scheme specifies the power to be injected in each phase. The modified scheme is devised in the stationary reference frame, and is capable of compensating unbalanced loads, but requires a greater extent of communication than the original scheme.

Another way of compensating voltage unbalances was proposed in [9], in which each distributed generator (DG) consists of two-inverters, capable of controlling the voltage unbalance in addition to the power flow. However, this increases both the cost and size of the DG converter. In [10], a decentralized way of compensating load unbalance is proposed, in which a harmonic conductance is drooped against negative sequence reactive power.

The approach in [11] utilized a hierarchical control structure, with droop control as the primary control loop. The secondary controller set a reference for each inverter in order to achieve a certain voltage unbalance factor (VUF) at the point of common coupling (PCC). An extension of the hierarchical scheme is given in [12], where a tertiary controller is employed for allowing different portions of the microgrid to have different VUFs. This approach is effective, but is associated with relatively large time constants due to the hierarchical control.

The aim of this paper is to propose a modification of the PBC applicable to the synchronous reference frame, taking unbalanced loads into account, while minimizing the amount of required communication. A method for efficient unbalance compensation by letting the converters closest to the unbalances perform a larger share of the compensation is also presented. In particular, the scheme applies to three-phase three-wire systems containing unbalanced loads. The proposed control is based on a low-bandwidth communication (LBC) link between the master controller and DERs, and provides fast compensation capabilities.

The rest of the paper is organized as follows. Section II briefly describes the conventional PBC, before introducing the proposed scheme. Then, Section III describes the implementation of the control of each DER in the PBC. Section IV presents a set-up and simulation results for validation of the proposed scheme, before Section V discusses the findings. Finally, Section VI concludes the paper.

II. Power-Based Control

This section gives a brief overview of the power-based control. Then, the proposed modification will be presented for achieving a reduced communication requirement, in terms of exchanged quantities. Finally, an unbalance compensation scheme aimed at reducing the unbalance factor of the microgrid is proposed.

A. Original Power-Based Control

The original and extended PBC were presented in [7], and [8], respectively. In short, the PBC consists of three main subsystems; the utility interface (UI), energy gateways (EGs) and loads. The UI contains the point of connection to the distribution grid, an inverter with storage capabilities and a master controller (MC). The UI acts as a grid forming and grid following device in islanded and grid connected modes, respectively. The MC calculates set points for active and reactive power injection by the EGs, which are subsystems containing both energy storage and production, e.g., PV or wind turbines with a battery. This calculation is done in the MC based on $11N$ variables from the EGs, where *N* is the number of EGs. The 11 variables from EG *n* are the active and reactive power per phase, $P_{n,abc}$ and $Q_{n,abc}$, the estimated total active power during the next control cycle, $\hat{P}_n$, the minimum and maximum estimated power during the next control cycle, $\hat{P}_{n,min}$ and $\hat{P}_{n,max}$, the apparent power rating $\hat{A}_n$ and the temporary overloading capability $\hat{A}_{n,over}$. The set points are transmitted through LBC links, by distributing the six variables α_{Pabc} and α_{Qabc}. Here, *abc* represent each of the three phases. The resulting communication requirement for the PBC is shown in Fig. 1a).

The original PBC only accounted for balanced, positive sequence power [7]. This led to low communication requirements, as only two values were distributed by the MC, and each EG sent seven power quantities, since the total active and reactive power could be specified as three-phase quantities, instead of the per phase values. However, this strategy cannot compensate load unbalance over the microgrid. The PBC proposed in [8] extended the original scheme to apply for each phase, thus requiring the MC to distribute six variables, and each EG returning up to eleven variables.

B. Proposed Power-Based Control in the dq-Frame

Figure 1b) shows the proposed PBC for the synchronous reference frame. In terms of communication, it represents a middle ground between the original and the modified PBC, as only four variables are distributed by the MC, whereas each EG returns seven variables. The scheme is valid for three-phase three-wire systems, in which the zero-sequence is not present. Excluding the zero-sequence limits the degrees of freedom, such that the power demand can be completely specified by four variables: α_{d+} and α_{q+} give the set point for the positive sequence active and reactive power as in the conventional PBC, whereas α_{d-} and α_{q-} determine the set point for compensating the negative sequence components. They are defined and calculated in the MC as follows:

$$\alpha_{d-}(k+1) = \frac{\frac{3V_{rms}}{\sqrt{2}} i_{g,d-}(k)}{\sqrt{P_{Ltot}^2(k) + Q_{Ltot}^2(k)}} + \alpha_{d-}(k) \tag{1}$$

$$\alpha_{q-}(k+1) = \frac{\frac{3V_{rms}}{\sqrt{2}} i_{g,q-}(k)}{\sqrt{P_{Ltot}^2(k) + Q_{Ltot}^2(k)}} + \alpha_{q-}(k) \tag{2}$$

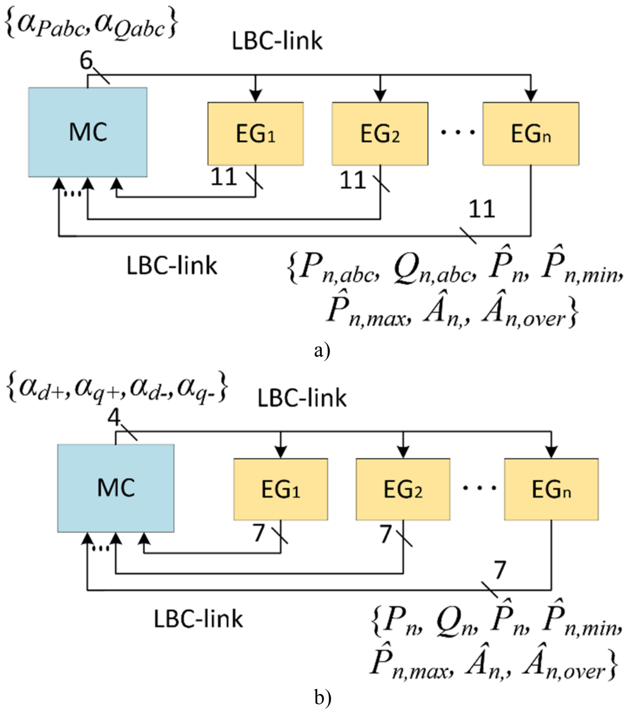

Fig. 1. Communication in the a) conventional and b) proposed PBC.

Here, $i_{g,dq-}$ denotes the negative sequence of the grid currents in the dq frame, V_{rms} is the nominal phase voltage of the grid voltage, k denotes the control cycle, while P_{Ltot} and Q_{Ltot} denote the sum of the active and reactive power delivered by each EG, the grid and the UI.

The main goal with this definition of α_{dq-} is that the negative sequence power will be supplied by the EGs, and not be drawn from the grid. This is achieved since the equations are recursive, and update as long as the there is a negative sequence grid current i_{gdq-}. The EGs then simply multiply their apparent power with α_{d-} and α_{q-} to find the negative sequence power they shall inject. This is described more closely in Section III.

Setting α_{d-} and α_{q-} according to (1) and (2) ensures that the negative sequence currents are only injected by the EGs. In particular, no negative sequence currents are drawn from the grid in steady state. Compared to the original PBC formulation, no extra measurements are needed. In particular, it is not necessary to measure the power of each phase individually. The only additional requirement is to calculate the negative sequence of the grid current.

C. *Proposed Weighting Factor for Shared Unbalance Compensation*

It is important that the EGs in the network share the load according to their availability of power and rating of the converters. This is ensured in the original formulation of the PBC. However, when it comes to unbalance compensation in cases where there are considerable distances between the EGs, it might be more desirable that the converter closest to the unbalance compensates a larger share, in order to limit the negative sequence voltage drop over long distances. This can be achieved by multiplying the variables α_{dq-} with a weighting factor implemented locally at each EG controller. A method for achieving this is proposed in the following.

In order to determine the electrical distance between an EG and the load it is supplying, the collective rms voltage $\boldsymbol{V}_{cn}$ is calculated for each EG n, as defined in:

$$\boldsymbol{V}_{cn} = \sqrt{V_{a,rms,n}^2 + V_{b,rms,n}^2 + V_{c,rms,n}^2} \tag{3}$$

where $V_{abc,rms,n}$ are the rms values of each of the phase voltages. Each EG sends this information to the master controller, which calculates the average value of the collective rms voltages of the EGs as given by:

$$\overline{\boldsymbol{V}} = \frac{1}{N}\sum_{n=1}^{N} \boldsymbol{V}_{cn} \tag{4}$$

This value is then distributed to the EGs. The difference between the local collective rms voltage and the average collective rms value is then used as an error signal to adjust the local weighting factor. The proposed weighting factor is given by:

$$\gamma = 1 + (\overline{\boldsymbol{V}} - \boldsymbol{V}_{cn})k_{wf}, \qquad 0 \le \gamma \le 2 \tag{5}$$

where k_{wf} is a weighting factor gain that determines how much each EG alters its unbalance compensation. A larger gain means that the weighting factor reacts more to the error signal, and hence that the unbalance compensation becomes more unevenly distributed between EGs. The weighting factor is lower bounded to zero so that no EG demands unbalanced power. The weighting factor upper bound is added for achieving symmetry for the weighting factors. The upper bound for the unbalance compensation is also affected by the remaining available capacity of the EG, in order to respect the ratings of the device.

The weighting factor is finally multiplied with the variables α_{dq-}, to produce the local unbalance gain, as given in:

$$\alpha_{EG,dq-} = \gamma\alpha_{dq-} \tag{6}$$

This ensures that the EGs contribute to the unbalance compensation based on their respective operating point.

III. Proposed Control of EGs

This section describes the proposed control of the EGs. The control consists of an outer power controller and an inner current controller. A phase-locked loop (PLL) is used to transform the variables to the synchronous reference frame in which the control is done.

The PLL is shown in Fig. 2. A standard PLL is used, in which the dq-frame is formed by forcing the q-component voltage to zero by means of a PI controller. The resulting frequency is then summed with a frequency reference and integrated to get the Park transformation angle θ.

The EG positive and negative sequence power controller is shown in Fig. 3. The positive sequence current references i_{dq+}^* are created by dividing the power references P^* and Q^* by the d-component voltage v_d [2]. The power references are generated as given in the original PBC [7].

The lower part of Fig. 3 shows how the negative sequence current references, i_{dq-}^* are created. As mentioned in Section II, $\alpha_{EG,dq-}$ is multiplied by the positive sequence apparent power reference of the EG in order to find the negative sequence power reference. This is further divided by the d-component voltage. In order to achieve the negative sequence currents, the dq to abc transformation utilizes the negative angle created by the PLL, before the positive angle is used as normal for the abc to dq transformation. Summation of i_{dq+}^* with the negative sequence currents, i_{dq-}^*, forms the reference for the current controller, i_{dq}^*.

The current controller is shown in Fig. 4. It utilizes feedforward of the output voltage, and a decoupling network to cancel the cross-coupling effects in steady state. In addition to this, a PI controller is used. The resulting duty cycle reference is passed through a PWM block, giving the references for the inverter. A simple L-filter is used on the ac side, while the dc side is modelled by a constant voltage source.

IV. Validation Through Numerical Simulation

To validate the proposed scheme under unbalanced load conditions, the microgrid set-up in Fig. 5 was simulated. It consists of a test microgrid with two EGs, a UI and a common load. Only the ac side dynamics of the EGs are considered, such that the dc side is modelled by a constant voltage source. The load consists of a balanced and unbalanced part. For simplicity, the UI is modelled as an ideal voltage source. The main parameters are listed in Table I. The control cycle of the MC, and hence the update rate of the α variables, is 20 ms.

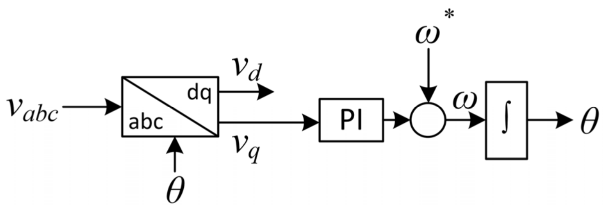

Fig. 2. Controller Phase-Locked Loop.

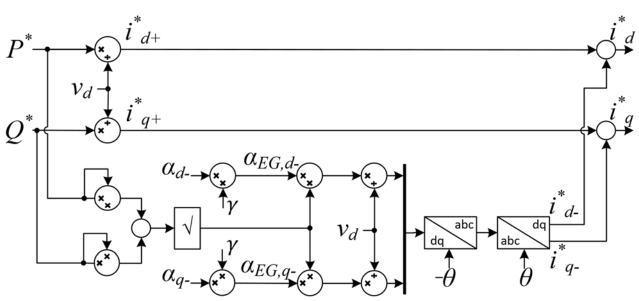

Fig. 3. Structure of EG power controller.

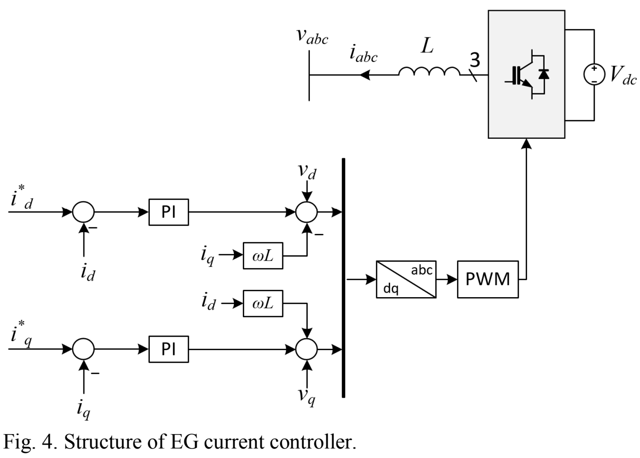

Fig. 4. Structure of EG current controller.

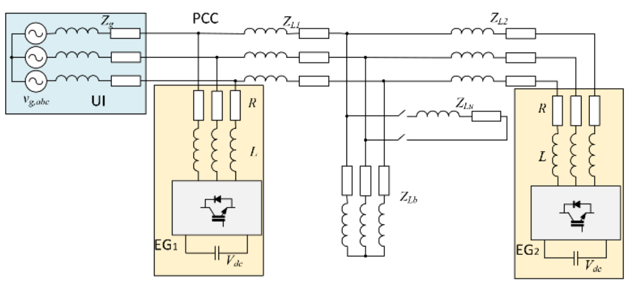

Fig. 5. Simulation setup of the test microgrid.

TABLE I
Simulation Parameters

Parameter	Value	Parameter	Value
Line voltage	400 V	V_{dc}	800 V
Frequency	50 Hz	R	0.533 Ω
EG rating	4 kVA	L	25.5 mH
Z_g	$0.6 + j\,0.3\Omega$	K_{pi}	9.89
Z_{L1}	$2.4 + j\,1.2\Omega$	K_{ii}	424
Z_{L2}	$1.2 + j\,0.6\Omega$	k_{wf}	1.2

In order to more easily see the effective elimination of the negative sequence components, island operation is considered, such that no current is supplied by the UI in steady state. The sequence of events is explained in the following. The EGs are off to begin with, such that all power is supplied by the UI. At this point, only a balanced load of 1.2 kW + 0.7 kVAr is connected. At $t = 0.5$ s, the EGs are delivering power according to the original PBC formulation [7]. At $t = 1$ s, a resistor of 100 Ω is connected between phases a and b. At $t = 1.5$ s, the proposed control is enabled without utilizing the weighting factor, before the weighting factors are enabled at $t = 2$ s. Finally, a balanced load is connected at $t = 2.5$ s.

The response of some selected currents is shown in Fig. 6. Initially, all power is supplied by the UI, before the EGs are enabled at $t = 0.5$ s, taking over the entire load current. Once the unbalanced load is connected, the EGs increase their power to cover all positive sequence current, while the UI is supplying the necessary negative sequence current. At $t = 1.5$ s, the proposed control is enabled, effectively supplying all the power and compensating the load unbalance, thereby forcing the UI current to zero. The effect of the weighting factor at $t = 2$ s is that more of the unbalanced power is supplied by EG2, as this is located electrically closer to the unbalanced load. Naturally, the currents of EG1 become more balanced. Finally, after the load step at $t = 2.5$ s, it can be seen that the UI is supplying the power transiently, before the EGs again ensure that the UI is delivering zero current.

The load voltage is shown in Fig. 7 for the different control strategies. The largest unbalance is observed for Fig. 7a), in which the original PBC is acting. The proposed PBC with and without the weighting factor enabled is shown in Fig. 7b) and c), both of which clearly improves the unbalance factor.

For a quantitative assessment of the effect of the weighting factor, consider Table II, which shows the voltage unbalance factor of selected nodes under the different PBC strategies. For the original PBC, the negative sequence currents are solely coming from the UI, which is located electrically the furthest from the load. The resulting unbalanced voltage drop leads to a relatively large VUF, particularly at the load and at the terminals of EG2. With the proposed PBC, the reduction is large at all terminals, since the unbalance compensation is shared, and it is done closer to the unbalanced load. This leads to smaller voltage drops by the negative sequence currents, thereby improving the voltage quality. The VUF at the PCC is 0 % since the UI is not delivering any negative sequence current, and the ideal grid has a VUF of 0 %.

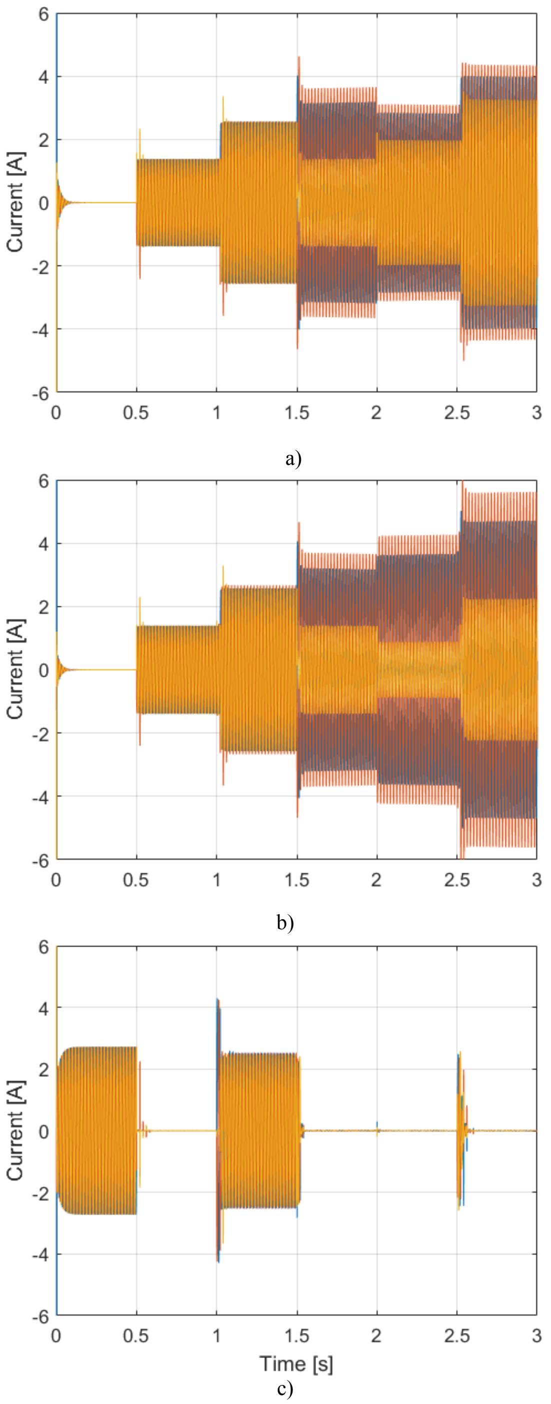

Fig. 6. Currents during simulation for a) EG1, b) EG2 and c) the UI.

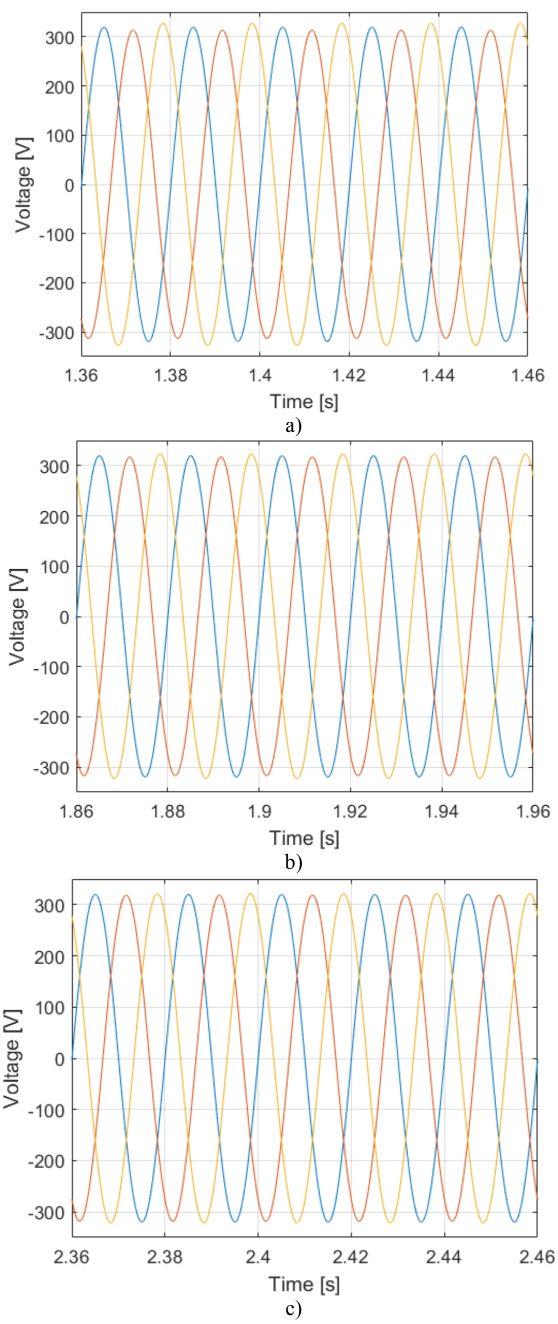

Fig. 7. Load voltages under a) the original PBC, b) the proposed PBC and c) the proposed PBC with weighting factor.

TABLE II
VOLTAGE UNBALANCE FACTOR AT SELECTED NODES

Type of PBC	VUF at PCC	VUF at EG2	VUF at Load
Original	0.51 %	2.59 %	2.63 %
Proposed without weighting factor	0 %	0.54 %	1.10 %
Proposed with weighting factor	0 %	0.29 %	0.55 %

With the proposed weighting factor, the VUF is further reduced for the load and EG2. This occurs because EG1 is supplying a smaller portion of the negative sequence load current, thereby giving a smaller negative sequence voltage drop across Z_{L1}.

V. DISCUSSION

The previous section demonstrates that the proposed scheme is capable of compensating unbalanced loads, due to its ability of compensating both positive and negative sequence currents. This enables improved voltage unbalance factors, since the negative sequence can be removed from the grid current. This can be beneficial in terms of compliance to grid codes.

The proposed scheme is designed for three-phase three-wire systems. Since zero-sequence currents are not present, this leads to a reduced need for communication compared to the case in [8], where the active and reactive power are specified for each phase individually. The reduced communication results from only four values being distributed by the MC, compared to six in [8]. In addition, in the conventional unbalanced approach, the active and reactive power of each phase has to be sent to the MC, while in the proposed scheme, only the total active and reactive power need to be sent from each EG. On the other hand, contrary to [8], the proposed scheme is not directly applicable to single-phase converters.

A disadvantage of the scheme is the need for communication. Proper actions need to be defined in case of communication failure, in order to ensure the reliability of the system. That is beyond the scope of this paper. However, as most of the microgrids being installed today utilize an LBC-link, the proposed solution seems feasible. In fact, [13] argues that the main feature of the smart grid system is a communication infrastructure.

The use of the proposed weighting factor needs to be carefully considered in a real microgrid. For a geographically small microgrid, or microgrid where it is known that the EGs are located in fairly similar distance to the load, it may not be necessary to utilize the proposed weighting factor. That way, all EGs will contribute according to their availability and rating, as in the original PBC. As long as the feeders of each of the EGs do not differ too much, the unbalance factor will remain low in most parts of the grid. However, in cases where the feeders differ more in magnitude, the proposed weighting factor can be an efficient means of improving the voltage quality of the grid by letting some EGs contribute more to the unbalance compensation than others.

Utilizing the weighting factors increases the amount of information to be sent by the EGs and the MC by one. Thus, this increases the communication requirement of the power-based control. However, the necessary variables are still less than those of the conventional PBC [8].

VI. Conclusions

This paper has proposed a modification of the original power-based control in order to take unbalanced loads into account considering lower number of exchanged variables with the master controller. The scheme is based in the synchronous reference frame. It is valid for three-phase three-wire systems, and is based on adding a negative sequence current component to the reference of the EGs. Two more variables need to be distributed by the MC compared to the original PBC, which leads to a larger need for communication. In addition, a weighting factor is proposed which enables the EGs to compensate the load unbalance based on the distance to the load, in order to improve voltage quality of the microgrid. The proposed schemes are implemented in an example microgrid, showing the effectiveness of the scheme.

Acknowledgment

This project has received funding through the research centre for environmentally friendly energy CINELDI (Centre for Intelligent Electricity Distribution), supported by the Research Council of Norway. The authors are also grateful to the Research Council of Norway (f261735/H30) for supporting the NB_POCCREI project and the related international collaboration.

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