Mathematical Foundations for Balancing Single-Phase Residential Microgrids Connected to a Three-Phase Distribution System

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This work was supported by the National Sciences and Engineering Research Council (NSERC) Discovery Grants Program under Grant RGPIN-2018-05654.

ABSTRACT With the increased installation of single-phase rooftop PV systems, in-house battery storage units, and high-power plug-in loads (i.e., EVs) at single-phase residential sites, it is prevalent that an increasing number of residential distribution systems are becoming severely unbalanced, causing power quality problems and thermal risks at distribution sub-stations. While different techniques have been investigated to resolve this issue, there is still a lack of adequate theoretical foundations to guide these approaches. In this study, a detailed analytical analysis is carried out for a typical North American residential community with single-phase power generation, storage, and high-power random plug-in loads. This analysis has laid the foundation for a class of operating scenarios and provides an essential theoretical basis to unify different techniques for dynamically balancing single-phase microgrids connected to three-phase distribution systems. Detailed formulations have been developed for the first time to draw explicit power transfer relationships among power surplus and power-deficient phases to achieve an overall dynamic balance. A user-friendly, free interactive online tool has also been developed for potential users to evaluate their own application scenarios.

INDEX TERMS Single-phase microgrids, distributed generation (DG), intra- and inter-phase power management, unbalanced systems, back-to-back converters.

I. INTRODUCTION
There has been a tremendous surge in the number of installations of residential rooftop PV systems (with local storage) over the past few years [1]. Because these systems are often connected to one phase of a three-phase system, conventional passive residential distribution networks have gradually evolved into active networks of local phase generation, causing a high degree of phase imbalance [2]. With high penetration of local generation and storage, distribution companies can strategically group a number of houses on different phases to form a three-phase microgrid [3], while power from all three phases can be used to support common facilities, such as shopping centers and schools, which are predomi-nately three-phase loads. The power imbalance among different phases can potentially be reduced or even eliminated by using interfacing back-to-back converters for power transfer from power surplus phases to power-deficient phases. Hence, such power rebalancing techniques have become a necessity for distribution networks connected with local single-phase generation [4], [5].

A power management strategy to coordinate coupled islanded microgrids is introduced in [6]. The strategy involves, polling individual microgrids for over/under load scenarios, by requesting the DG units for their unused power capacity (UPC). If the UPC of a microgrid falls below a threshold value, i.e. an overload state, the intertie switch between microgrids closes for power transfer. The architecture presented in the paper is inefficient, as it requires an additional stage of synchronization between the two microgrids before real power can be exchanged. Isolation between microgrids can be achieved through power electronics based solution.

The configuration of a typical residential single-phase microgrid is shown in Fig.1. The system allows customers to connect their PV generation and battery storage to a single-phase local network. The three single-phase networks are connected through respective back-to-back converters,
Phase-balancing techniques for three-phase microgrids is proposed in [10], [11]. In [10], a repetitive controller was developed to deal with unbalanced loads and reduce harmonic distortions. In [11], a robust controller is proposed for the same purpose. These types of controllers can be used to reduce the effects of positive and negative sequence currents caused by unbalanced loads. However, they cannot re-establish the power balance in the three phases, as in the aforementioned cases. Other power-balancing topologies that rely on converters are investigated [12]–[18]. An active power filtering technique to inject the harmonic current to compensate nonlinear loads at the DC link is introduced in [12]. Improved converter topologies using mid-point capacitors [13]–[16] or a three H-bridge single-phase inverter topology [17], [18] are proposed as active filters for balancing nonlinear loads in microgrids. The control strategies in [12]–[18] can only deal with systems having a common DC link, such as centralized PV generation and battery storage installation in the distribution network. They cannot be easily adopted for residential microgrids because there is no common DC link for a group of houses with individual PV and battery installations in a single phase.

In single-phase microgrids, the control of converters through the typical 3-phase vector control schemes is infeasible. This is because of the absence of quadrature control variables [19]. The use of proportional resonant controller is proposed in [20], [21]. Through this control scheme, the odd harmonics are damped via cascaded compensator networks. Although this solution is capable of compensating for the lower order harmonics, but the additional cascaded networks makes the control strategy complex [22]. The single-phase converter’s output current also needs to be controlled indirectly [23]. Hence, an effective control strategy needs to be developed for single-phase converters to achieve the required goals of power management under the proposed architecture.

Power management strategies for three-phase balanced MG systems are studied in [24]–[28]. Various control schemes are developed to coordinate different generation units with energy storage systems. One of these techniques is the use of a multi-segment droop control technique [24]–[26]. However, this approach works only for balanced three-phase systems, and its effectiveness is limited in residential microgrids possessing diverse, independent phase-wise power generation, distributed storage, and different load profiles in each phase.

Coordination of the three individual single-phase microgrids, involving three separate PV/battery hybrid systems, is proposed in [29], using back-to-back converters. The control of these converters between a microgrid and grid connection has also been explored. The DG units in each phase support their own loads as much as possible. However, whenever the load demand in a particular phase increases beyond the capacity of its own DG units, the utility provides additional power through the back-to-back converters to satisfy the load demand. When the local demand is lower than the local generation, the surplus power can be exported back to the grid through the back-to-back converter.

The control of an islanded single and three-phase microgrid through back-to-back converters is considered in [30]. The architecture is similar to a distribution system with single-phase loads connected to local DG units. As such, phases A and B constitute the DG units and local loads, whereas phase C contains only the load. The power exchange between phases is carried out by controlling the back-to-back converters among the three phases with unidirectional power flow to the load in phase C. An extensive control model using backstepping technique is developed in [30]. Although not all system-level equations are elaborated, they do consider some scenarios for single-phase residential microgrids. It will be shown that the mathematical formulation derived in this study can consolidate different scenarios, including some of the scenarios described in [30] with minor modifications.

Although the primary and secondary control layer strategies for single-phase residential microgrids have been developed by the same authors [7]–[9], the control strategies for transferring power from the surplus phase to the power-deficient phases have not been detailed.

In the current study, the relationship among three single-phase microgrids are analyzed, a set of formulas have...
been developed to determine the right amount of power needs to be transferred among these single-phase microgrids to establish a balanced three-phase microgrid under various operating conditions. This constitutes the main objective of the current study. The novelties lie in the fact that these formulations are fundamental in nature and are not tied to any specific phase-balancing technique; hence, they can be used by other phase-balancing techniques. As an example, these formula can be used together with three back-to-back converters connecting the three phases, as shown in Fig.1.

To the best of knowledge of the authors, it is the first time that this novel technique has been presented in the literature.

To demonstrate the effectiveness of such a formulation, six case studies were presented to cover various practical scenarios. Interested readers are also invited to try themselves with an online interactive tool kit to determine the inner workings associated with their own situations. For this purpose, a demonstrative video is provided, and an interactive tool can be downloaded using the hyperlink.

The remainder of this paper is organized as follows: In Section II, the concept of a power circle is used to describe the relationships among three single-phase microgrids in a three-phase configuration. The potential operating modes are examined in Section III, where six unique scenarios have been identified. Subsequently, detailed formulations for power transfer are developed for these scenarios in Section IV, considering the power transfer losses. The effectiveness of these formulations is demonstrated in Section V, where some existing techniques for phase balancing are shown to be special cases under this general formulation.

II. RELATIONSHIP AMONG THREE PHASES

As shown in Fig.1, the three single-phase microgrids are connected to the secondary side of the substation transformer. To minimize the stress inflicted on the transformer by the unbalanced currents drawn by these single-phase microgrids, it is desirable for the three single-phase microgrids to form a balanced three-phase system. Unlike traditional passive networks, where the balance condition corresponds to equal impedance in three phases, these active microgrids may have their own local generation, energy storage devices, and unique load profiles, such as randomly plugged in heavy loads.

These unique operating characteristics make phase balancing a challenging task. This condition can be intuitively represented by a power circle, as shown in Fig.2. The power circle consisted of three independently operated microgrids in each phase. This configuration is an accurate representation of an existing residential distribution system, where different phases are often associated with different streets or a cluster of houses. For example, Phase A has its own local loads, PV generation, battery storage, and a droop-based control system for power management, as represented by $P_{PV}^1$, $P_{Batt}^1$, and $P_{Droop}^1$ in Fig.2. Similar situations can be observed in the other two phases. The local generation and stored energy in individual phases are used to support their own loads as much as possible through a modified vector control strategy and the improved multi-segment droop strategy (see Fig.3) that have been previously proposed [7]–[9].

A. MODIFIED VECTOR CONTROL STRATEGY

For a typical 3-phase system, the implementation of vector control makes use of the inherent presence of orthogonal components of the AC voltages and currents. It uses conventional PI controllers in voltage and current control loops. However, in single-phase circuits, the presence of only real components requires the generation of orthogonal components. This methodology uses a pre-filter stage, which is a modification of the conventional vector control for 3-phase systems as shown in Fig.4, $i_f$ and $v_f$ are the converter’s output current and voltage [7]–[9]. The transfer function of the filter $G(s)$, is given by:

$$G(s) = \frac{-s + \omega_0}{s + \omega_0}$$  \hspace{1cm} (1)
FIGURE 4. Modified vector control for a single-phase converter.

where, \( \omega_0 \) is the nominal frequency of the system in rad/s. The filter characteristics include a unity gain and a 90\(^\circ\) phase shift of the real components. The quadrature components are then evaluated using this strategy to form \( \alpha - \beta \) frames for single-phase systems. The reference frames can be interchanged between \( \alpha - \beta \) and \( d - q \) by using (2) [31].

\[
\begin{bmatrix}
  d \\
  q
\end{bmatrix} = T \begin{bmatrix}
  \alpha \\
  \beta
\end{bmatrix} \Leftrightarrow \begin{bmatrix}
  \alpha \\
  \beta
\end{bmatrix} = T^{-1} \begin{bmatrix}
  d \\
  q
\end{bmatrix} \tag{2}
\]

where, \( T \) and \( T^{-1} \) are the transformation matrices to map between the \( \alpha - \beta \) and \( d - q \) reference frames, which are typical of 3-phase systems. The \( d - q \) components derived from this strategy are then used for the voltage and current control loops of the single-phase converters. This is illustrated in Fig.4.

B. IMPROVED MULTI-SEGMENT DROOP CONTROL STRATEGY

The improved multi-segment droop control strategy allows for frequency regulation in \( \phi_x \), where \( x \) can be any of phases A, B, or C. The control for different system components was carried out locally to that phase, as shown in Fig.2. This approach allows for proper coordination of the PV/battery with droop units under various operating conditions, together with the status of the battery and the capacities of the DG units. A more detailed \( P/f \) characteristics of this strategy is shown in Fig.3, where individual zones represent the contribution from different energy sources in a priority order as the load increases [7]–[9].

C. INTER-PHASE POWER MANAGEMENT

Owing to the uneven rates of local generation and consumption, it is seldom the case that these three microgrids have identical operating conditions. Therefore, viewing from the substation transformer, these three single-phase microgrids appear to be unbalanced three-phase systems. Each phase draws a different amount of current from the transformer. However, dynamic phase balancing can be achieved if power is allowed to be exchanged among the three phases. The coordination of power exchanges can be achieved through an inter-phase power management strategy, as shown in the outer arches of the power circle in Fig.2, using the improved multi-segment droop strategy developed in [7]–[9].

The inter-phase power management strategy is not limited between the two phases. In fact, the phase with surplus power can provide the required power to the other two power deficit phrases simultaneously, so that neither phase would have to draw additional currents from the substation transformer. Hence, a dynamic balance system was achieved. The back-to-back converters are controlled through multi-loop PI control schemes comprising the previously proposed modified vector control strategy, as outlined in Fig.3 [7]–[9].

D. OPERATING SCENARIOS AND MANAGEMENT OF POWER EXCHANGES

Even though the power circle in Fig.2 illustrates the basic concept of dynamic balancing among the three single-phase microgrids, it is important to consider specific conditions under different operating conditions. In total, there were six possible operating scenarios, as illustrated in Table 1. Note that the following symbols are used to represent modes of operations among these scenarios: “=” means a balanced condition with no need for any power transfer, “\( \rightarrow \)” means power transferred from the current phase to other phases; “\( \leftarrow \)” power received from another phase; and finally, “\( \leftarrow \rightarrow \)” stands for importing power from the substation transformer or shedding some local load to return to Cases 3, 4, or 5. Similar scenarios can be repeated, but with different phase designations. These are omitted herein for brevity.

E. PROBLEM STATEMENT

With the establishment of the six operating scenarios, some phases would have surplus power and other phases might run power deficiency; the important questions are: how much power should be transferred among phases so that a balanced three-phase system can be achieved in an islanded condition? More specifically, this question can be further divided into three sub-questions:

| Case | Scenarios | \( \phi_A \) | \( \phi_B \) | \( \phi_C \) |
|------|-----------|-------------|-------------|-------------|
| 1    | \( P_{Gen_A} = P_{Load_A} \) \( P_{Gen_B} < P_{Load_B} \) \( P_{Gen_C} < P_{Load_C} \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) |
| 2    | \( P_{Gen_A} > P_{Load_A} \) \( P_{Gen_B} > P_{Load_B} \) \( P_{Gen_C} > P_{Load_C} \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) |
| 3    | \( P_{Gen_A} < P_{Load_A} \) \( P_{Gen_B} < P_{Load_B} \) \( P_{Gen_C} < P_{Load_C} \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) |
| 4    | \( P_{Gen_A} > P_{Load_A} \) \( P_{Gen_B} < P_{Load_B} \) \( P_{Gen_C} < P_{Load_C} \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) |
| 5    | \( P_{Gen_A} < P_{Load_A} \) \( P_{Gen_B} > P_{Load_B} \) \( P_{Gen_C} < P_{Load_C} \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) |
| 6    | \( P_{Gen_A} < P_{Load_A} \) \( P_{Gen_B} < P_{Load_B} \) \( P_{Gen_C} > P_{Load_C} \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) | \( \leftarrow \rightarrow \leftarrow \rightarrow \) |
1) How much power need to be transferred from one phase to another phase?
2) How much power need to be transferred from one phase to the two other phases, and
3) How much power need to be transferred from the two power surplus phases to the power deficient phase?

The objective of this paper is to provide comprehensive answers to the above questions.

III. MATHEMATICAL FOUNDATIONS FOR POWER TRANSFER AMONG PHASES

Mathematical derivations are performed for the scenario in which the local intra-phase power management is unable to support the load, and the inter-phase power management must intervene to balance the phases. In short, the purpose is to determine the required power in the power deficit phase and intervene to balance the phases. In short, the purpose is to determine the required power in the power deficit phase and intervene to balance the phases. In short, the purpose is to determine the required power in the power deficit phase and intervene to balance the phases.

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For an unbalanced wye-network with local generation and consumption within a particular single-phase microgrid. Rewriting (2)–(4) using these impedances gives,

\[
V_{an} = (z_y + \Delta r_y + z_n) I_a + z_n I_b + z_n I_c 
\]

Similarly,

\[
V_{bn} = z_n I_a + (z_y + z_n) I_b + z_n I_c 
\]

\[
V_{cn} = z_n I_a + z_n I_b + (z_y + z_n) I_c 
\]

Rewriting (2)-(4) in a matrix form gives,

\[
\begin{bmatrix}
V_{an} \\
V_{bn} \\
V_{cn}
\end{bmatrix} =
\begin{bmatrix}
(z_y + z_n) & z_n & z_n \\
z_n & (z_y + z_n) & z_n \\
z_n & z_n & (z_y + z_n)
\end{bmatrix}
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix}
\]

where, \( z_n \) is the impedance in the neutral path, and \( I_a \), \( I_b \) and \( I_c \) are the line currents in the respective phases.

For an unbalanced wye-network with local generation and storage, a single-line diagram is shown in Fig.5(b). The local DG sources are at the front end of a voltage-controlled single-phase inverter, which are shown as AC sources in all three phases in Fig.5(b). To represent different scenarios, the impedance in each phase is represented by \( \Delta z_{y1} \), \( \Delta z_{y2} \) and \( \Delta z_{y3} \), where they can either be positive or negative. The distribution lines were considered resistive for this study with \( X/R \ll 1 \). Hence \( z_n \approx r_n \) and \( \Delta z_{y1,2,3} \approx \Delta r_{y1,2,3} \). The non-zero value is indicative of a mismatch between the local generation and consumption within a particular single-phase microgrid. Rewriting (2)–(4) using these impedances gives,

\[
V_{an} = (z_y + \Delta r_y + z_n) I_a + z_n I_b + z_n I_c 
\]

Similarly,

\[
V_{bn} = z_n I_a + (z_y + \Delta r_y + z_n) I_b + z_n I_c 
\]

\[
V_{cn} = z_n I_a + z_n I_b + (z_y + \Delta r_y + z_n) I_c 
\]

When local load changes, \( \Delta z_{y1,2,3} \) in each phase will change accordingly,

\[
V_{an} \neq V_{bn} \neq V_{cn}
\]

A. BALANCED CONDITIONS

Considering the first scenario in Table 1, where all phases are balanced, \( \Delta z_{y1} = 0 \). The power delivered to individual loads in each phase is given by,

\[
P_{\phi_c} = \frac{V_{an}^2 \cos \theta_L}{(z_y + \Delta r_y)}
\]

where, \( \phi_c \) represents one of the three-phases in the microgrid.

B. POWER TRANSFER FROM A SURPLUS PHASE TO A DEFICIT PHASE

To balance such a system without increasing the neutral current, the proposed methodology relies on back-to-back converters between phases for power sharing, as noted in zone D of Fig.3. A single-line diagram for this mode of operation is shown in Fig.6, where an equivalent circuit diagram is used to represent the voltage and current interrelationships in the back-to-back converter.

Without loss of generality, assuming that \( \phi_A \) is the power surplus phase and \( \phi_C \) is the power-deficient phase, the line current in \( \phi_C \) can be written as,

\[
I_{L_{\phi_C}} = I_c + I_c'
\]

where, \( I_{L_{\phi_A}} \) is the load current, \( I_c \) is the line current, and \( I_c' \) is the surplus current from \( \phi_A \) through the back-to-back
The single-phase power in \( \phi_C \) can then be written as,

\[
P_{\phi_C} = V_{cn}I_{\phi_C} \cos \theta_L
\]

where, \( \cos \theta_L \) is the line power factor. Substituting (13) in (14) yields,

\[
P_{\phi_C} = V_{cn}I_c \cos \theta_L + V_{cn}I'_c \cos \theta_L
\]

where, from Fig.6, \( I'_c \) and \( I_c \) can be derived as,

\[
I'_c = \frac{m_c V_{DC}}{z_y + \Delta r_{y3}}
\]

and

\[
I_c = \frac{V_{cn}}{z_y + \Delta r_{y3}}
\]

where, \( m_c \) is the modulation index of the back-to-back converter for \( \phi_C \) and \( V_{DC} \) is the voltage across the DC link capacitor in the back-to-back converter. Substituting (16) and (17) into (15), one gets,

\[
P_{\phi_C} = \frac{V_{cn}^2}{z_y + \Delta r_{y3}} \cos \theta_L + \frac{V_{cn}m_c V_{DC}}{z_y + \Delta r_{y3}} \cos \theta_L
\]

Simplifying (18) leads to:

\[
P_{\phi_C} = V_{cn} \cos \theta_L \left[ \frac{V_{cn} + m_c V_{DC}}{z_y + \Delta r_{y3}} \right]
\]

For the back-to-back converter connecting \( \phi_A \), the \( m_A V_{DC} \) product can be written as,

\[
m_A V_{DC} = I'_a (z_y + \Delta r_{y3})
\]

\[
V_{DC} = \frac{I'_a (z_y + \Delta r_{y3})}{m_A}
\]

Substituting (20) in (18) with proper simplification, it can be expressed as,

\[
P_{\phi_C} = V_{cn} \cos \theta_L \left[ \frac{V_{cn} + I'_a m_c V_{DC}}{m_A} \left( \frac{z_y + \Delta r_{y3}}{z_y + \Delta r_{y3}} \right) \right]
\]

Separating terms in (21) gives,

\[
P_{\phi_C} = \frac{V_{cn}^2 \cos \theta_L}{z_y + \Delta r_{y3}} + \cdots + \frac{V_{cn}I'_a m_c \cos \theta_L}{m_A} \left( \frac{z_y + \Delta r_{y3}}{z_y + \Delta r_{y3}} \right)
\]

Inter-phase

\[
+ \frac{V_{cn}I'_a m_c \cos \theta_L}{m_A} \left( \frac{z_y + \Delta r_{y3}}{z_y + \Delta r_{y3}} \right) E_{B2B\phi_A}
\]

where, the factor \( E_{B2B\phi_A} \) in (22) represents the imbalance between phases, and \( E_{B2B\phi_A} \) is the enabling signal for the back-to-back converter connecting \( \phi_A \) and \( \phi_C \).

To express (22) in terms of individual power contributions from each DG unit, (20) can be rewritten as,

\[
m_A I'_a = -\eta \cdot n \cdot \left( P_{total,A} - P_{load,A} \right) \frac{V_{DC}}{P_{PV,A}^{max} + P_{batt,A}^{max} + P_{droop,A}^{max} - P_{load,A}}
\]

where, \( \eta \) is the power loss factor of the converters, and \( n \) is the power ratio between the power deficiency in one phase and the power surplus in another phase, which determines the amount of power transferred by the inter-phase power management scheme. Furthermore, (23) can be written as,

\[
m_A I'_a = \frac{\eta \cdot n \cdot \left( V_{DC} \right)}{P_{PV,A}^{max} + P_{batt,A}^{max} + P_{droop,A}^{max} - P_{load,A}}
\]

Expanding (24) further gives,

\[
m_A I'_a = \frac{V_{DC} \left( P_{PV,A}^{max} + P_{batt,A}^{max} + P_{droop,A}^{max} - P_{load,A} \right) - \eta \cdot n \cdot \left( V_{DC} \right)}{P_{PV,A}^{max} + P_{batt,A}^{max} + P_{droop,A}^{max} - P_{load,A}}
\]

Assuming that the loss factors for power transfer between phases are identical and that \( I'_a \) is in the opposite direction to that of \( I_c \), then,

\[
m_CI_c = \eta \left[ \frac{P_{PV,A}^{max} + P_{batt,A}^{max} + P_{droop,A}^{max} - P_{load,A}}{V_{DC}} \right]
\]

The intra-phase power management in \( \phi_A \) is governed by the following criteria:

\[
\begin{align*}
P_{PV,A} & \quad \text{if} \quad P_{load,A} \leq P_{PV,A} \\
P_{batt,A} & \quad \text{if} \quad P_{PV,A} < P_{load,A} \leq P_{batt,A} \\
P_{droop,A} & \quad \text{if} \quad P_{PV,A} + P_{batt,A} < P_{load,A} \leq P_{droop,A}
\end{align*}
\]
where, $P_{pv,A}$ is the PV power production, which is dependent on the time of the day and environmental conditions. $P_{batt,A}$ is the power supplied by the battery. It is also dependent upon its state of charge, while $P_{droop,A}$ is the power supplied by the droop unit. These DG units operate under an enhanced multi-segment droop control strategy, as shown in (27). Based on (27), the priority for the power contribution within these DG units is set as,

$$\text{Priority}_{pv} > \text{Priority}_{batt} > \text{Priority}_{droop} \quad (28)$$

The frequency reference in (27) is determined using the improved multi-segment droop control strategy, as shown in Fig.7. The anti-windup logic in Fig.7 acts as a power limit controller for the contribution from the droop unit during the load sharing process, while the frequency is regulated between $f_{\text{min}}$ and $f_{\text{min}}$ of the P/f characteristics of the enhanced multi-segment droop strategy in each phase. Furthermore, saturation blocks are used to limit the frequency reference between $[f_0 + \Delta f_{\text{max}}, f_{\text{min}}]$, where $f_{\text{min}}$ is the minimum system frequency for each phase, which needs to be maintained, as this frequency reference is used by the modified vector control to generate quadrature voltage and current components for the single-phase converters.

Taking the ratio of $mC_L$ and $mI_A$, gives,

$$P_{\phi C} = \frac{V_{DC}mC_L}{\eta} - n \cdot (P_{\text{total},A} - P_{\text{load},A}) \quad (29)$$

Hence, the total power in $\phi C$ can be shown as,

$$P_{\text{total},A} + n \cdot (P_{\text{total},A} - P_{\text{load},A}) = \frac{mC_L V_{DC}}{\eta} \quad (30)$$

The variables on the left hand side of (30) can be substituted in place of the control variables in (22).

Taking the inter-phase component from (22), the power transferred from $\phi A$ can be represented as,

$$P_{\phi A | PT} = P_{B2B_{\phi A}}^{\text{ref}} = \frac{V_{cn} \left( I_0 - I_{L_{\phi A}} \right) mC cos \theta_L}{m_A} \cdot \left( \frac{z_y + \Delta r_y}{z_y + \Delta r_y} \right) \cdot E_{B2B_{\phi A}} \quad (31)$$

The control objective of the inter-phase power management ensures that the necessary back-to-back converters are activated during the power transfer between phases, as shown in Fig.8. This scenario is represented by zone $D$ in Fig.3. During this scenario, the PV, battery, and droop units reach their unit capacities in each phase and are unable to support the load. Based on this information, a decision for the power-contributing phase was made. Because the DG units, within a phase, operate at their maximum capacities, the frequency of $\phi_x$ is regulated at $f_{\text{min}}$.

The single-phase back-to-back converter with its control strategy is shown in Fig.8. A modified vector control was used for the inner current control loops. The DC link voltage or real power flow was regulated by the outer control loops. The control loop of mode $A$ in Fig.8 was used by the power surplus phase to regulate the DC link voltage. This occurs prior to the power-sharing mode. During the power transfer between phases, the control loop switches to mode $B$. This regulates the required real power flow between phases. The switching of control modes is determined by the digital signals $E_{B2B_{\phi A}}, E_{B2B_{\phi B}}, E_{B2B_{\phi C}}$, as shown in (31). These signals are shown in Fig.8, where,

$$E_{B2B_{\phi A}}, E_{B2B_{\phi B}}, E_{B2B_{\phi C}} \in \{0, 1\} \quad (32)$$

From Fig.8, the current references during power transfer are stated as,

$$i_{\phi A}^* = K_1 (e_1(t)) \times \left( K_{p1} + K_1^1 \right) \int e_1(t) \, dt$$

$$i_{\phi B}^* = K_2 (e_2(t)) \times \left( K_{p2} + K_2^2 \right) \int e_2(t) \, dt$$

$$i_{\phi C}^* = K_3 (e_3(t)) \times \left( K_{p3} + K_3^3 \right) \int e_3(t) \, dt \quad (33)$$

where, $i_{\phi A}^*, i_{\phi B}^*$ and $i_{\phi C}^*$ are the current references for each of the single-phase back-to-back converters during power transfer; $e_1(t), e_2(t)$ and $e_3(t)$ denote the net real power required by the deficient phase from the power-surplus phase and is given by,

$$e_x(t) = P_{\text{load},x} \cdot P_{\text{total},x} \quad (34)$$

where, $P_{\text{load},x}$ is the loading requirement in the power-deficient phase, $x$, $K_1$, $K_2$ and $K_3$ in (33) are the controller parameters. The required gating signals are generated through $m_1$, $m_2$ and $m_3$. It is assumed that while the power exchange occurs, the third phase operates independently with no inter-phase power transfer.

In the worst-case scenario, where the load demand further increases and exceeds the local phase generation and storage capacities, as well as the maximum power that can be exchanged between phases, load shedding is required to maintain the safe and reliable operation of the system. This is represented by zone $E$ in Fig.3. However, introducing a load-shedding technique is beyond the scope of this study.

**C. TWO PHASES SHARE POWER EQUALLY/UNEQUALLY WITH THE DEFICIT PHASE**

For scenarios, where multiple phases jointly contribute power to the power deficient phase, (22) and (31) need to be revised.

**FIGURE 7. A multi-segment droop control strategy for intra-phase power management.**

![Diagram](image-url)
Assuming that \( \phi_c \) is the power deficit phase, while \( \phi_A \) and \( \phi_B \) are the power surplus phases, (22) and (31) can be written as,

\[
P_{\phi_c} = \frac{V_{\phi_c}^2 \cos \theta_L}{(z_y + \Delta r_{y1})} + \frac{V_{m}\cos \theta_L}{m_y} \left( \frac{z_y + \Delta r_{y2}}{z_y + \Delta r_{y3}} \right) E_{B2B_{\phi_A}} + \frac{V_{m}\cos \theta_L}{m_y} \left( \frac{z_y + \Delta r_{y2}}{z_y + \Delta r_{y3}} \right) E_{B2B_{\phi_B}}
\]

(35)

\[
P_{\phi_A} - P_{\phi_B} = P_{\phi_A}^{ref} - P_{\phi_B}^{ref}
\]

(37)

where, \( P_{\phi_A}^{ref} \) and \( P_{\phi_B}^{ref} \) are the power transferred from \( \phi_A \) and \( \phi_B \) respectively, while \( P_{\phi_A}^{ref} \) and \( P_{\phi_B}^{ref} \) are the power references for the back-to-back converters connecting \( \phi_C \) with \( \phi_A \) and \( \phi_B \). The amount of power delivered by the power surplus phases depends upon the local net power demand.

For the case in which there are two power deficit phases, the power surplus phase can also provide power to both, if it has sufficient reserve. The power transfer equations in this case can be written as,

\[
P_{\phi} = \frac{V_{\phi}^2 \cos \theta_L}{(z_y + \Delta r_{y1})} + n. \frac{V_{m}\cos \theta_L}{m_y} \left( \frac{z_y + \Delta r_{y3}}{z_y + \Delta r_{y2}} \right) E_{B2B_{\phi}}
\]

(38)

\[
P_{\phi} = \frac{V_{\phi}^2 \cos \theta_L}{(z_y + \Delta r_{y3})} + m. \frac{V_{m}\cos \theta_L}{m_y} \left( \frac{z_y + \Delta r_{y3}}{z_y + \Delta r_{y2}} \right) E_{B2B_{\phi}}
\]

(39)

where \( n \) and \( m \) are the ratios dependent upon the power requirement in power deficit phases, \( P_{req} \), and are given by,

\[
n = \frac{P_{req|\phi_A}}{P_{surplus|\phi_A}}, \quad m = \frac{P_{req|\phi_B}}{P_{surplus|\phi_B}}
\]

(40)

### IV. LOSS DURING POWER TRANSFER

It is important to point out that the formulas in the previous section are derived under ideal conditions, and power losses during the course of power transfer have not been taken into account. In practice, any power transfer would incur losses. Consider a scenario in which \( \phi_x \) has surplus power, \( P_{sup|\phi_x} \), and \( \phi_y \) requests power, \( P_{req|\phi_y} \), to be exchanged, the power loss in this transfer process can be expressed as,

\[
P_{sup|\phi_x} - P_{loss|\phi_x} - P_{loss|\phi_y} = P_{req|\phi_y}
\]

(41)

Equation (41) can further be expanded to,

\[
P_{sup|\phi_x} = P_{req|\phi_y} + \left[ (I_2 R_x) \right]_{\phi_x} + P_{loss|\phi_x} + T_{fr} \]

(42)

where \( R_x \) and \( R_y \) are the resistances of the transfer lines and the service line going to individual residential units. \( P_{loss|\phi_x} \) are the losses incurred in the back-to-back converter stage, and \( T_{fr} \) are the losses in transformers connecting the back-to-back converter to individual phases.

The power loss in the back-to-back converter, \( P_{loss|\phi_x} \), in (42) is composed of two components:

\[
P_{loss|\phi_x} = P_{loss|\phi_x}^c + 2 P_{loss|\phi_x}^T
\]

(43)

where, \( P_{loss|\phi_x}^c \) is the loss across the inductance of the back-to-back converter and is dependent upon its equivalent series resistance, and \( P_{loss|\phi_x}^T \) is the conduction losses due to switching of gates in the dc-to-dc converters.

For power exchange between residential units that are on different phases, the power loss equation (41) can be modified as,

\[
-P_{sup|\phi_x} - \kappa_1 + P_{sup|\phi_y} = P_{req|\phi_y} + \kappa_2
\]

(44)

Solving for \( P_{sup|\phi_y} \) leads to:

\[
P_{sup|\phi_y} \approx P_{req|\phi_y} + \kappa_3
\]

(45)

where \( \kappa_1, \kappa_2 \) and \( \kappa_3 \) are constants associated with losses in capacitor, gate-switching and transformer at \( \phi_y \).

The power loss factor \( \eta \) can then be derived as:

\[
\eta = 1 - \frac{\kappa_3}{P_{sup|\phi_y}}
\]

(46)
S. A. Raza, J. Jiang: Mathematical Foundations for Balancing Single-Phase Residential Microgrids Connected

VOLUME 10, 2022

This parameter represents the overall efficiency of the power sharing operation among different phases in achieving a dynamic phase balance for the three single-phase microgrids.

V. DEMONSTRATION OF DYNAMIC PHASE BALANCING PROCESSES

This section presents the demonstrations of local power balancing for the scenarios considered in Table 1. Detailed residential microgrids with hybrid PV/battery droop units in each phase, with interconnecting back-to-back converters, have been simulated in PSCAD/EMTDC. The simulation time step is kept at 0.5 µs. The results are shown in Figs. 9-14.

A. ALL PHASES ARE BALANCED

Assuming that initially all three-phases are operating in a steady-state and each phase has sufficient capacity to meet its own load demand prior to a load change, as shown in Fig.9. These detailed results are shown for φB only. Similar results can be achieved for other phases as well. Between t = 0s and t = t3, the PV and battery units, in each phase, are capable of supporting the loads through the intra-phase power management strategy. As the load increases in each phase, the generation and storage capacity of these phases decreases, but as far as the local distribution transformer is concerned, the phases appear to be balanced. Since, local generation and storage is sufficient to serve the loads, there is no need for inter-phase power exchange before t = t4, through the tertiary layer, nor import power from the distribution transformer. Hence, P_B2B_{φA,φB} = 0W as shown in Fig.9. This validates Case#1 in Table 1.

B. SURPLUS PHASE SHARES POWER WITH THE DEFICIT PHASE(S)

A gradual step change of 288W is applied to the load demand to illustrate the contributions of the DG units. The simulations are run for 75s. Other key variables, including the frequency, DC and AC phase power and battery’s SOC, are shown in Fig.9. For illustration purposes, results for only one phase are shown here. A constant PV generation of 1000W is assumed throughout the simulation run. This is represented by P_{pvφB}.

The multi-segment P/f characteristics of these scenarios is shown in Fig.10. The initial SOC of the battery is assumed to be approximately 71.2%. Since the load demand at the start of simulation is low, the battery is charged with the available surplus PV power in φB. This is because the initial SOC < SOC_{max}. The negative battery power between t1 = 0s and t2 = 5s, illustrates the charging state of the battery. The PV unit still supports the load between t2 = 5s and t = 10s. The lack of any excess power from the PV unit ensures that the battery is in floating state, i.e., P_{battφB} = 0W. Since P_{pvφB} = P_{loadφB}, the battery does not participate in regulating power. The system continues to operate at f0. As the load demands moves from zone A to zone B between t = 10s and
$t_1 = 25s$, both the PV and battery units start supporting the load. This is represented by positive battery, $P_{\text{batt}}$, in Fig.9. Since both PV and battery units handle the load at this stage, the system operates below the nominal frequency, $f_0$.

At $t_3 = 25s$, the battery unit reaches its capacity, $P_{\text{batt}}^\text{max}$. The system starts operating at $f_{\text{min}}$, the inter-phase power transfer is initiated. The power deficient and surplus phases are determined by the logic signals $E(A, B, C)$. For this particular scenario, $\phi_A$, with its surplus local power generation, supplies the deficit power to $\phi_B$. This required power is given by $P_{\text{ref}}^\phi_B$ and $P_{\text{ref}}^1$. The initialization of the power transfer between the two phases causes the DC link voltage of the back-to-back converter to decrease as shown in Fig.11. The AC voltages and currents as observed at the distribution transformer are shown in Figures 12(a) and 13(a). For each of these figures, zoomed in versions are shown before the back-to-back converter is enabled i.e. in Figures12(b) and 13(b), to show that the system is unbalanced, while Figures 12(c) and 13(c), shows how the system balances itself through the power transfer from power surplus phase to the power deficit phase. This validates Case#2 in Table 1.

At the onset of decrease in load demand between $t_5 = 35s$ and $t_7 = 70s$, the contribution from the droop unit decreases to 0W. Once again, the hybrid PV and battery unit start supporting the load. The battery charging resumes again at $t = 60s$, as the load demand falls below $P_{\text{pv}}$. This is illustrated by the increase in the SOC of the battery in Fig.9. Similar results can be achieved when multiple phases are in power deficit to validate Case#3 in Table 1.

C. TWO PHASES SHARE POWER EQUALLY/UNEQUALLY WITH DEFICIT PHASE

In this case, the load in $\phi_B$ increases abruptly beyond the total generation capacity of that phase, as illustrated in Fig.14(a). There is a net power shortage of 106W in $\phi_B$, as represented by $-106W$ in Fig.14(c). At $t = t_1$, both $\phi_A$ and $\phi_C$ have surplus capacities. The back-to-back converters connecting the surplus phases with the deficit phase are enabled. The power
transferred from both \( \phi_A \) and \( \phi_C \) is represented by \( P_{B2B_{\phi_A}} \) and \( P_{B2B_{\phi_C}} \) in Fig.14(b). The total power received by \( \phi_B \) is represented by \( P_{B2B_{\phi_A \phi_C}} \). At this stage, all the three-phases appear to be balanced from the local distribution transformer standpoint. This validate Cases #4 and 5. With different loading profiles in \( \phi_A \) and \( \phi_C \) it can be shown that unequal power sharing from surplus power phases take place with \( \phi_B \).

D. ALL PHASES ARE IN POWER DEFICIENCY

The final scenario deals with a situation in which all three residential microgrids have power deficiency. As a result, neither intra nor inter-phase power management strategies alone will be able to balance the loads on their own. The systems are in zone E in Fig.3. Hence, load shedding must take place, or grid support is required. This situation corresponds to Case#6.

It is important to note that both intra and inter-phase power management schemes still work while extra power is imported from the grid. By doing so, the distribution transformer provides balanced power supply to the three single-phase microgrids, even though the power demand in each phase can be different. This difference will be resolved ‘internally’ among the three phases using the intra and inter-phase power management schemes.

VI. CONCLUSION

To maintain phase balance in the presence of single-phase generation and energy storage in residential microgrids, power transferred among different phases using back-to-back converters has been considered as an effective solution. This study systematically analyzed the fundamental relations behind this approach by establishing mathematical formulations for six potential operating scenarios. These formulas have formed the basis for achieving dynamic balancing among three single-phase microgrids under various load and generation profiles to form a dynamically balanced three-phase system. This is the first time that such relationships have been explicitly represented. A free user-friendly online interactive program was developed for interested readers to evaluate different power exchange scenarios of their own applications.

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