Voltage Balancing Capability of Grid-Forming Inverters

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ABSTRACT The objective of this paper is to analyze and identify the range of voltage balancing capability of grid-forming inverters serving three-phase unbalanced loads. These inverters are designed to compensate for voltage imbalance by controlling the negative-sequence components of voltage and current. However, the magnitude of the negative-sequence current an inverter can supply is limited by its relatively low rated current. Moreover, it becomes more challenging to estimate the amount of current needed for an unbalanced load when the inverter is interfaced using a delta-wye grounded interconnection transformer. Therefore, we investigate the range of negative-sequence current the inverter can supply and derive formulas to determine the minimum inverter’s capacity required to compensate for voltage imbalance while supplying unbalanced loads connected through a delta-wye grounded transformer. The proposed formulas can be used to estimate the capacity of an inverter in lieu of detailed analyses and electromagnetic transient simulations. The proposed equation is implemented in small and large scale microgrid systems and validated using a detailed model developed in PSCAD/EMTDC.

INDEX TERMS Inverter-interfaced distributed generator, grid-forming inverter, distributed microgrid, voltage unbalance.

I. INTRODUCTION

Inverter-interfaced distributed generators (IIDGs) are an emerging energy source in power distribution networks [1]. Single-phase IIDGs introduced the challenge of voltage imbalance [2]. According to ANSI C84.1, voltage imbalance in electric supply systems must not exceed 3% [3]. In many modern microgrids, IIDGs are the primary power source, so they must participate in compensation for grid voltage imbalance. Unbalanced voltage compensation control of IIDGs depends on the mode of operation. IIDGs in microgrids generally operate in two modes: 1) grid-following and 2) grid-forming mode [4]. Inverters operating in both modes could mitigate voltage unbalance by controlling their output currents.

Grid-following inverter’s unbalanced voltage mitigating control is analyzed in [5], [6], [7], and [8]. A control strategy based on symmetrical components for short-term unbalanced voltage sags is proposed in [5]. Controls for long-term voltage imbalance are proposed in [6] and [7] with different control objectives. In [6], the grid-following inverter aims to maximize active power injection. The control scheme presented in [7] focuses on minimizing negative-sequence voltage magnitude and inverter output current. Reference [8] proposed to control reactive power supplied by grid-following inverters to mitigate voltage unbalance. However, grid-following inverters, which are modeled as a current source with active and reactive power reference signals, can mitigate voltage imbalance only to an extent but cannot completely eliminate the negative-sequence voltage.

IIDGs operating in grid-forming mode have better control over unbalanced voltages because they control the grid voltage magnitude and frequency [9], [10], [11], [12]. Grid-forming inverters can reduce the negative-sequence voltage to a negligible level by controlling the positive- and
negative-sequence voltages separately [9]. The stability of an inverter operating based on this method was evaluated in [10]. A collaborative voltage imbalance mitigation control for grid-forming inverters was proposed in [11]. Reference [12] showed that grid-forming inverter could control sequence components and maintain balanced voltage both in grid-connected and islanded microgrids.

Previous studies [9], [10], [11], [12] showed that grid-forming inverters are capable of maintaining balanced voltage. However, the range of unbalanced load the inverter can handle without losing balanced voltage is not addressed. Although inverters are equipped with a negative-sequence voltage controller, they often cannot supply a large amount of negative-sequence current because of their low rated current compared to synchronous machines.

This work aims to identify the range of unbalanced currents a grid-forming inverter can supply without losing balanced voltage. The work focuses on three-phase three-legged grid-forming inverters commonly used in distribution systems [13]. They can deliver positive- and negative-sequence currents, but do not have a path for zero-sequence current, which can be provided by the inverter’s interconnection transformer or a separate grounding transformer. Therefore, we analyze the possible range of sequence components of inverter current with different interconnection transformer connections.

Additionally, this paper proposes a method to calculate the required capacity of the grid-forming inverter to supply a given unbalanced system. With a delta connection on the inverter side of the interconnection transformer, it is challenging to estimate the amount of required current when the system is unbalanced. The proposed method accounts for the delta-wye grounded connection of the inverter transformer, and the inverter’s size can be computed using only the load size and power factor without requiring analytical methods or simulations. The main contributions of this work are as follows:

- Transformer winding configuration and grounding connections are critical in supporting a three-leg grid-forming inverter to achieve balanced voltage. It is shown that a grounding transformer such as a delta-Yg configuration provides the zero-sequence current and path to the unbalanced load. Without a grounding transformer, a three-leg grid-forming inverter alone cannot balance the microgrid voltage. The analysis is presented in Section II.
- The range of negative-sequence current, which is necessary for unbalanced loads, the grid-forming inverter can supply is examined. The analysis presented in Section III shows that the negative-sequence current the grid-forming inverter supply cannot exceed 57.7% of the rated current. Otherwise, the inverter cannot maintain balanced voltage.
- A method for calculating the minimum capacity of an inverter interfaced with a delta-Yg transformer to maintain balanced voltage is proposed. As discussed in Section IV, the delta-Yg configuration makes it challenging to compute the required inverter capacity when supplying unbalanced loads. The proposed method does not rely on simulation and only uses the parameters of the load in the microgrid. Case studies presented in Section V show that the inverter size calculated using the proposed method is consistent with the result obtained from EMT simulation.

II. VOLTAGE BALANCING CONTROL OF GRID-FORMING INVERTER BASED ON SYMMETRICAL COMPONENTS

This section presents a control strategy for a three-phase three-leg grid-forming inverter based on the symmetrical components of voltage and current. The inverter maintains balanced grid voltage by controlling positive- and negative-sequence components separately. The zero-sequence current, which is also important for balancing the load side voltage, originates from the interconnection transformer. Thus, the voltages on both sides of the transformer with different connections are also analyzed.

A. CONTROL STRATEGY OF GRID-FORMING INVERTER BASED ON SYMMETRICAL COMPONENTS

The overall control structure of the grid-forming inverter is shown in Fig. 1 [9]. The voltage and current notation with a subscript 1 (i.e., \( V_1 \) or \( I_1 \)) represents the positive-sequence components and those with a subscript 2 denote the negative-sequence voltage and current components. The upper portion (blue) controls the positive-sequence voltage and the lower part (red) controls the negative-sequence voltage separately. The positive-sequence voltage controller regulates the grid voltage and frequency at their nominal values \( V^* \) and \( \omega^* \). On the other hand, the negative-sequence voltage controller limits the negative-sequence voltage to a negligible magnitude to keep the voltage balanced. Since the inverter is modeled as a three-phase three-leg inverter that does not have

![FIGURE 1. Sequence-based controller of grid-forming inverter for unbalanced circuit. Notice the microgrid is islanded.](image-url)
a ground connection, the zero-sequence voltage controller is not needed.

The inverter controls the grid voltage using the symmetrical components of the voltage and current in the rotating dq-frame. The voltage and current are controlled by cascade PI controllers based on the voltage equation between the grid voltage \( E_{dq} \) and the inverter voltage \( V_{dq} \). The voltage relationship for positive- and negative-sequence voltages could be written as follows,

\[
E_{1,dq} = L_{inv} \frac{dI_{1,dq}}{dt} + j\omega L_{inv} I_{1,dq} + V_{1,dq},
\]

\[
E_{2,dq} = L_{inv} \frac{dI_{2,dq}}{dt} - j\omega L_{inv} I_{2,dq} + V_{2,dq},
\]

where \( L_{inv} \) is the equivalent inductance of the inverter. Equations (1) and (2) show that positive- and negative-sequence voltage and current are decoupled. Thus, the inverter controls positive- and negative-sequence voltages separately.

**B. CURRENT LIMITER DESIGNED FOR UNBALANCED CURRENTS**

The inverter has to be equipped with current limiters to protect its switches from overcurrents. Current limiters are generally implemented in the dq-frame to limit the current. The inverter currents on each phase are regulated separately.

\[
I_{lim}^{abc} = \begin{cases} 
I_{abc}^*, & \text{when } I_{rms} < I_{lim}, \\
I_{lim}, & \text{when } I_{rms} > I_{lim}.
\end{cases}
\]

The inverter currents on each phase are regulated separately by multiplying \( I_{lim}^{abc} \) to \( I_{abc}^* \) when their RMS values are larger than \( I_{lim} \). The current reference limit signal \( I_{abc,lim}^{abc} \) in the abc-frame is transformed back to the positive- and negative-sequence current reference \( I_{1dq,lim} \) and \( I_{2dq,lim} \) in the dq-frame. When the current of any phase exceeds the rated current, the inverter cannot supply enough current and fails to control grid voltage. Since this work focuses on the long-term voltage unbalance during continuous operation, \( I_{lim} \) is determined the same as the rated current.

**C. INTERCONNECTION TRANSFORMER CONNECTION AND ZERO-SEQUENCE CURRENT**

The three-leg inverter with the controller presented in Fig. 1 can control the positive- and negative-sequence components of voltage. However, zero-sequence current is also needed to balance the load side voltage. Therefore, the inverter transformer must supply zero-sequence current. This section analyzes the importance of transformer winding configuration and grounding connection. Among possible transformer connections, the commonly used delta-wye grounded (Yg) and Yg-Y transformers are shown in Fig. 3 and Fig. 5. The inverter on the primary side and the load on the secondary side are replaced by equivalent impedance \( Z_{inv} \) and \( Z_{load} \), respectively, and \( Z_t \) indicates the transformer impedance. The inverter is a three-phase three-leg inverter rated at 0.6 kV and 500 kVA. The load is an unbalanced load composed of 200 kW, 100 kW, and 100 kW on each phase with rated voltage of 12.47 kV.

Fig. 3 shows that the inverter side of the delta-Yg transformer does not have a zero-sequence connection. Yet, there is a zero-sequence path on the load side because of the grounding on the Yg side. Thus, the transformer can supply zero-sequence current to the load, and the inverter can balance the voltage on both sides by controlling positive- and negative-sequence components.

The performance of the inverter’s voltage balancing control when interfaced with a delta-Yg transformer is demonstrated in Fig. 4. Fig. 4(a) and (b) show the inverter side voltage and current, and Fig. 4(c) and (d) present those measured on the load side. Both voltage and current are per-unitized to compare primary and secondary side measurements.

Fig. 4(a) and (c) show that both inverter and load voltages consist only of the positive-sequence component without negative- and zero-sequence voltage. Fig. 4(b) and (d) indicate that the inverter does not supply zero-sequence current, but the transformer grounding path does inject zero-sequence current to the loads. Simulation results show that the
inverter can balance both voltages by installing the inverter with delta-Yg transformer and sufficiently low grounding impedance.

However, the equivalent circuit of the Yg-Y transformer presented in Fig. 5 shows that both the primary and secondary sides have no ground connection. Also, the zero-sequence networks of the inverter and the load are not connected. In this case, the inverter side, which does not have a ground connection, does not require zero-sequence current. In contrast, the load is connected to the ground and requires zero-sequence current to make the voltage balanced.

The simulation results with a Yg-Y transformer are shown in Fig. 6. Fig. 6(a) indicates that there is only a positive-sequence voltage of 1 pu, which shows that the inverter side voltage is controlled well and balanced. On the other hand, the load voltage shown in Fig. 6(c) shows that the secondary side voltage has a zero-sequence component and is not balanced. By comparing Fig. 4 (d) and Fig. 6 (d), it can be noticed that zero-sequence current is not supplied to the load in the case with Yg-Y transformer because neither the inverter nor the transformer can supply zero-sequence current, as shown in Fig. 6(b) and (d). As a result, even if the inverter controls the negative-sequence voltage, the load side voltage remains unbalanced.

The results shown in Fig. 4 suggest that without a separate grounding transformer, a three-phase three-leg inverter must be interfaced with a delta-Yg transformer to balance voltages on both sides of the transformer. As presented in Fig. 6, other transformer connections cannot supply zero-sequence current and the secondary side load voltage becomes unbalanced.

The analysis above shows that transformer winding connection and grounding path have a major role in voltage balancing. Analysis results present that three-phase three-leg inverters, which do not have a zero-sequence connection, need to be interfaced with a delta-Yg transformer to supply zero-sequence current to the unbalanced load.

### III. OPERATION REGION OF GRID-FORMING INVERTERS USED IN UNBALANCED SYSTEMS

This section analyzes the range of positive- and negative-sequence current the inverter can supply while maintaining balanced voltage. The range of negative-sequence current the inverter can inject could be used to understand how much imbalance the inverter can handle. Negative-sequence current injection is limited by the rated capacity of the inverter, which is given as an RMS value. The relationship between the negative-sequence current and the rated capacity could be investigated using the transformation matrix shown in (4).

\[
\begin{bmatrix}
I_a \angle \theta_a \\
I_b \angle \theta_b \\
I_c \angle \theta_c
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
1 & 1 & 1 \\
1 & a & a^2 \\
1 & a^2 & a
\end{bmatrix} \begin{bmatrix}
I_0 \angle \theta_0 \\
I_1 \angle \theta_1 \\
I_2 \angle \theta_2
\end{bmatrix}. \tag{4}
\]

In (4), \(I_{abc} \angle \theta_{abc}\) represents the inverter currents in each phase, and \(I_{012} \angle \theta_{012}\) indicates the symmetrical component of the inverter current. However, it can be seen that six parameters (three angles and three magnitudes given in the abc-frame) are needed to calculate the range of current the inverter can supply.

Therefore, we use an alternative method which requires only the RMS values of the currents in each phase [19]. The magnitude of the positive- and negative-sequence currents...
and the ratio of those in the inverter can supply are shown in Fig. 7. Each axis represents the inverter current in each phase from 0 to 1 pu, and the color map shows the range of (a) positive-sequence current magnitude $I_1$, (b) negative-sequence current magnitude $I_2$, respectively.

Fig. 7(a) shows that the inverter can supply a positive-sequence current from 0 to 1 pu, and its maximum value is 1 pu at the center of the three-dimensional figure when currents are balanced (when $I_a = I_b = I_c = 1$ pu). However, Fig. 7(b) shows that the maximum negative-sequence current inverter can deliver is 0.577 pu at the triangular surface’s vertices. The coordinates of vertices, $I_2$ $(1,0,1)$, $I_2$ $(0,1,1)$, and $I_2$ $(0,0,1)$, show that negative-sequence current is the largest when 1 pu current is flowing in two phases and no current flows in the remaining phase. It can be seen that the positive-sequence current on the vertices of the triangular surface of Fig. 7(a) are also 0.577 pu. Therefore, the maximum $I_a$ ratio the inverter can provide is 100% and the minimum $I_a$ ratio is 0%, when currents are balanced.

The operation region of the grid-forming inverter where it can maintain balanced voltage could be summarized as follows. The inverter could compensate for unbalanced voltage only when the negative-sequence current required from the loads is smaller than 0.577 pu, and the $I_a$ ratio is less than 100%, in other words, $I_2$ is no larger than $I_1$.

IV. FORMULAS TO DETERMINE THE MINIMUM CAPACITY OF THE INVERTER REQUIRED TO BALANCED THE VOLTAGE

The range of unbalanced current the inverter can supply was analyzed in the previous section. This section proposes equations to determine the minimum capacity of the inverter when maintaining balanced voltage and operating within the range investigated in Section III.

When the system is balanced we can simply calculate the required inverter size by aggregating all the loads in the system. However, calculating the capacity required to supply an unbalanced load is not straightforward. Moreover, due to the delta-Yg transformer requirement to supply zero-sequence current, it becomes challenging to estimate the required inverter size. When interfaced using a delta-Yg transformer, the current supplied to the delta side will not be proportional to the size of load on the Yg side, especially when the phase angles of currents in each phase are unbalanced. Thus, equations to estimate the required size of the inverter on the delta side are derived using the size of load on the Yg side. The equation used to determine the current that has to be supplied from phase A of the inverter (delta-side) could be computed using the currents required on the Yg side. Line-to-neutral quantities in per units are used to derive the proposed equation. The current on the delta side is calculated as shown below,

$$I_a \angle \theta_a = I_{aY} \angle \theta_{aY} - I_{cY} \angle \theta_{cY}.$$  \hspace{1cm} (9)

In (9), $I_a$ and $\theta_a$ represent the magnitude and angle of the current on the delta side, and $I_{aY}$ and $\theta_{aY}$ are those measured on the Yg side. Separating the real and imaginary parts to
calculate the magnitude of the current required on phase A results in,

\[
\begin{align*}
Re[ia \angle \theta_a] &= I_{aY} \cos(\theta_{aY}) - I_{cY} \cos(\theta_{cY}), \quad (10) \\
Im[ia \angle \theta_a] &= I_{aY} \sin(\theta_{aY}) - I_{cY} \sin(\theta_{cY}). \quad (11)
\end{align*}
\]

Next, (10) and (11) are used to derive an equation used to determine the inverter current required on the delta side to supply the loads on the Yg side. The proposed equation for phase A is presented below,

\[
|ia| = Re[ia \angle \theta_a]^2 + Im[ia \angle \theta_a]^2 = I_{aY}^2 + I_{cY}^2 - 2I_{aY}I_{cY} \cos(\theta_{aY} - \theta_{cY}). \quad (12)
\]

It can be noticed that the right side of (13) consists only of the wye side quantities. Using (13), we can estimate the magnitude of current inverter has to supply.

The inverter’s rated current should be higher than the current magnitude calculated using (13). Thus, inequalities can be used to decide the minimum rated current of a grid-forming inverter. Inequalities for all three phases could be written as below,

\[
\begin{align*}
I_{aY}^2 + I_{cY}^2 - 2I_{aY}I_{cY} \cos(\theta_{aY} - \theta_{cY}) &\leq S_{lim,a}^2, \quad (14) \\
I_{bY}^2 + I_{cY}^2 - 2I_{bY}I_{cY} \cos(\theta_{bY} - \theta_{cY}) &\leq S_{lim,b}^2, \quad (15) \\
I_{cY}^2 + I_{cY}^2 - 2I_{cY}I_{cY} \cos(\theta_{cY} - \theta_{cY}) &\leq S_{lim,c}^2, \quad (16)
\end{align*}
\]

where \(S_{lim,a}, S_{lim,b}, \) and \(S_{lim,c}\) are current limits of each phase.

Assuming that both the inverter and load side voltage magnitudes are controlled at 1 pu with balanced phase angles, current magnitudes in (14) - (16) could be substituted with load sizes \(S_{abc} \). Inequalities written in load sizes and power factor angles are given as,

\[
\begin{align*}
S_{aY}^2 + S_{cY}^2 - 2S_{aY}S_{cY} \cos(\theta_{aY} - \theta_{cY}) &\leq S_{lim,a}^2, \quad (17) \\
S_{bY}^2 + S_{cY}^2 - 2S_{bY}S_{cY} \cos(\theta_{bY} - \theta_{cY}) &\leq S_{lim,b}^2, \quad (18) \\
S_{cY}^2 + S_{cY}^2 - 2S_{cY}S_{cY} \cos(\theta_{cY} - \theta_{cY}) &\leq S_{lim,c}^2, \quad (19)
\end{align*}
\]

where \(S_{lim,a}, S_{lim,b}, \) and \(S_{lim,c}\) are required powers in each phase. Assuming the load has a unity power factor, we can remove cosine terms in (17) - (19) and simplify to have only the load size terms as follows,

\[
\begin{align*}
S_{aY}^2 + S_{cY}^2 + S_{aY}S_{cY} &\leq S_{lim,a}^2, \quad (20) \\
S_{bY}^2 + S_{cY}^2 + S_{bY}S_{cY} &\leq S_{lim,b}^2, \quad (21) \\
S_{cY}^2 + S_{cY}^2 + S_{cY}S_{cY} &\leq S_{lim,c}^2. \quad (22)
\end{align*}
\]

The range of loads that satisfies all three inequalities presented in (20) - (22) are illustrated in Fig. 8. If the coordinate of the unbalanced load is located below the curved surface, the inverter can deliver power without losing the balanced voltage. On the other hand, given a load demand, the inverter capacity calculated using the proposed equation is the minimum required capacity for maintaining balanced voltage at steady-state and does not account for contingencies.

The inverter capacity required in each phase could be determined by solving (17) - (19). If three single-phase inverters are installed in each phase, their sizes will be \(S_{lim,a}, S_{lim,b}, \) and \(S_{lim,c}\), respectively. When the inverter has three-phase configuration, we determine its capacity as shown below,

\[
S_{lim,3\phi} = 3 \cdot \max\{S_{lim,a}, S_{lim,b}, S_{lim,c}\}. \quad (23)
\]

We choose the largest value among the calculated values, and multiply by 3 to determine the three-phase capacity.

V. CASE STUDIES AND VALIDATION OF THE PROPOSED EQUATION

This section demonstrates the implementation of the proposed inequality and validates the solution by running a PSCAD/EMTDC simulation. The required inverter capacities for each case are calculated using the proposed equations. The performance of the inverter with the computed capacity is examined using a detailed model with controller shown in Fig. 1.

A. CASE 1: CALCULATING THE MINIMUM REQUIRED INVERTER CAPACITY FOR GIVEN LOAD SIZE

In the first case, we determine the inverter capacity needed to maintain balanced voltage while supplying an unbalanced load in an islanded microgrid. The test system shown in Fig. 9 consists of a grid-forming inverter, a delta-Yg transformer, and total 300 kVA unbalanced load. The size and power factor of the unbalanced load are:
• phase A: 150 kVA, pf = 0.9,
• phase B: 100 kVA, pf = 0.8,
• phase C: 50 kVA, pf = 0.7.

First, the phase angle of each load is calculated using the given power factor. Phase shifts of 240° and 120° are applied to phase B and C. For example, the phase angle of phase A is calculated as,

$$\theta_{\alpha Y} = -\cos^{-1}(0.9) = -25.84^\circ,$$

By substituting load sizes and phase angles into (17) - (19), required inverter capacities are computed for each phase as,

$$95.93 \text{ kVA} \leq S_{\text{lim},a},$$
$$131.74 \text{ kVA} \leq S_{\text{lim},b},$$
$$78.97 \text{ kVA} \leq S_{\text{lim},c}. $$

Equation (28) shows that the inverter must be greater than 395.70 kVA. It is larger than the combined size of the individual single phase loads. The calculated inverter capacity is validated using PSCAD/EMTDC. Since the calculated values do not consider losses in the system, inverters with slightly larger capacities were used for validation. Inverters with sizes of 395 kVA and 400 kVA were selected and voltage and current measured on the inverter side were analyzed.

The voltage and current measured on the delta side of the interconnection transformer with different sized inverters are presented in Fig. 10. The blue curve displays the positive-sequence components, and the orange curve shows the negative-sequence components. Superscripts for voltages and currents indicate the inverter size.

The voltage presented with solid line in Fig. 10(a) shows that the 400 kVA inverter can successfully control the voltage. The positive sequence-voltage is controlled at 1 pu, and the negative-sequence voltage is regulated to 0 pu. In contrast, the dotted curve shows that the voltage is not controlled when the inverter size is reduced to 395 kVA, which is smaller than the calculated value shown in (28). The positive-sequence voltage dropped to 0.6 pu, and the negative-sequence voltage is not limited at 0 pu. This is because the rated current of 395 kVA inverter is lower than required. The current limiter is activated at t = 0.5s, and the voltage starts to drop sequentially. Simulation results prove that the required capacity lies between 395 kVA and 400 kVA, which matches well with the computed value shown in (28).

B. CASE 2: CALCULATING THE MINIMUM REQUIRED INVERTER CAPACITY FOR GIVEN CURRENT REQUIREMENTS

The second example case shows how to determine the inverter size when system requirements are given as the wye-side current magnitude and the $I_2/I_1$ ratio. The current magnitude that the inverter has to supply is specified, for example, 10 A with $I_2/I_1$ of 20% for this case. We use the same test system presented in Fig. 9.

However, wye-side current magnitude and the $I_2/I_1$ ratio are not sufficient to calculate the minimum inverter size. The phase angle of the negative-sequence current is also required to calculate the inverter size accurately. Hence, the range of inverter size is determined with negative-sequence phase angle varying from $-180^\circ$ to $180^\circ$. The sequence components of current are transformed to the abc-frame using the matrix shown in (4) and solve (17) - (19).

Fig. 11 presents the required inverter size with different negative-sequence current angles. The red line shows the maximum of the three curves. For example, when the angle is $0^\circ$, the inverter has to be larger than 240.51 kVA. When the phase angle is $-60^\circ$ or $60^\circ$, the required inverter size increases to 259.18 kVA. Thus, we choose 259.18 kVA to meet the current requirement at all phase angles.

The calculated minimum inverter capacity when the negative-sequence current angle is $60^\circ$ is validated using...
PSCAD/EMTDC. Angle of 60° is chosen because the required capacity becomes the largest as shown in Fig. 11. Current requirements are converted to corresponding constant PQ loads to be used in PSCAD/EMTDC. The load size is specified as follows:

- Phase A: \( S_a = 79.2 \text{ kW} - j12.47 \text{ kvar} \)
- Phase B: \( S_b = 79.2 \text{ kW} + j12.47 \text{ kvar} \)
- Phase C: \( S_c = 57.6 \text{ kW} \)

Inverter sizes of 255 kVA and 262 kVA are chosen to validate the limit we calculated in Fig. 11. The voltage and current measured on the delta side of the interconnection transformer are presented in Fig. 12. Similar to Fig. 10, the superscripts indicate the inverter size and the subscripts represent the positive- and negative-sequence components.

The solid curve in Fig. 12(a) shows that the voltage is well controlled when the inverter size is 262 kVA. Both positive- and negative-sequence voltages are controlled at their desired values, 1 pu and 0 pu, respectively. However, reducing the inverter size to 255 kVA resulted in unstable voltage. Since the 255 kVA inverter cannot supply enough current to maintain balanced voltage, both positive- and negative-sequence voltages are controlled at their desired values, 1 pu and 0 pu, respectively. However, reducing the inverter size to 255 kVA resulted in unstable voltage.

Since the 255 kVA inverter cannot supply enough current to maintain balanced voltage, both positive- and negative-sequence voltages are not controlled. Therefore, we can assume that the inverter size requirement is between 255 kVA and 262 kVA. The result validates the solution presented in Fig. 11.

### C. CASE 3: APPLYING THE PROPOSED EQUATIONS TO A LARGER SYSTEM

This case presents the implementation of the proposed inequalities in a larger system, the modified IEEE 34 node test feeder presented in Fig. 13. The voltage source at Bus 800 is replaced by a grid-forming inverter and interfaced using a delta-Yg transformer. The inverter size is determined by running an hourly quasi-static time series (QSTS) simulation for 24 hours using OpenDSS. The hourly load profiles for each phase are presented in Fig. 14. The size of loads installed in each phase are:

- Phase A: 606 kW + j357 kvar = 703.34 kVA
- Phase B: 584 kW + j344 kvar = 677.78 kVA
- Phase C: 579 kW + j343 kvar = 672.97 kVA

The required inverter size is calculated every hour using (17) - (19) and (23), and the maximum value during peak load hours is determined as the required inverter size. The complex power and power factor angle needed on the Yg side of the feeder transformer are used to compute the required inverter capacity for each phase. The inverter output current is obtained from OpenDSS and used to validate the calculated inverter capacity.

The computed inverter size and current flowing in each phase are displayed in Fig. 15. The required inverter size is shown as a bar graph, and current is presented using a curve. The maximum inverter capacity required is 2172.19 kVA on phase A at 16:00, and the peak current is 2074.09 A in phase B. Fig. 15 shows that the maximum current is flowing in phase B, but phase A is the phase which needs the largest capacity due to the delta-Yg transformer. Phase A of the delta side, which supplies current to phase A and B on the Yg side, requires the largest capacity because phase A and B are heavily loaded compared to phase C. Therefore, 2172.19 kVA is selected as the inverter size.

The calculated required inverter capacity is validated by comparing the current limits of inverters obtained from different methods. Equations (29) and (30) show the equations for calculating the inverter size in a balanced three-phase system.
FIGURE 15. Required inverter sizes to supply IEEE 34 node test system.

The inverter output current obtained from OpenDSS and the current limit of inverters with different sizes are shown in Fig. 16. The inverter sizes are calculated using (17) - (19), (29), and (30). The current limits of each inverter are illustrated with horizontal lines. It can be seen that the current limits calculated by (29) and (30) are much lower than the largest inverter current on phase B at 16:00. The current required on phase B is 2074.09 A, but the rated currents calculated using (29) and (30) were only 1976.55 A and 2021.02 A, respectively.

In contrast, the rated current of the inverter with a size calculated using (17) - (19) is large enough to deliver the peak current required on phase B. The computed current limit is 2090.19 A, which is slightly larger than the current needed on phase B. The simulation result shows that the proposed equation could be applied to large systems, and the current limit shown in Fig. 16 verifies the solution obtained from proposed inequalities.

VI. CONCLUSION

This paper analyzed the grid-forming inverter’s voltage balancing capability based on the range of unbalanced current the inverter can supply. The range of possible negative-sequence is investigated considering inverter’s rated current. Also, equations to determine inverter size needed to maintain a balanced voltage while supplying unbalanced loads are proposed. Case studies showed that the proposed equations could be applied to both small and large systems. Simulation results using a detailed model verified that inverters with calculated capacities can effectively control both positive- and negative-sequence voltages.

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