

A Comprehensive Analysis and Control Strategy for Nullifying Negative- and Zero-Sequence Currents in an Unbalanced Three-Phase Power System Using Electric Springs

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Abstract—This paper presents a general analysis and a control strategy that enables electric springs (ES) to mitigate the negative-sequence and zero-sequence currents in unbalanced three-phase power systems. The analysis indicates that under certain load conditions, power balance can be restored without the need for active power from the ES. Outside such conditions, the theory can pinpoint the precise operating point at which power balance can be achieved with the minimum active power from the ES. Thus, the optimum use of energy usage and battery size for providing/storing active power can be realized. Simulation and experiment results obtained from a 3-kW hardware setup have verified the new theory and the control method.

Index Terms—Electric springs, radial-chordal decomposition, power imbalance, symmetrical components, neutral current, negative-sequence currents.

I. INTRODUCTION

POWER flow imbalance among different power phases is a general phenomenon in three-phase AC power utility grids. Such power imbalance can be classified as short-term and long-term [1]. For short-term imbalance, unbalanced currents are relatively larger than those of the long-term ones. They are caused by unsymmetrical faults such as the phase-to-neutral short circuit in power lines and equipment failures [1]. If these large unbalanced currents are not properly handled, generator trips can occur [2]. For long-term imbalance, unbalanced currents are typically milder (smaller amplitude). They are generated by an uneven distribution of loadings on different power phases [1] [3] [4]. These unbalanced line currents can cause severe disturbance to induction machines [5], excessive flows of neutral currents [6], significant power losses [7], reduction in system's efficiency [8], low power factor [8] and severe reactive power burdens [8]. Furthermore, over the past decades, there is an increasing use of non-linear loads, such as adjustable speed drives, computer power supplies, and asynchronous AC-DC-AC links [4] [8]. As a result, both of system power balance and power-quality are adversely affected.

Many solutions have been proposed to resolve the issue of long-term power imbalance and other power quality related

issues such as power factor degradation and current/voltage harmonic contaminations. These solutions can be classified into four types: (i) transformers and synchronous condensers, (ii) passive filters (PF), (iii) active filters (AF), and (iv) hybrid filters (HF). Conventional devices, such as synchronous condensers and transformers with tap changers, have been used to address power quality issues [3] [9]. The drawbacks of these methods are their large physical size, heavy weight and high maintenance cost [3] [6]. The installation of PF, such as fixed capacitor banks and LC filters, are alternative solutions [5] [8] [10] [11]. However, PF are incapable of eliminating random and time-varying harmonic pollution that is generated from solid-state controlled devices. In this respect, a fast dynamic and adaptive solution such as the AF is required [12]–[17]. In general, AF can be connected in either series or in parallel with the power network. The static var compensator (STATCOM) and the static synchronous series compensator (SSSC) are typical examples of shunt-type (parallel) and series-type AF, respectively [12], [13]. The combination of AF and PF forms the HF. (e.g. the unified power flow controller (UPFC) is formed by combining a STATCOM and an SSSC coupled by a common DC link [15]). Another example of HF is a STATCOM connected in series with an inductor [16]. The reasons for the use of HF are to improve the dynamic performance and to reduce the size of filter devices [4].

Although the aforementioned techniques can achieve substantial improvements on different aspects of power quality issues in conventional power networks, the new challenges arising from emerging power grids pose an entirely different set of problems that are not resolvable through these techniques and that should be handled by new solutions. Increasing use of intermittent renewable energy could lead to instantaneous imbalance between power supply and demand, which is a key factor for grid voltage amplitude and frequency fluctuations [18]. Electric springs (ES) have been proposed to resolve this imbalance issue and simultaneously serve to perform conventional power-quality improvement functions [6] [19]–[21]. The first version of ES has been initially proposed for grid voltage stabilization through reactive power compensation and active power control of a non-critical (NC) load. This ES is configured by a voltage source converter (VSC) that is connected in series with an NC load (such as an electric heater) [19]. The second version of ES includes battery storage for providing both active and reactive power

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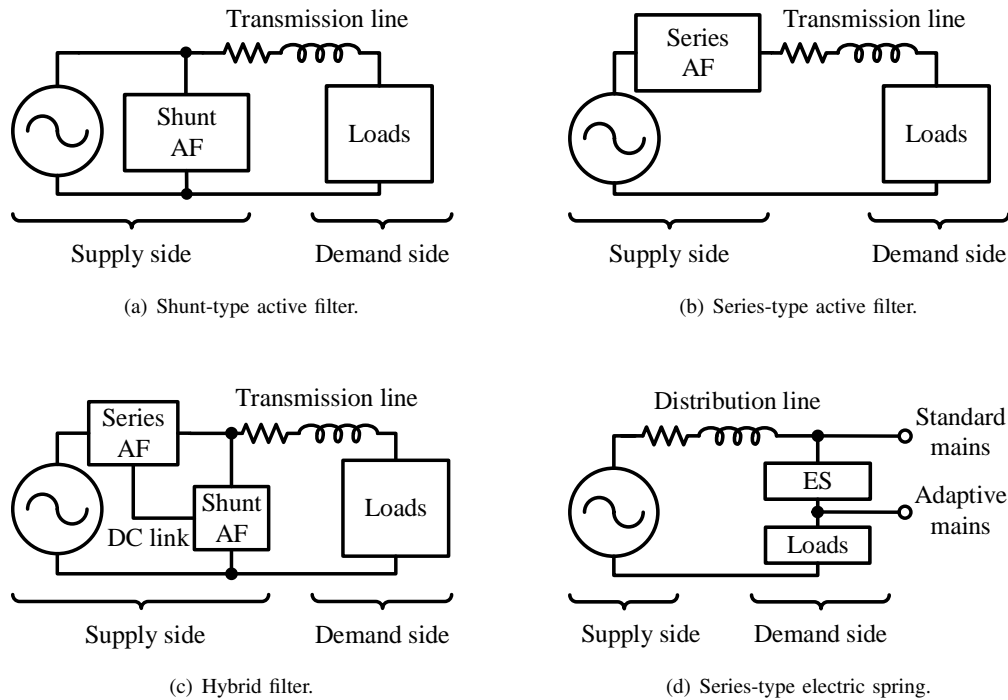


Fig. 1. Illustration of a power system with a shunt active filter, a series active filter, and hybrid filter and an electric spring installed.

compensations [20]. These two versions of ES are defined as series-type ES. Further research works have been conducted on using ES for power factor correction [20], harmonic compensation [21] and neutral current mitigation [6].

Fig 1(a), 1(b), 1(c) and 1(d) show the simplified block diagrams of a shunt-type AF, a series-type AF, a HF and a series-type ES, respectively. The supply-side voltage in each of these figures represents the upstream part of the power network. That can be the output of the step-up transformer inside a power generation plant (in the cases of Fig. 1(a), 1(b) and 1(c)) or the output of the step-down transformer of the distribution substation (in the case of Fig. 1(d)). The loads in the figures represent the combination of the loads at the demand side. ESs are different from traditional FACTS devices by (i) using an input-voltage control to regulate the standard mains and (ii) providing an adaptive mains for NC loads. Unlike the traditional AF that are the large-scale infrastructures and are installed at transmission levels, the ES are small power-electronic devices and are targeted to be installed at distribution levels. They can be distributed over the distribution network to form a distributed active suspension system. Since ES can dynamically modulate the NC load power, they form a distributed demand-response solution to balance the power supply and demand.

Some preliminary work on the reduction of power imbalance using ES was reported in [6]. Due to the lack of a systematic analysis, previous work obtained near-optimum solutions based on Genetic Algorithm (GA) to reduce neutral current in a three-phase power system. Other important power imbalance issues (such as negative-sequence and zero-sequence currents, and optimum power compensation and battery capacity) remain unsolved. Excessive negative-sequence

current can affect the reliability of power systems [1] [2] [22] [23]. For instance, in the direct-and-quadrature (dq) control commonly adopted in power compensators, the presence of negative-sequence components can cause the dq variables to vary at twice the fundamental grid frequency [22]. Hence, the compensation algorithm for power balancing would not work well because of calculation errors introduced by such variations [23]. European Standard EN 600341 has been initiated to govern the acceptable negative-sequence currents in synchronous machines [24].

In this paper, a comprehensive analysis on the use of ES for reducing power imbalance in a three-phase system is presented. It provides a new theoretical platform to work out the precise control strategy and analytical solution for a series-type three-phase ES in order to reduce both zero-sequence and negative-sequence currents in an unbalanced power system. Under certain conditions, this method can reduce system power imbalance without requiring real power from the ES. Beyond such conditions, the theory can pinpoint the precise condition at which the minimum active power is required from the ES to restore power balance. Therefore, the battery storage on the DC link of the ES can be minimized. Simulation and experiment results obtained from a 3-kW prototype are included to validate the proposed method.

II. THREE-PHASE POWER BALANCING VIA ELECTRIC SPRINGS

Three-phase power imbalances can be commonly found in large residential buildings [25], of which the general electrical system diagram is shown in Fig. 2. The system can be divided into three sections, namely the supply-side section, the centralized-load section and the single-phase residential-

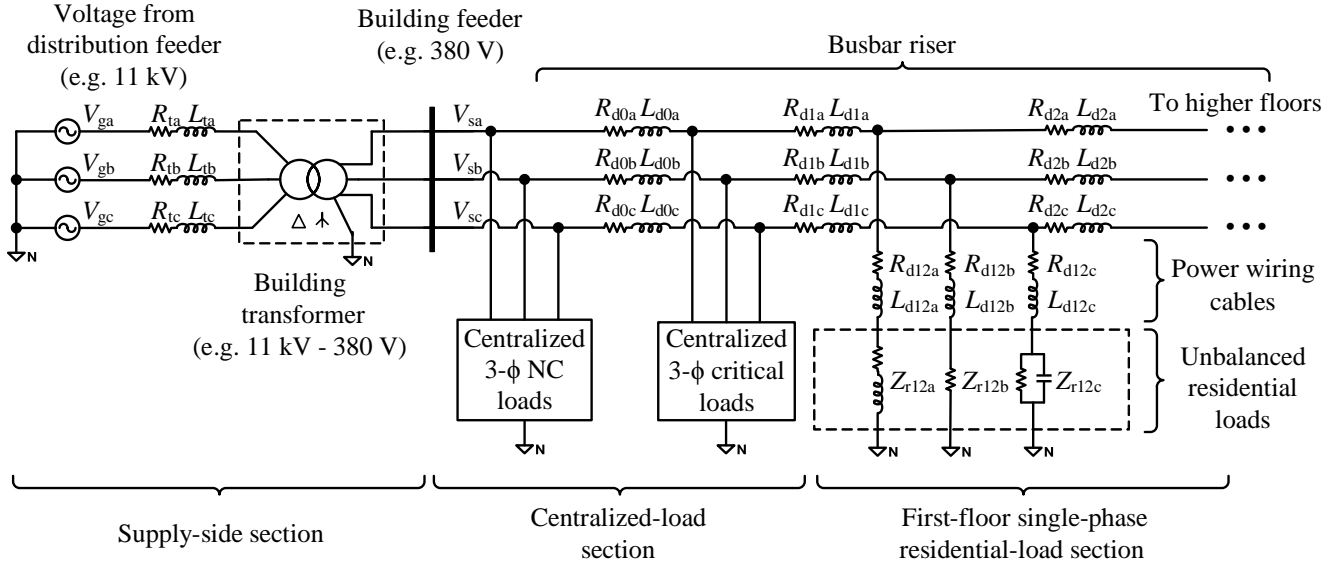


Fig. 2. The general electrical system diagram of a large residential building.

load section. In the supply-side section, the building acquires power from a distribution feeder. The distribution voltage is stepped down to the utility level via a building transformer and its output voltage is denoted as the building supply voltage V_{si} on phase i , where $i = a, b$ or c . The centralized-load section consists of three-phase electrical devices, such as lifts, escalators, central air-conditioning systems, and central water heaters. The single-phase residential-load section involves loads fed by individual phases. Power consumptions among different phases are usually not identical. Since the power supply units of centralized three-phase loads are generally close to the building transformer, their associated parasitic impedances are ignored in this analysis.

The centralized three-phase loads can be categorized into critical loads and NC loads. Critical loads are fed by the standard AC mains (V_{sa}, V_{sb}, V_{sc}) tightly regulated through an input-voltage control loop by the ES. Examples are lifts and escalators. The ES also provides an adaptive AC mains (V_{oa}, V_{ob}, V_{oc}) with a higher tolerance of supply voltage for the NC loads. A centralized three-phase water heating system can be considered as an NC load.

In this section, a comprehensive steady-state analysis of using ES for restoring power balance in a three-phase power system is presented. A simplified block diagram of the electric system with an ES installed in a residential building is shown in Fig. 3. It is assumed that the three-phase supply voltage of the building is constant and balanced, of which the root-mean-square (RMS) magnitude of the voltage is denoted as

$$|V_{s_Ref}| = |V_{sa}| = |V_{sb}| = |V_{sc}| \quad (1)$$

The NC load (e.g. a centralized water heater) on phase i can be represented by a complex impedance $Z_{oi} = R_{oi} + jX_{oi}$. The other impedances of the building on phase i , including (i) the critical three-phase loads, (ii) the parasitic impedances of the busbar riser and (iii) the impedances of devices in all domestic electric loads, are combined together and are represented by

a branch complex impedance $Z_{bi} = R_{bi} + jX_{bi}$. Note that the impedance of the centralized water heater can be assumed to be purely resistive R_{oi} . Nevertheless, a complex impedance form Z_{oi} will be used in this analysis to prevent the loss of generality as different types of loads with complex impedance are applicable as an NC load [20]. Under this configuration, the complex power of the whole building (S_{sa}, S_{sb}, S_{sc}) consists of two parts: (i) the complex power consumed by the ES-associated smart load ($S_{sla}, S_{slb}, S_{slc}$) and (ii) the complex power consumed by the branch loads (S_{ba}, S_{bb}, S_{bc}) as highlighted in Fig. 3. Considering the situation that the ES is not activated. The voltage of the adaptive AC mains is equal to that of the standard AC mains. The smart-load complex power of phase i can be expressed as

$$S_{sli} = S_{nom_sli} = P_{nom_sli} + jQ_{nom_sli} = V_{si} \frac{\overline{V_{si}}}{Z_{oi}} \quad (2)$$

where S_{nom_sli} is defined as the nominal value of S_{sli} . The branch complex power on phase i is

$$S_{bi} = P_{bi} + jQ_{bi} = V_{si} \frac{\overline{V_{si}}}{Z_{bi}} \quad (3)$$

Hence, the three-phase nominal power of the building (with the ES deactivated) S_{nom_s} is

$$S_{nom_s} = S_{nom_sl} + S_b \quad (4)$$

where $S_{nom_sl} = S_{nom_sla} + S_{nom_slb} + S_{nom_slc}$ and $S_b = S_{ba} + S_{bb} + S_{bc}$ are the three-phase nominal smart-load complex power and the three-phase branch complex power of the building, respectively (Fig. 3). Consider the situation that the ES is activated and that it can deliver a certain ES voltage on each phase such that the system operates to behave as a load that consumes a balanced three-phase power. The balanced per-phase active and reactive power of the building are denoted as P_{s_bal} and Q_{s_bal} , respectively. Thus, $P_{sa} = P_{sb} = P_{sc} = P_{s_bal}$ and $Q_{sa} = Q_{sb} = Q_{sc} = Q_{s_bal}$. The

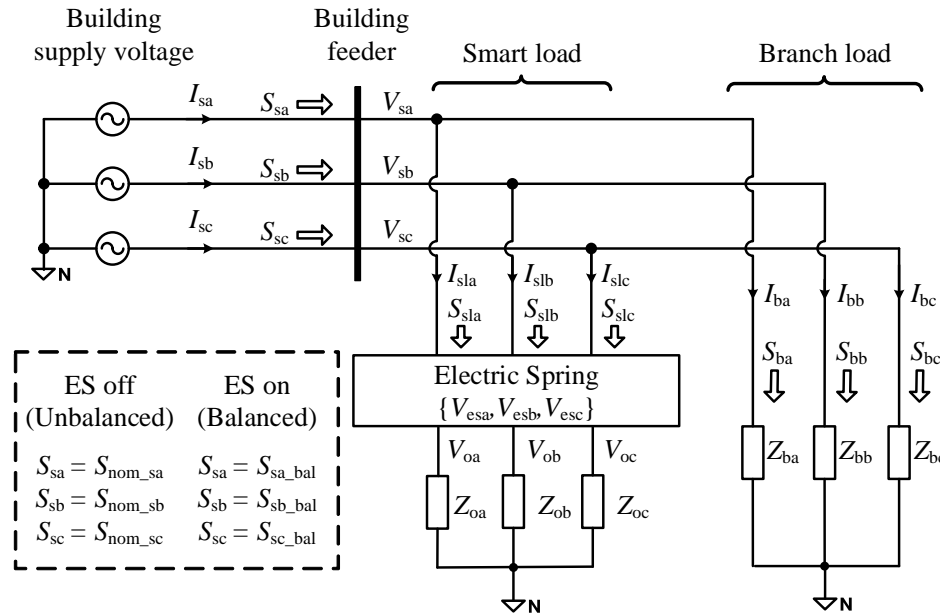


Fig. 3. A simplified electrical diagram of a large residential building.

active and reactive branch power (P_{bi} and Q_{bi}) are unchanged and (3) remains valid after the activation of the ES because the supply voltage level is remained at $|V_{s_Ref}|$. In this balanced system, the smart-load active power ($P_{sli} = P_{s_bal} - P_{bi}$) and reactive power ($Q_{sli} = Q_{s_bal} - Q_{bi}$) on phase i can be expressed by using the power conservation analysis. Thus, the smart-load apparent power on phase i can be expressed as

$$|S_{sli}| = \sqrt{(P_{s_bal} - P_{bi})^2 + (Q_{s_bal} - Q_{bi})^2} \quad (5)$$

The operating voltage of the ES on each phase has to be determined according to the power requirement described in equations (2) to (5). The calculation of the ES voltage can be a tedious process if an improper mathematical approach is adopted. Unlike [6] in which Generic Algorithm is adopted to estimate the numerical results (in order to avoid the solving of complex equations), the analysis here is based on the radial-chordal decomposition (RCD) method [26]. It can provide the precise analytical solution to achieve power balance. The RCD method decomposes the ES voltage into radial and chordal sub-components such that the power angle and the power magnitude of the ES-associated smart load can be independently controlled. According to equations (20) and (21) given in [26], the power amplitude (apparent power) of the ES-associated smart load and that of the NC load can be respectively calculated as

$$|S_{sli}| = \frac{|V_{s_Ref}| \left(|V_{s_Ref}| - \overrightarrow{V_{esri}} \right)}{|Z_{oi}|} \quad (6)$$

and

$$|S_{oi}| = \frac{\left(|V_{s_Ref}| - \overrightarrow{V_{esri}} \right)^2}{|Z_{oi}|} \quad (7)$$

where $\overrightarrow{V_{esri}}$ is the magnitude of the radial ES voltage on phase i with the polarity indicating that it is either in phase

(positive) or in antiphase (negative) with the NC load voltage. The magnitude of the radial ES voltage on phase i can be calculated by using (5) and (6) as

$$|V_{esri}| = |V_{s_Ref}| - \frac{|Z_{oi}| \sqrt{(P_{s_bal} - P_{bi})^2 + (Q_{s_bal} - Q_{bi})^2}}{|V_{s_Ref}|} \quad (8)$$

The active power of the NC load on phase i can be found from (5), (7) and (8) as

$$\begin{aligned} P_{oi} &= \frac{\left(|V_{s_Ref}| - \overrightarrow{V_{esri}} \right)^2}{|Z_{oi}|} \cos \phi_{oi} \\ &= \frac{\left[(P_{s_bal} - P_{bi})^2 + (Q_{s_bal} - Q_{bi})^2 \right] |Z_{oi}| \cos \phi_{oi}}{|V_{s_Ref}|^2} \end{aligned} \quad (9)$$

where ϕ_{oi} is the power angle of the NC load on phase i . Using (9), the ES active power on phase i can be calculated as

$$\begin{aligned} P_{esi} &= P_{sli} - P_{oi} \\ &= P_{s_bal} - P_{bi} - P_{oi} \\ &= P_{s_bal} - P_{bi} - \frac{\left[(P_{s_bal} - P_{bi})^2 + (Q_{s_bal} - Q_{bi})^2 \right] |Z_{oi}| \cos \phi_{oi}}{|V_{s_Ref}|^2} \end{aligned} \quad (10)$$

Since the active and reactive branch power (P_{bi} and Q_{bi}), the supply-side reference voltage $|V_{s_Ref}|$, the impedance of the NC load $|Z_{oi}|$, and the power angle of the NC load ϕ_{oi} are all constant in the steady state, only the balanced per-phase active and reactive power of the building (P_{s_bal} and Q_{s_bal}) are considered as variables in (10). The three-phase

ES active power is the sum of the ES active power on each phase. According to (10), which can be expressed as

$$P_{es} = P_{esa} + P_{esb} + P_{esc} \\ = K_1 P_{s_bal}^2 + K_3 Q_{s_bal}^2 + K_2 P_{s_bal} + K_4 Q_{s_bal} + K_5 \quad (11)$$

where $K_1, K_2, K_3, K_4,$ and K_5 are indicated in (12).

Note that a positive quantity of P_{es} means that an active power flows from the power system to the ES and vice versa. Equation (11) indicates that P_{es} is a circular paraboloid function (as $K_1 = K_3$) of P_{s_bal} and Q_{s_bal} in three-dimensional $P_{s_bal}-Q_{s_bal}-P_{es}$ space. The three-phase power system in Fig. 3 is symmetrically power balanced if the system operates at any point on the surface of this circular paraboloid. Also, a desired active power injection from (or absorption by) the ES can be chosen under a specified active and reactive power operation of the system (P_{s_bal}, Q_{s_bal}). By applying a first-order partial differentiation on P_{es} in (11) with respect to the specified power, we have

$$\frac{\partial P_{es}}{\partial P_{s_bal}} = 2 K_1 P_{s_bal} + K_2 \quad (13)$$

and

$$\frac{\partial P_{es}}{\partial Q_{s_bal}} = 2 K_3 Q_{s_bal} + K_4 \quad (14)$$

Hence, there exists a unique stationary point on the circular paraboloid function located at $(P_{s_bal}, Q_{s_bal}) = (-K_2/2K_1, -K_4/2K_3)$. Application of the second-order partial differentiation on P_{es} gives

$$\frac{\partial^2 P_{es}}{\partial P_{s_bal}^2} = \begin{cases} 2 K_1 < 0 & \text{for } (R_{oa} + R_{ob} + R_{oc}) > 0 \\ 2 K_1 > 0 & \text{for } (R_{oa} + R_{ob} + R_{oc}) < 0 \end{cases} \quad (15)$$

$$\frac{\partial^2 P_{es}}{\partial Q_{s_bal}^2} = \begin{cases} 2 K_3 < 0 & \text{for } (R_{oa} + R_{ob} + R_{oc}) > 0 \\ 2 K_3 > 0 & \text{for } (R_{oa} + R_{ob} + R_{oc}) < 0 \end{cases} \quad (16)$$

and

$$\frac{\partial^2 P_{es}}{\partial P_{s_bal} \partial Q_{s_bal}} = 0 \quad (17)$$

Equations (15) to (17) are used for classifying the stationary point of the function P_{es} in (11). The determinant $D(P_{s_bal}, Q_{s_bal})$ of the Hessian matrix of the function P_{es} , $\mathbf{H}(P_{s_bal}, Q_{s_bal})$, is

$$D(P_{s_bal}, Q_{s_bal}) = \det(\mathbf{H}(P_{s_bal}, Q_{s_bal})) \\ = \det \begin{bmatrix} \frac{\partial^2 P_{es}}{\partial P_{s_bal}^2} & \frac{\partial^2 P_{es}}{\partial P_{s_bal} \partial Q_{s_bal}} \\ \frac{\partial^2 P_{es}}{\partial P_{s_bal} \partial Q_{s_bal}} & \frac{\partial^2 P_{es}}{\partial Q_{s_bal}^2} \end{bmatrix} \quad (18) \\ = \frac{\partial^2 P_{es}}{\partial P_{s_bal}^2} \cdot \frac{\partial^2 P_{es}}{\partial Q_{s_bal}^2} - \left(\frac{\partial^2 P_{es}}{\partial P_{s_bal} \partial Q_{s_bal}} \right)^2$$

where \det is the denotation for determinant. According to the second-partial-derivative test for two variables [27], since $D(P_{s_bal}, Q_{s_bal})$ is always positive (referring to the results in (15) to (18)), the stationary point $(P_{s_bal}, Q_{s_bal}) = (-K_2/2K_1, -K_4/2K_3)$ must be a unique extremum of the function P_{es} . This extremum is the maximum point and the circular paraboloid is concave downward when $\partial^2 P_{es}/\partial P_{s_bal}^2 < 0$. This is the case where the constant $K_1 <$

TABLE I
PARAMETERS OF THE SYSTEM IN EXAMPLES

Case	Variable	Phase a	Phase b	Phase c
		(p.u.)	(p.u.)	(p.u.)
/	$ V_{si} $	1	1	1
/	P_{s_bal}	1	1	1
A	$P_{oi} + Q_{oi}$	$0.5 + j0.0$	$0.5 + j0.0$	$0.5 + j0.0$
	$P_{bi} + Q_{bi}$	$0.6 + j0.2$	$0.5 + j0.1$	$0.4 + j0.0$
B	$P_{oi} + Q_{oi}$	$0.3 + j0.2$	$0.3 + j0.2$	$0.3 + j0.2$
	$P_{bi} + Q_{bi}$	$0.7 + j0.3$	$1.0 + j0.2$	$0.4 + j0.0$
C	$P_{oi} + Q_{oi}$	$-0.7 + j0.0$	$0.8 + j0.0$	$0.6 + j0.0$
	$P_{bi} + Q_{bi}$	$0.8 - j0.6$	$0.9 - j0.4$	$0.6 - j0.0$
D	$P_{oi} + Q_{oi}$	$-0.6 + j0.0$	$-0.6 + j0.0$	$-0.6 + j0.0$
	$P_{bi} + Q_{bi}$	$1.7 - j0.6$	$1.8 - j0.4$	$1.3 + j0.0$
E	$P_{oi} + Q_{oi}$	$-0.6 - j0.2$	$-0.6 - j0.2$	$-0.6 - j0.2$
	$P_{bi} + Q_{bi}$	$1.7 - j0.6$	$1.8 - j0.4$	$1.3 + j0.0$
F	$P_{oi} + Q_{oi}$	$0.7 + j0.0$	$-0.8 + j0.0$	$-0.6 + j0.0$
	$P_{bi} + Q_{bi}$	$1.0 - j0.6$	$1.5 - j0.4$	$1.2 + j0.0$

0 as indicated in (15). On the other hand, the extremum is the minimum point and the circular paraboloid is concave upward when $\partial^2 P_{es}/\partial P_{s_bal}^2 > 0$ ($K_1 > 0$). It is concluded that the concavity of the circular paraboloid function (determined by the constant K_1) depends on the summed value of the resistive part of the NC load on each phase as described by (15).

To show the properties of the circular paraboloid function, six cases of the NC load power and the branch power in per-unit (p.u.) representation are included as shown in Table I. The magnitude of the supply voltage (V_{si}) and the average per-phase nominal active power of the system ($P_{nom_s}/3$) are chosen to be 1 p.u. Figures 4(a), 4(b) and 4(c) show the phasor diagram of the NC load impedance in case A, B and C, respectively, where their NC loads are respectively balanced positive pure-resistive, balanced positive-resistive inductive and unbalanced pure-resistive. Their corresponding circular paraboloid functions are plotted in Fig. 5(a), 5(b) and 5(c), respectively. The constant K_1 in all the three cases is negative and these circular paraboloid functions are all concave downward. On the other hand, Fig. 4(d), 4(e) and 4(f) show the phasor diagram of the NC load impedance in case D, E and F, respectively, where their NC loads are respectively balanced negative pure-resistive, balanced negative-resistive capacitive and unbalanced pure-resistive. Their corresponding circular paraboloid functions are plotted in Fig. 5(d), 5(e) and 5(f), respectively. For all the three cases, the constant K_1 is positive and the circular paraboloid functions are all concave upward.

Equation (11) can be used to determine the corresponding value of the ES voltage on each phase. Given a specific desired balanced active and reactive power operating point of the system (P_{s_bal}, Q_{s_bal}), the corresponding radial (V_{esri}) and chordal ES voltage (V_{esci}) on phase i can be calculated as

$$|V_{esri}| = |V_{s_Ref}| - \frac{|Z_{oi}| \sqrt{(P_{s_bal} - P_{bi})^2 + (Q_{s_bal} - Q_{bi})^2}}{|V_{s_Ref}|} \quad (19)$$

$$\begin{aligned}\theta_{\text{esri}} &= \theta_{\text{oi}} \\ &= \phi_{\text{oi}} - \phi_{\text{sli}} \\ &= \phi_{\text{oi}} - \arg[(P_{\text{s_bal}} - P_{\text{bi}}) + j(Q_{\text{s_bal}} - Q_{\text{bi}})]\end{aligned}\quad (20)$$

$$|V_{\text{esci}}| = \sqrt{2|V_{\text{s_Ref}}|^2 (1 - \cos(\theta_{\text{oi}}))}\quad (21)$$

$$\theta_{\text{esci}} = -\text{sgn}(\theta_{\text{oi}}) \frac{\pi - |\theta_{\text{oi}}|}{2}\quad (22)$$

where θ_{esri} , θ_{oi} , θ_{esci} are respectively the phasor angle of the radial ES voltage, NC load voltage and chordal ES voltage with respect to their corresponding grid voltage (V_{si}) on phase i. The notations $\arg(\cdot)$ and $\text{sgn}(\cdot)$ are defined as the argument of the complex number and the signum function, respectively. Equation (19) and (20) are for the radial ES voltages while (21) and (22) are for the chordal ones. The derivations of (19) to (22) and their explanations can be found in [26].

III. OPTIMUM OPERATING CONDITIONS FOR RESTORING POWER BALANCE

The circular paraboloid function given in (11) can be used to (i) determine the three-phase power-balanced operating point of a power system regulated by the ES and (ii) optimize the active power usage in the ES such that the battery storage capacity can be minimized. Two conditions are possible with the system shown in Fig. 3:

1. The power balance can be restored by the ES with active power injection into the system. While there are multiple solutions, there exists a solution that requires minimum active power from the ES.
2. The power balance can be restored by the ES without active power injection into the system. While there are multiple solutions, there exists an optimum solution that involves the minimum deviation from the original average active power value of the three-phase system (P_{nom_s}).

These two cases are separately discussed in this section. The minimum use of active power would lead to the minimization of the energy storage capacity in the ES.

The ES under consideration is a bi-directional DC-AC power converter with a battery storage connected to its DC bus. The active power delivered from the battery storage (denoted as $P_{\text{es_dc}}$) is equal to the sum of the power loss in the bi-directional converter (denoted as $P_{\text{es_loss}}$) and the ES active power injected to the grid (i.e., $P_{\text{es_dc}} = P_{\text{es_loss}} + P_{\text{es}}$). If the power loss of this bi-directional converter is neglected ($P_{\text{es_loss}} = 0$ W) and the ES does not deliver active power to the grid ($P_{\text{es}} = 0$ W), there is no requirement for energy storage in the ES ($P_{\text{es_dc}} = 0$ W). Under this premise, the operating point of the system should lie on the locus defined by the intersection of the circular paraboloid function and the plane $P_{\text{es}} = 0$ p.u. This locus is

$$K_1 P_{\text{s_bal}}^2 + K_3 Q_{\text{s_bal}}^2 + K_2 P_{\text{s_bal}} + K_4 Q_{\text{s_bal}} + K_5 = 0\quad (23)$$

A. Restoring Power Balance with Minimum Active Power by the ES

In the case that (23) does not give a real solution, it means that there is no intersection between the circular paraboloid function and the plane $P_{\text{es}} = 0$ p.u. In this case, P_{es} cannot reach zero and a minimized value of $|P_{\text{es}}|$ should be determined. Equation (23) can be rewritten as

$$\begin{aligned}\left(P_{\text{s_bal}} + \frac{K_2}{2K_1}\right)^2 + \left(Q_{\text{s_bal}} + \frac{K_4}{2K_1}\right)^2 = \\ \left(\frac{K_2}{2K_1}\right)^2 + \left(\frac{K_4}{2K_1}\right)^2 - \frac{K_5}{K_1}\end{aligned}\quad (24)$$

This is the equation of a circle on the $P_{\text{s_bal}}-Q_{\text{s_bal}}$ plane with the origin located at $(-K_2/2K_1, -K_4/2K_1)$ and its radius equals to the square root of the right hand side of the equation. The condition for this circle to be imaginary is that the radius must be smaller than zero, which gives

$$K_2^2 + K_4^2 < 4K_5K_1\quad (25)$$

Hence, a minimum value of $|P_{\text{es}}|$ exists and it is located at $(P_{\text{s_bal}}, Q_{\text{s_bal}}) = (-K_2/2K_1, -K_4/2K_1)$ (which is the

$$\begin{aligned}K_1 &= -\frac{|Z_{\text{oa}}| \cos(\phi_{\text{oa}})}{|V_{\text{s_Ref}}|^2} - \frac{|Z_{\text{ob}}| \cos(\phi_{\text{ob}})}{|V_{\text{s_Ref}}|^2} - \frac{|Z_{\text{oc}}| \cos(\phi_{\text{oc}})}{|V_{\text{s_Ref}}|^2} \\ K_2 &= 3 + 2\frac{P_{\text{ba}}|Z_{\text{oa}}| \cos(\phi_{\text{oa}})}{|V_{\text{s_Ref}}|^2} + 2\frac{P_{\text{bb}}|Z_{\text{ob}}| \cos(\phi_{\text{ob}})}{|V_{\text{s_Ref}}|^2} + 2\frac{P_{\text{bc}}|Z_{\text{oc}}| \cos(\phi_{\text{oc}})}{|V_{\text{s_Ref}}|^2} \\ K_3 &= -\frac{|Z_{\text{oa}}| \cos(\phi_{\text{oa}})}{|V_{\text{s_Ref}}|^2} - \frac{|Z_{\text{ob}}| \cos(\phi_{\text{ob}})}{|V_{\text{s_Ref}}|^2} - \frac{|Z_{\text{oc}}| \cos(\phi_{\text{oc}})}{|V_{\text{s_Ref}}|^2} \\ K_4 &= 2\frac{Q_{\text{ba}}|Z_{\text{oa}}| \cos(\phi_{\text{oa}})}{|V_{\text{s_Ref}}|^2} + 2\frac{Q_{\text{bb}}|Z_{\text{ob}}| \cos(\phi_{\text{ob}})}{|V_{\text{s_Ref}}|^2} + 2\frac{Q_{\text{bc}}|Z_{\text{oc}}| \cos(\phi_{\text{oc}})}{|V_{\text{s_Ref}}|^2} \\ K_5 &= -P_{\text{ba}} - \frac{(P_{\text{ba}}^2 + Q_{\text{ba}}^2)|Z_{\text{oa}}| \cos(\phi_{\text{oa}})}{|V_{\text{s_Ref}}|^2} - P_{\text{bb}} - \frac{(P_{\text{bb}}^2 + Q_{\text{bb}}^2)|Z_{\text{ob}}| \cos(\phi_{\text{ob}})}{|V_{\text{s_Ref}}|^2} - P_{\text{bc}} - \frac{(P_{\text{bc}}^2 + Q_{\text{bc}}^2)|Z_{\text{oc}}| \cos(\phi_{\text{oc}})}{|V_{\text{s_Ref}}|^2}\end{aligned}\quad (12)$$

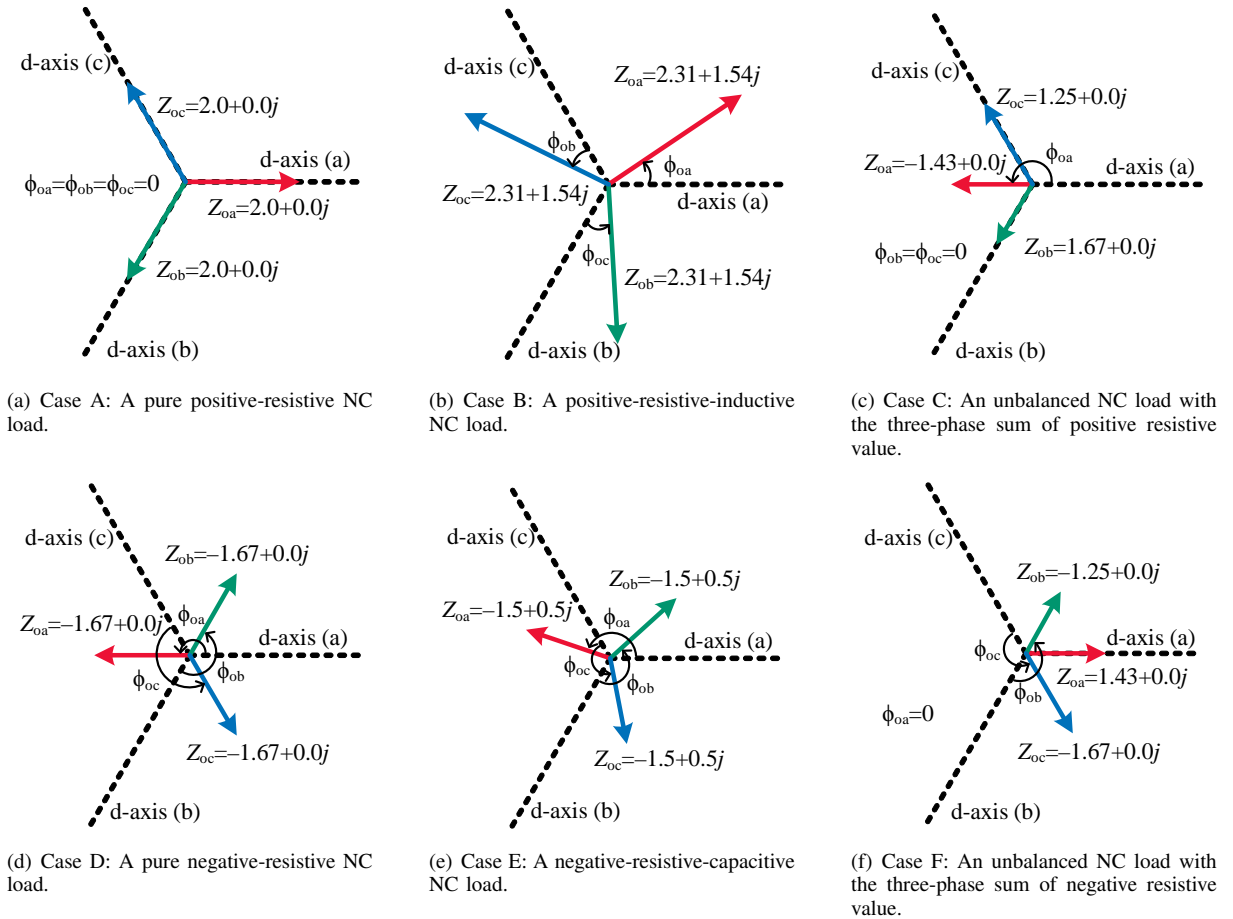


Fig. 4. Six cases of NC loads with respect to the corresponding nominal complex power indicated in Table I. (Per-unit representation)

vertex and the extremum of the circular paraboloid function) if and only if (25) holds. Figure 5(a) and 5(d) are redrawn with the plane of $P_{es} = 0$ p.u. They are shown in Fig. 6(a) and 6(b), respectively.

In Fig. 6(a), the circular paraboloid function in case B is concave downward with the maximum value of $P_{es} = -0.198$ p.u. at the vertex. Any operating point on the surface of the circular paraboloid is a solution for the ES to restore power balance. The vertex is therefore the optimum solution because it has the shortest distance to the plane of $P_{es} = 0$ p.u. Operating at the vertex point means in this case that power balance can be restored with the battery of the ES being discharged to provide the minimum amount of active power.

On the other hand, Fig. 6(b) shows the condition for case D. The circular paraboloid function is concave upward and the minimum amount of active power absorbed by the ES is $P_{es} = 0.094$ p.u. Operating at this vertex is the optimum solution because the battery of the ES will be charged to absorb the minimum active power in order to restore the power balance.

B. Restoring Power Balance without Active Power from the ES

The ES does not need to inject active power into the system if (23) exists real solutions. In this case, the plane

$P_{es} = 0$ p.u. intersects with the surface of the paraboloid as shown in an example of Fig. 6(c). Unlike the condition in Section III-A of which an optimum operating point of the system is unique (at the vertex of the circular paraboloid function), the system discussed in this section can operate at any intersection point lying on the circle in (23). In order to visualize the characteristics of the circular paraboloid function and quantitatively identify the locus of (P_{s_bal}, Q_{s_bal}) , the data in case A as shown in Table I is used as an example. Substituting the parameters of case A in Table I into (11) gives

$$P_{es} = -6 P_{s_bal}^2 + 9 P_{s_bal} - 6 Q_{s_bal}^2 + 1.2 Q_{s_bal} - 3.14 \quad (26)$$

Figure 6(c) shows the circular paraboloid function in (26) and the plane $P_{es} = 0$ p.u. Since the NC load is positive-resistive, the vertex of the circular paraboloid function is the maximum point of P_{es} . This point is located at $(P_{s_bal}, Q_{s_bal}, P_{es}) = (0.75 \text{ p.u.}, 0.1 \text{ p.u.}, 0.295 \text{ p.u.})$, which can be obtained from (13), (14) and (26).

The operating locus of the system power (P_{s_bal}, Q_{s_bal}) that the ES operates in case A such that no active power is injected by the ES during the power-balanced condition is shown in Fig. 7. Its equation is

$$-6 P_{s_bal}^2 + 9 P_{s_bal} - 6 Q_{s_bal}^2 + 1.2 Q_{s_bal} - 3.14 = 0 \quad (27)$$

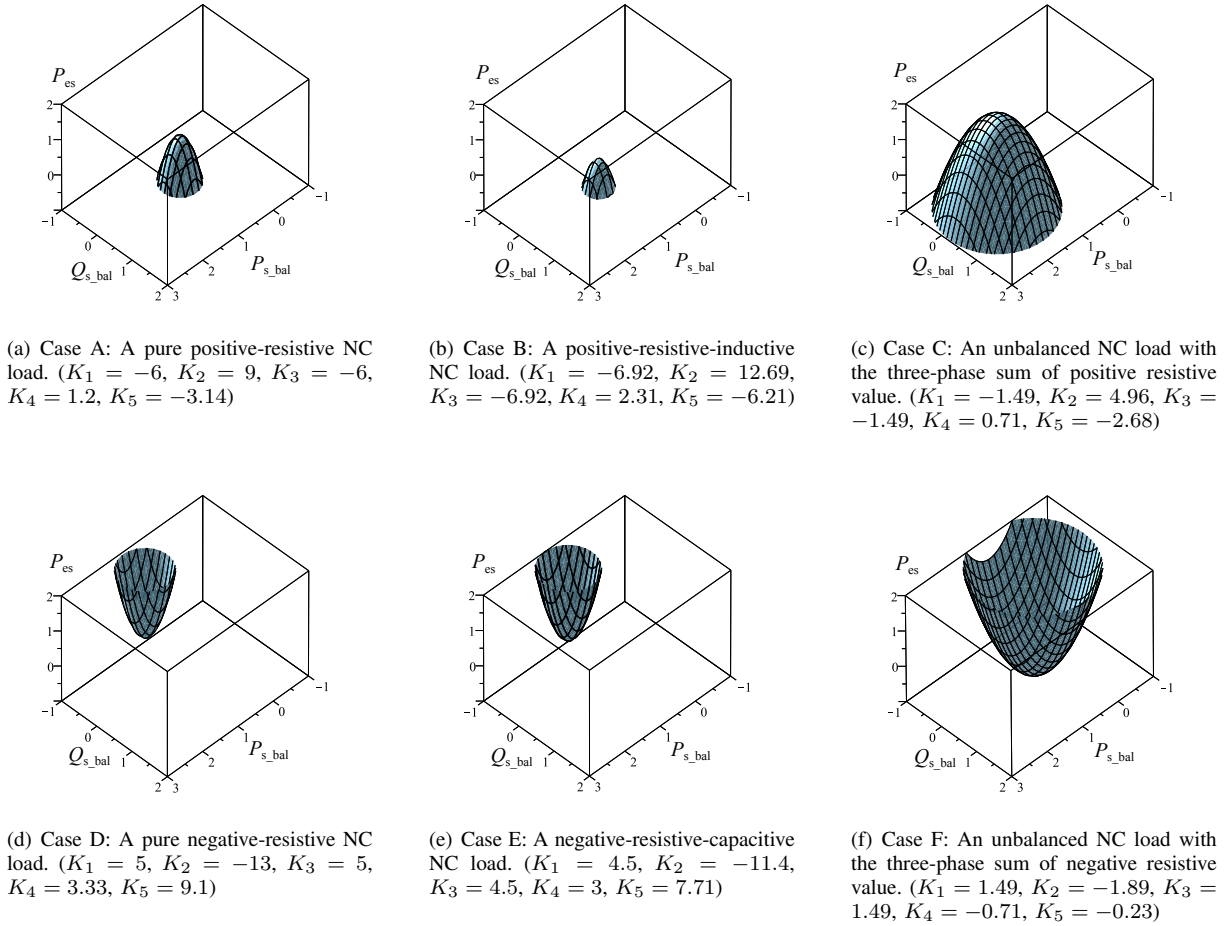


Fig. 5. Six cases of the circular paraboloid function in (11) with respect to the corresponding parameters in Table I. (Per-unit representation)

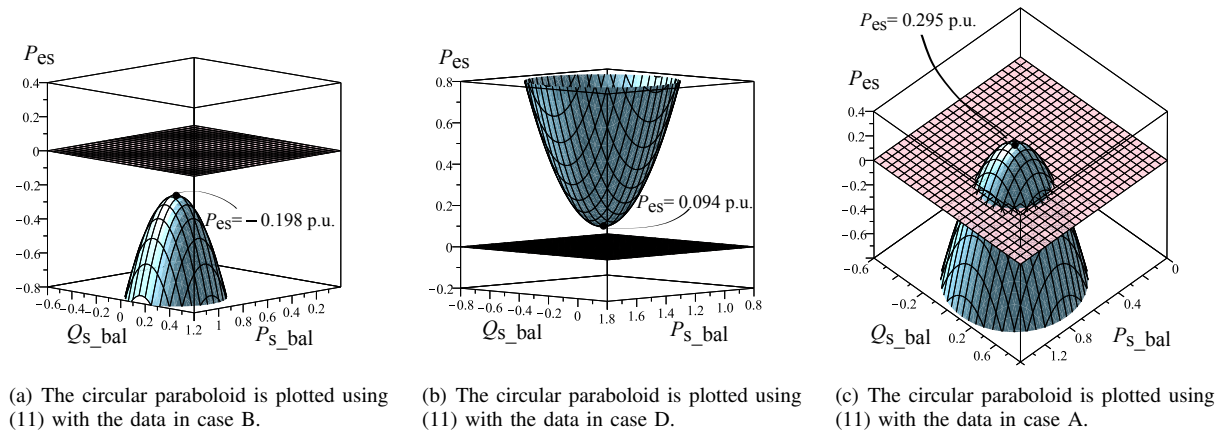


Fig. 6. Three examples show different scenarios in the circular paraboloid function interacting with the plane $P_{es} = 0$. (Per-unit representation)

This equation represents a circle obtained by considering the intersection of the circular paraboloid function and the plane $P_{es} = 0$ p.u. as shown in Fig. 6(c). Next, the ES voltage V_{esi} on phase i can be obtained from equations (19) to (22). Since there is no explicit function to express the ES voltage, the locus of the ES voltage can be expressed in terms of P_{s_bal} and Q_{s_bal} , which is indicated in (28).

Hence, the locus of the ES voltage can be obtained by substituting the implicit function (27) into (28). Figure 8(a), 8(b) and 8(c) show the loci of the radial ES voltage, the chordal ES voltage and the resultant ES voltage (vector sum of V_{esri} and V_{esci}) of each phase, respectively.

It is important to find the optimum operating point of the system within these loci. One possible optimum point of the

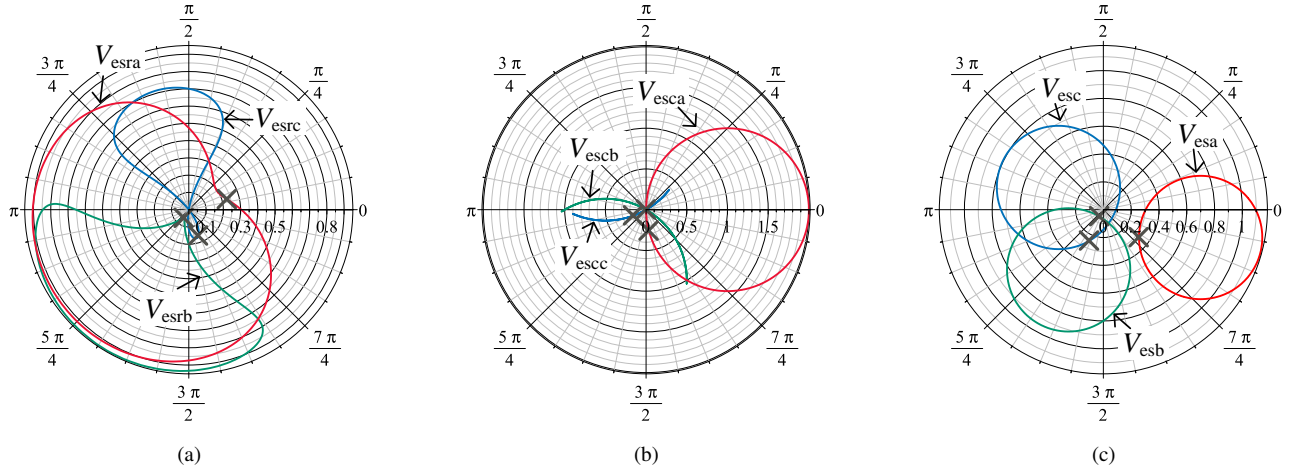


Fig. 8. The loci of (a) the radial ES voltages, (b) chordal ES voltages and (c) resultant ES voltages in case A. (Phase a: red, phase b: green, phase c: blue) (The polar angles on each phase are: phase a: θ_{esa} , phase b: $(\theta_{esb} - 2\pi/3)$, and phase c: $(\theta_{esc} + 2\pi/3)$.) (The cross markers are the optimum operating points.)

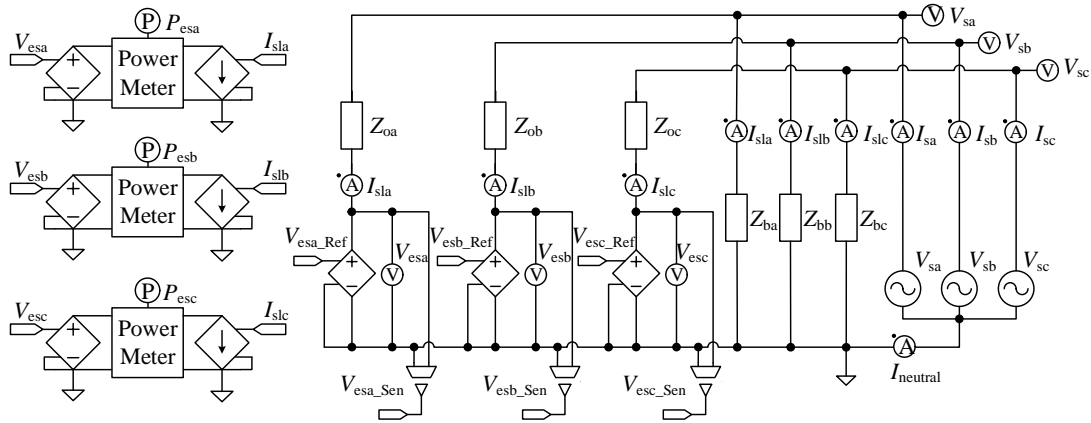


Fig. 10. The power stage of the ES adopted in the PSIM simulation in Section IV.

system is that the balanced per-phase active power of the system P_{s_bal} should be as close as possible to the average per-phase nominal active power that $(P_{nom_s}/3)$ (which is highlighted in a dotted line in Fig. 7)¹. As a result, the

optimization criterion is to minimize the difference between P_{s_bal} and $P_{nom_s}/3$. This minimized difference, in geometry sense, is equivalent to the shortest distance between a point on the line $P_{s_bal} = 1$ p.u. and a point on the circle (in (27)), as shown in Fig. 7. Consequently, the optimum operating point is located at where the value of $|P_{s_bal}|$ is maximum. By applying a first-order partial differentiation on (23) with respect to Q_{s_bal} , we have

$$Q_{s_bal} = -\frac{K_4}{2K_3} \quad (29)$$

¹It should be noted that for illustration purpose, only one optimum operating point that is closest to the average per-phase active power of the system is chosen and presented in the analysis. There are other possible optimum operating points in regard to the parameters being optimized. For example, another possible optimum operating point can be found when the reactive power of the system is regarded as zero (or minimum) to maximize the power factor of the system.

$$\begin{aligned} V_{esi} &= V_{esri} + V_{esci} \\ &= |V_{esri}| \angle \theta_{esri} + |V_{esci}| \angle \theta_{esci} \\ &= \left[|V_{s_Ref}| - \frac{|Z_{oi}| \sqrt{(P_{s_bal} - P_{bi})^2 + (Q_{s_bal} - Q_{bi})^2}}{|V_{s_Ref}|} \right] \angle \{ \phi_{oi} - \arg [(P_{s_bal} - P_{bi}) + j(Q_{s_bal} - Q_{bi})] \} + \\ &\quad \left[\sqrt{2|V_{s_Ref}|^2 (1 - \cos(\theta_{oi}))} \right] \angle \left[-\text{sgn}(\theta_{oi}) \frac{\pi - |\theta_{oi}|}{2} \right] \end{aligned} \quad (28)$$

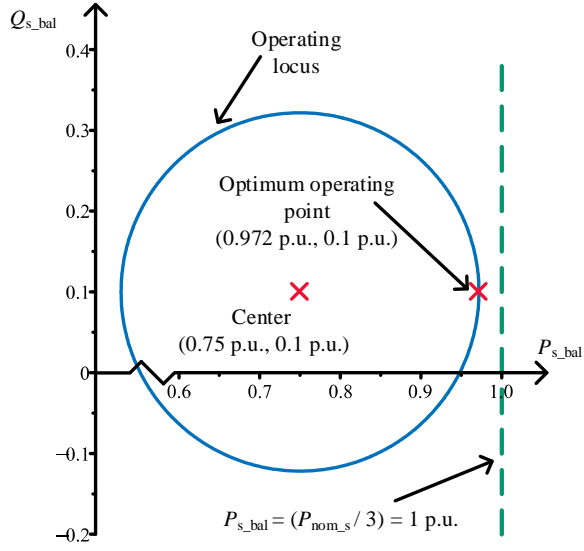


Fig. 7. The operating locus of the system power for the ES to regulate the system in case A to be power balanced without injecting active power from the ES.

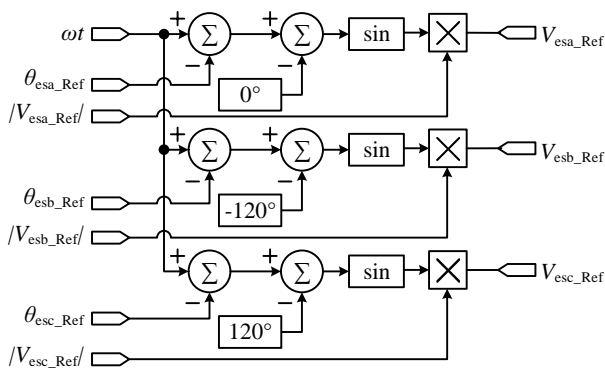


Fig. 9. The control circuit of the ES adopted in the PSIM simulation in Section IV.

By substituting (29) into (23), the optimum point of P_{s_bal} can be derived as

$$P_{s_bal} = \begin{cases} \frac{-K_2 K_3 + \sqrt{-4 K_1 K_3^2 K_5 + K_1 K_3 K_4^2 + K_2^2 K_3^2}}{2 K_1 K_3} & (\text{for } P_{s_nom} > 0) \\ \frac{-K_2 K_3 - \sqrt{-4 K_1 K_3^2 K_5 + K_1 K_3 K_4^2 + K_2^2 K_3^2}}{2 K_1 K_3} & (\text{for } P_{s_nom} < 0) \end{cases} \quad (30)$$

From (29) and (30), the optimum point of the system is calculated for case A as $(P_{s_bal}, Q_{s_bal}) = (0.972 \text{ p.u.}, 0.1 \text{ p.u.})$. The corresponding ES voltage on each phase is calculated, using (28), as $V_{esa} = 0.325 \angle -0.66 \text{ p.u.}$, $V_{esb} = 0.057 \angle 0 \text{ p.u.}$ and $V_{esc} = 0.246 \angle 2.19 \text{ p.u.}$ This optimum operating point of the ES voltage is marked on Fig. 8(a), 8(b) and 8(c).

IV. SIMULATION AND EXPERIMENTAL RESULTS

In the first part, a simulation is conducted to validate the proposed method for the restoration of power balance in a three-phase unbalanced power system. In the second part,

the ability of the proposed method for the optimization of active power usage in the ES is verified with simulation. The experimental validation is discussed in the third part.

A. Restoration of Power Balance

The validation on the proposed RCD method for the restoration of power balance in a three-phase unbalanced power system is conducted using the simulation software PSIM version 10.0. The system schematic adopted in the simulation is shown in Fig. 10, where three controlled voltage sources are adopted to model the three-phase ES. Both case B and case F shown in Table I are adopted in the simulation.

The magnitude of the phase-to-neutral grid voltage and the average per-phase nominal active power of the system are chosen as $|V_{si}| = 220 \text{ V}$ (1 p.u.) and $P_{nom_s}/3 = 1 \text{ kW}$ (1 p.u.) in the simulation, respectively. The ES voltage is pre-calculated by the proposed algorithm discussed in Section II and III. The calculated magnitude ($|V_{esa_Ref}|$, $|V_{esb_Ref}|$ and $|V_{esc_Ref}|$) and phases (θ_{esa_Ref} , θ_{esb_Ref} and θ_{esc_Ref}) of the ES voltage references are used as the controlled signals of these three controlled voltage sources as shown in Fig. 9.

The simulation is firstly conducted using the values of the NC load and the branch load in case B in Table I. Figure 11(a) shows the steady-state waveforms of the neutral and line currents before the activation of the ES. They are found as $|I_{sa}| \angle \theta_{sa} = 5.082 \angle -0.464 \text{ A}$, $|I_{sb}| \angle \theta_{sb} = 6.182 \angle -0.298 \text{ A}$ and $|I_{sc}| \angle \theta_{sc} = 3.308 \angle -0.278 \text{ A}$, and their phasor diagrams are shown in Fig. 11(b). The three-phase line currents are transformed into their symmetrical components using

$$\begin{bmatrix} |I_{szero}| \angle \theta_{szero} \\ |I_{spos}| \angle \theta_{spos} \\ |I_{sneg}| \angle \theta_{sneg} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} |I_{sa}| \angle \theta_{sa} \\ |I_{sb}| \angle \theta_{sb} \\ |I_{sc}| \angle \theta_{sc} \end{bmatrix} \quad (31)$$

where a is defined as $\cos(2\pi/3) + j \sin(2\pi/3)$, and $|I_{szero}| \angle \theta_{szero}$, $|I_{spos}| \angle \theta_{spos}$ and $|I_{sneg}| \angle \theta_{sneg}$ are respectively the zero-sequence, positive-sequence and negative-sequence component of the current. The phasor diagram of the symmetrical components is shown in Fig. 11(c). The objective of this transformation is to obtain the symmetrical-component values for indicating the degree of balance of the system.

Next, the simulation is repeated with the ES voltages calculated based on the proposed RCD method. Since the solution of (23) is imaginary, the optimum operating point of the system can be found from (13) and (14) as $P_{s_bal} = 917 \text{ W}$ and $Q_{s_bal} = 167 \text{ VAR}$. Substituting these values into (28) gives the ES voltage on each phase. They are $|V_{esa}| \angle \theta_{esa} = 209.65 \angle -0.738 \text{ V}$, $|V_{esb}| \angle \theta_{esb} = 273.82 \angle 0.0412 \text{ V}$ and $|V_{esc}| \angle \theta_{esc} = 133.76 \angle -2.401 \text{ V}$. The corresponding waveforms of the ES voltage in each power phase are shown in Fig. 15(a). The simulated line currents are $|I_{sa}| \angle \theta_{sa} = |I_{sb}| \angle \theta_{sb} = |I_{sc}| \angle \theta_{sc} = 4.235 \angle -0.180 \text{ A}$. Figure 12(a), 12(b) and 12(c) respectively show the simulated line-current waveforms, their phasor diagrams and their symmetrical components. According to Fig. 11(c) and 12(c), the proposed RCD control method can control the ES to mitigate both the zero-sequence and negative-sequence currents to zero.

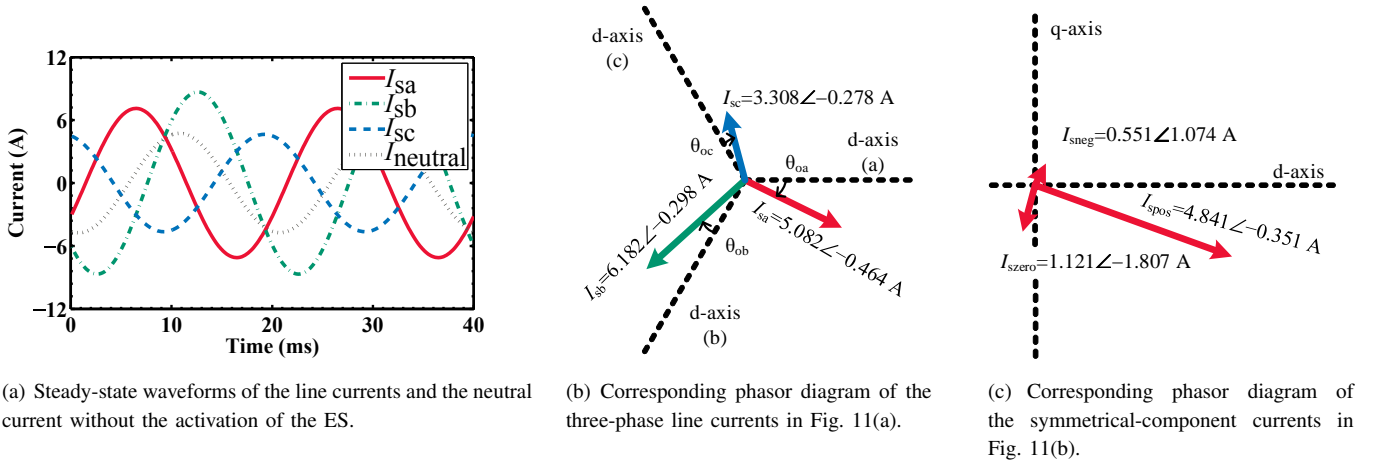


Fig. 11. The simulation results for case B with the ES deactivated.

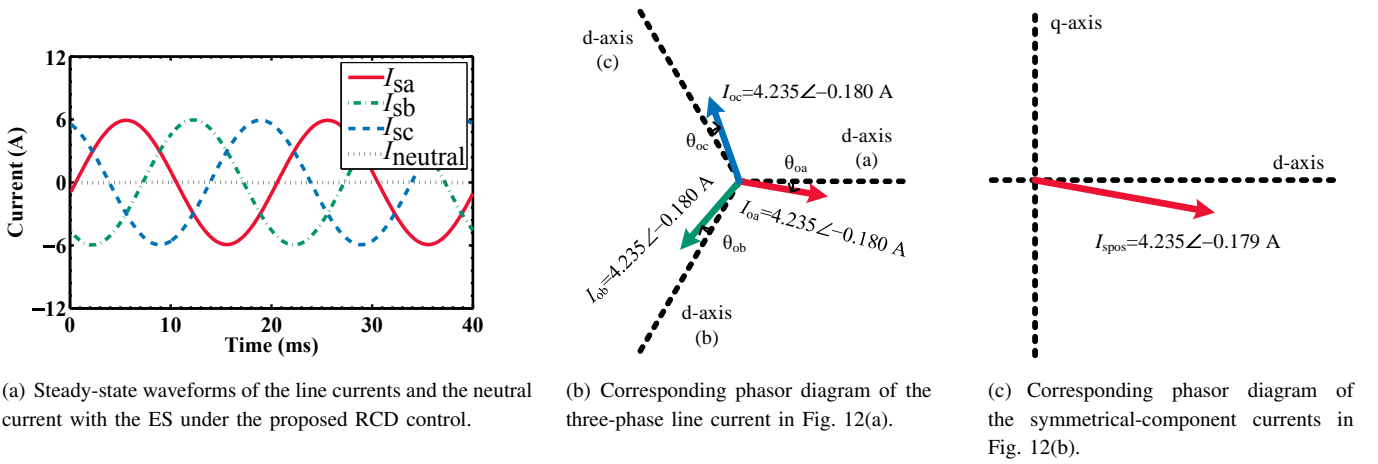


Fig. 12. The simulation results for case B with the ES under RCD control.

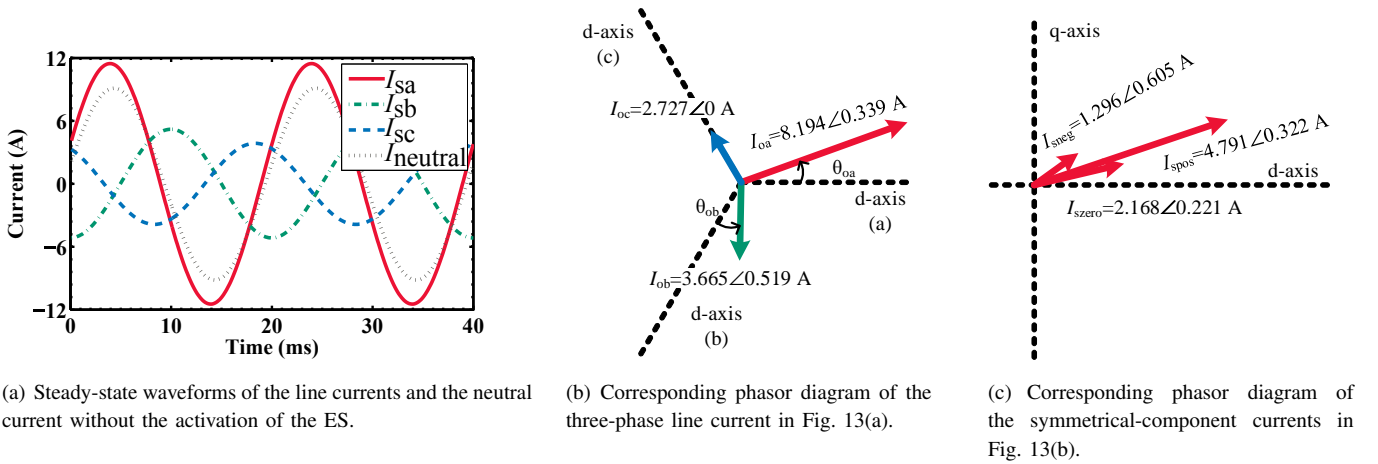


Fig. 13. The simulation results for case F with the ES deactivated.

The simulation is then repeated with the values of the NC load and the branch load given in case F. In the proposed RCD method, the operating point of the system is calculated following the analysis presented in Section III-B, which gives $P_{s_bal} = 1421 \text{ W}$, $Q_{s_bal} = 240 \text{ VAR}$, $|V_{esa}| \angle \theta_{esa} = 278.14 \angle 1.251 \text{ V}$, $|V_{esb}| \angle \theta_{esb} = 265.21 \angle -0.726 \text{ V}$, and

$|V_{esc}| \angle \theta_{esc} = 313.78 \angle -0.284 \text{ V}$. The simulation waveforms of the line currents, their phasor diagrams and their symmetrical components without the activation of the ES are shown in Fig 13(a), 13(b) and 13(c), respectively. The simulation waveforms of line currents with the ES under the RCD control method are shown in Fig. 14(a), 14(b) and 14(c). The corre-

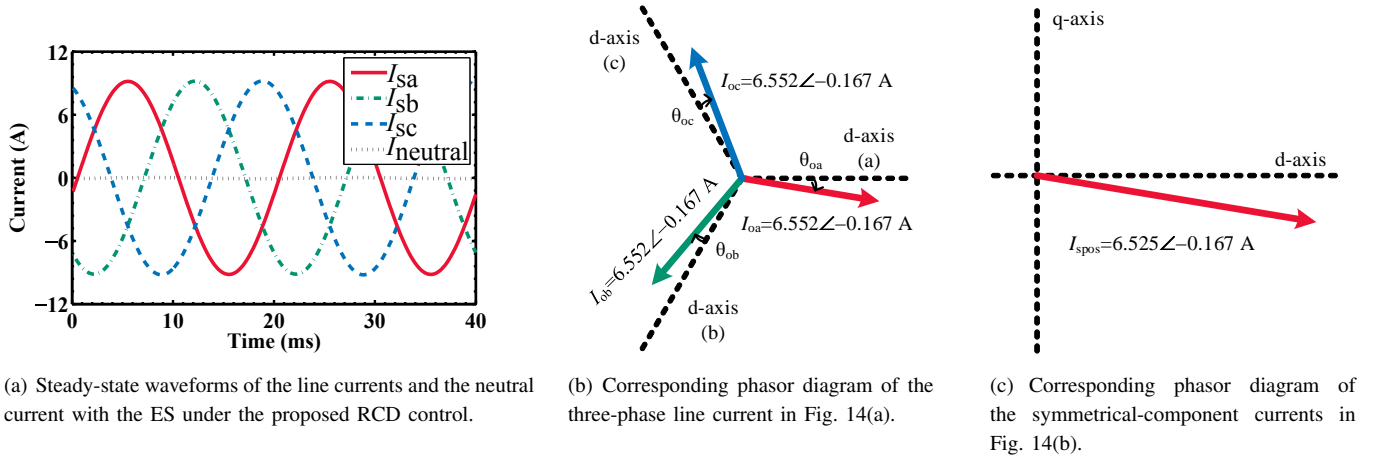


Fig. 14. The simulation results for case F with the ES under RCD control.

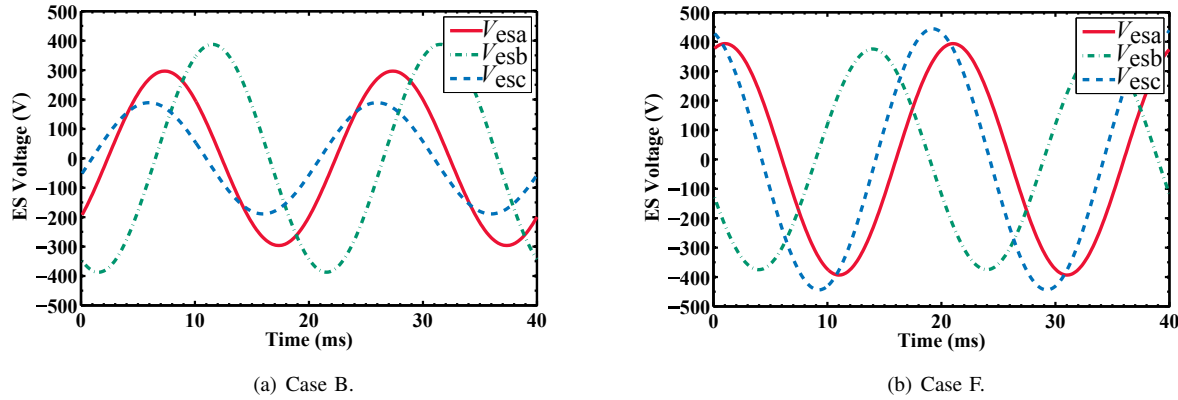


Fig. 15. Steady-state simulation waveforms of the ES voltage on each phase with the ES under the proposed RCD control.

sponding waveforms of the ES voltage in each power phase are shown in Fig. 15(b). The results depicted in Fig. 13(c) and 14(c) indicate that the proposed RCD method can control the ES to mitigate both zero-sequence and negative-sequence currents to zero.

From the presented results, it can be concluded that the proposed RCD method can be applied to the ES with both negative (case F) and positive (case B) resistive NC load and this NC load can be either balanced (case B) or unbalanced (case F), and this method can mitigate both the zero-sequence and the negative-sequence currents to zero such that the system is symmetrically power balanced.

B. Optimization on the Active Power Usage in the ES

This section verifies the ability of the proposed method for the optimization on the active power usage in the ES. The same configuration used in the simulation in Section IV-A is adopted. Case B is used to demonstrate the procedures on determining the minimized ES active power as discussed in Section III-A. Case F is used to demonstrate how zero ES active power is required for power balancing as discussed in Section III-B. In case B, the vertex of the circular paraboloid

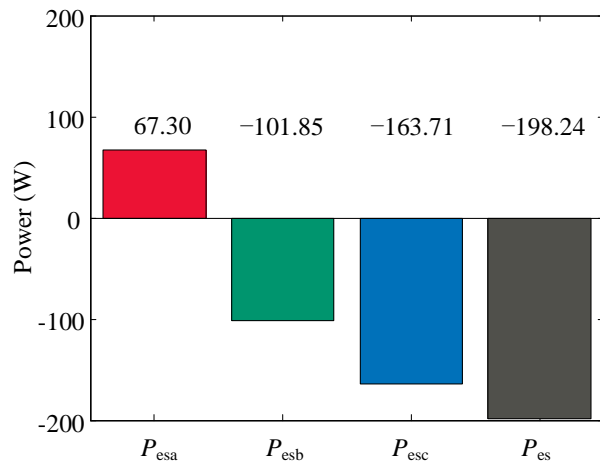
function in (11), according to (13) and (14), is located at

$$\begin{aligned} (P_{s_bal}, Q_{s_bal}) &= (-K_2/2K_1, -K_4/2K_3) \\ &= (917 \text{ W}, 167 \text{ VAR}) \end{aligned} \quad (32)$$

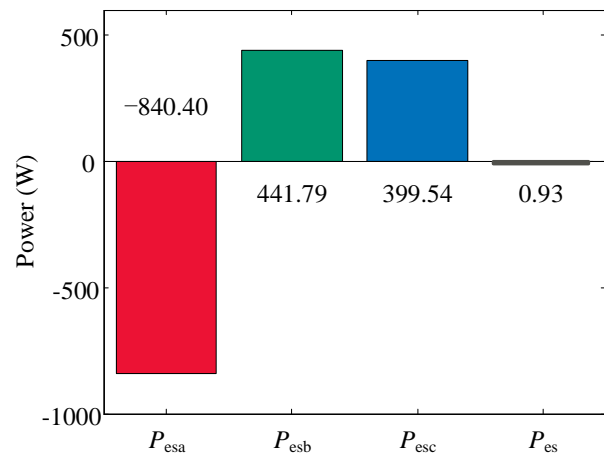
This is the optimum operating point, at which the ES delivers a minimum active power to the system in case B. Putting (32) and the data of case B in Table I into (11) gives

$$\begin{aligned} P_{es} &= P_{esa} + P_{esb} + P_{esc} \\ &= K_1 P_{s_bal}^2 + K_3 Q_{s_bal}^2 + K_2 P_{s_bal} + K_4 Q_{s_bal} + K_5 \\ &= -198.08 \text{ W} \end{aligned} \quad (33)$$

Fig. 16(a) shows the simulated value of the ES active power on each phase and the sum of these powers ($P_{es} = P_{esa} + P_{esb} + P_{esc}$) for case B. It indicates that the total active power delivered from the ES to the power system is 198.24 W when the RCD method is employed. The simulated active power of the ES (198.24 W) is closed to the analytical calculation (198.08 W). The simulation results of case F is shown in Fig. 16(b), which shows that the ES delivers nearly zero active power (0.93 W) to the system with the proposed RCD method. This is in line with the analysis in Section III-B. The two simulations verify that the ES active power can be either minimized (in case B) or eliminated (in case F), during the



(a) The simulation results of the total and per-phase active power usage of the ES in case B with the ES under the RCD control.



(b) The simulation results of the total and per-phase active power usage of the ES in case F with the ES under the RCD control.

Fig. 16. The total and per-phase active power usage of the ES in case B and case F.

TABLE II
PARAMETERS OF THE SIMULATION AND THE EXPERIMENT IN SECTION IV-C

Description	Parameter	Value
MOSFET switches	S_1 to S_6	IRFP31N50L (use ideal NMOS in simulation.)
Storage capacitors	C_1, C_2	6 pcs of 1500- μ F capacitors
Filter capacitor	C_{oi}	13.2 μ F
Filter inductor	L_{oi}	500 μ H
Batteries		LC-R127R2NA (18 pcs in series) (use ideal DC source in simulation.)
Switching frequency	f_{sw}	20 kHz

process of restoring power balance under the proposed RCD control method.

C. Experimental Validation

The parameters in case A in Table I are adopted. Both simulation and experiment are performed based on the power stage shown in Fig. 17, where a three-phase three-leg bi-directional power converter is chosen as an ES. In the simulation, the DC bus of the converter is connected to two series-connected ideal DC source V_{DC1} and V_{DC2} and the MOSFET switch S_1 to S_6 are configured as ideal NMOS without parasitic resistance and capacitance. The control circuit of the ES adopted in the simulation is shown in Fig. 18. It is connected to the circuit shown in Fig. 9. In the experiment, the two ideal DC sources V_{DC1} and V_{DC2} are realized with 18 units of serially connected 12-V lead-acid batteries. A digital signal processing (DSP) controller Texas Instrument TMS320F28069 is used to implement the control. The control depicted in Fig. 9 and 18 is digitally implemented inside the DSP controller using C programming. The system parameters are given in Table II.

The simulation and the experiment waveforms of the line and the neutral currents with the ES being deactivated are shown in Fig. 20. The magnitude of the line currents in

TABLE III
THE MEASURED ELECTRICAL PARAMETERS OF THE ES

Description	Phase a	Phase b	Phase c
ES RMS voltage (V)	71.427 V	12.559 V	54.181 V
ES RMS current (A)	1.7416 A	2.1258 A	2.5923 A
ES apparent power (VA)	124.4 VA	26.698 VA	140.46 V
ES power factor	0.6261	0.9983	-0.7437

the experiment are measured using the built-in power analyzer inside the AC power source (California Instruments CSW5550) and acquired through the Ethernet interface. The readings are shown in Fig. 20(c). It shows $|I_{sa}| = 5.121$ A, $|I_{sb}| = 4.557$ A and $|I_{sc}| = 4.047$ A. The simulation and experiment waveforms of these line currents are shown in Fig. 20(a) and Fig. 20(b), respectively.

Next, the required ES voltages, according to the proposed RCD method in Section III-B, are calculated as $|V_{esa}| \angle \theta_{esa} = 71.562 \angle -0.662$ V, $|V_{esb}| \angle \theta_{esb} = 12.436 \angle 0$ V and $|V_{esc}| \angle \theta_{esc} = 54.150 \angle 2.193$ V. The ES is operated with the calculated ES voltage and their voltage waveforms are shown in Fig. 22(a) (simulation) and Fig. 22(b) (experiment). The simulation and experiment line-current and neutral-current waveforms after the activation of the ES is shown in Fig. 21(a) and Fig. 21(b), respectively. Figure 21(c) shows that the magnitude of the experimentally measured line currents are $|I_{sa}| = 4.484$ A, $|I_{sb}| = 4.436$ A and $|I_{sc}| = 4.408$ A. The measured active and apparent power of the system are $P_{sa} = 979$ W, $P_{sb} = 969$ W, $P_{sc} = 963$ W and $|S_{sa}| = 986$ VA, $|S_{sb}| = 976$ VA, $|S_{sc}| = 970$ VA. These active and apparent powers are all nearly equal among the three phases. The results indicate that the neutral current can be mitigated to nearly zero and the line currents can be regulated to be symmetrically balanced. This validates experimentally that the proposed RCD method can achieve three-phase power balancing.

The magnitude of the ES voltages, the magnitude of the smart-load currents, the ES apparent power and the power

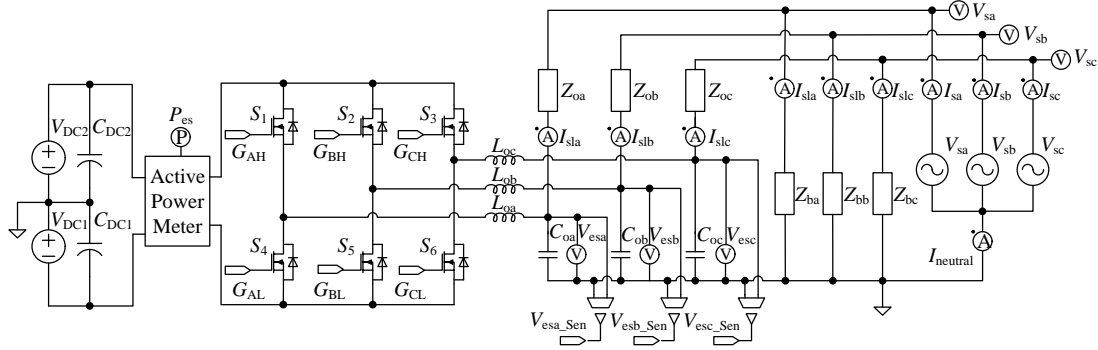


Fig. 17. The power stage of the ES adopted in the PSIM simulation and the experiment in Section IV-B.

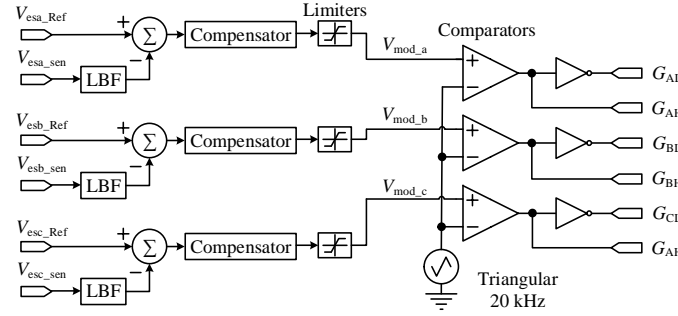
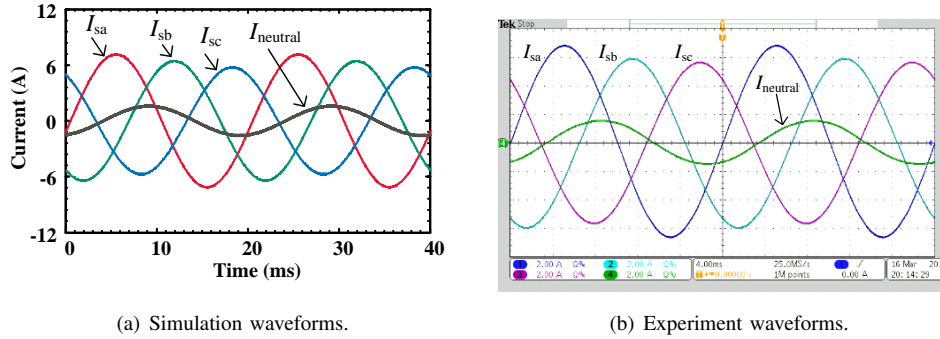


Fig. 18. The control circuit of the ES adopted in the PSIM simulation and the experiment in Section IV-B.



(a) Simulation waveforms.

(b) Experiment waveforms.

(c) Experiment measurement.

Fig. 20. The simulation and experiment waveforms and the measurement of the system line currents under the deactivation of the ES in case A.

factor of the ES on each phase are measured using a power analyzer (Voltech PM6000). The results are shown in Table III. The total active power delivered by the ES (P_{es}) can be

calculated as

$$\begin{aligned}
 P_{es} &= P_{esa} + P_{esh} + P_{esc} \\
 &= |S_{esa}|PF_{esa} + |S_{esh}|PF_{esh} + |S_{esc}|PF_{esc} \\
 &= 124.4 \times 0.6261 + 26.698 \times 0.9983 + 140.46 \times (-0.7437) \\
 &= 0.079351 \text{ W}
 \end{aligned}
 \tag{34}$$

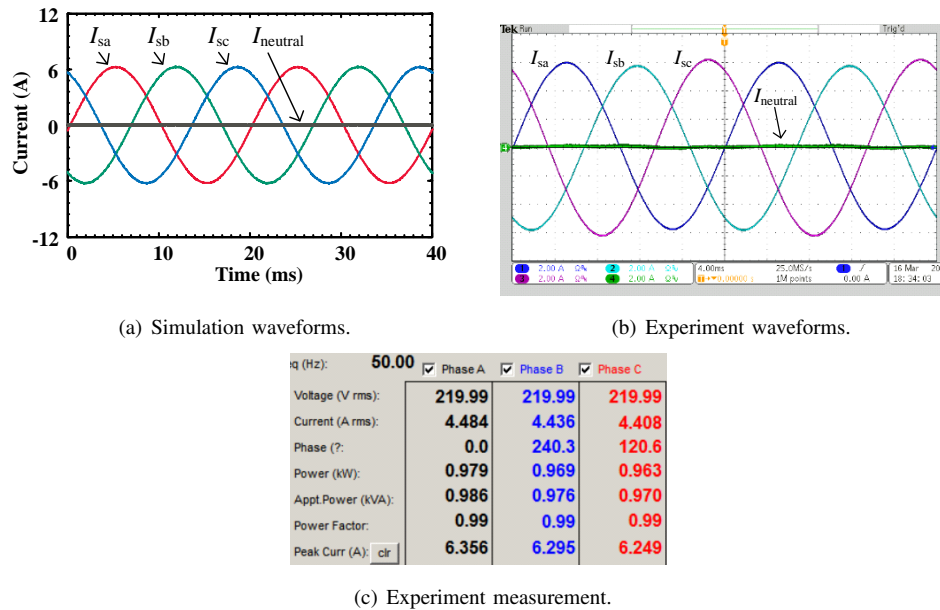


Fig. 21. The simulation and experiment waveforms and the measurement of the system line currents with the activation of the ES under the RCD control in case A.

where PF_{esa} , PF_{esb} and PF_{esc} are the power factor of the ES on phase a, b and c, respectively and $|S_{esa}|$, $|S_{esb}|$ and $|S_{esc}|$ are the apparent power of the ES on the corresponding phase. The measured ES active power is closed to zero which confirms that the proposed RCD method can control the ES such that it does not deliver active power to the grid while achieving three-phase power balancing. Note that in the hardware implementation, a certain amount of active power is delivered to the power converter from battery storages to compensate the power loss of the power converter (P_{es_loss}). The amount of active power delivered from batteries (P_{es_dc}) is measured by a power analyzer (Xitron 2801) as $P_{es_dc} = 21.52$ W. Since the ES is handling 1415 W power (the amount of the three-phase smart-load active power), the power loss of the ES is accounted to be around 1.5% of the smart-load active power. Although the amount of P_{es_dc} is relatively small, its non-zero value means that a small energy storage is still required. Alternatively, a possible work-around solution is to slightly adjust the phase of the three-phase ES voltage such that P_{es_dc} can be mitigated to zero. This will result in a slight power imbalance among the three phases, which is typically acceptable in practice.

V. CONCLUSIONS

This paper presents an in-depth analysis and a control strategy for electric springs (ES) to mitigate the negative-sequence and the zero-sequence currents in three-phase unbalanced power systems. The proposed control method is based on the radial-chordal decomposition approach, which allows precise calculation of the required ES voltage on each phase such that (i) the ES can restore the power balance and (ii) the active power delivered from the battery storage can be minimized. Simulation and experiment results are provided to verify the validity of the proposed control scheme. This method can be

potentially developed to include more advanced and multi-functioning controls such as power factor improvement and harmonic elimination.

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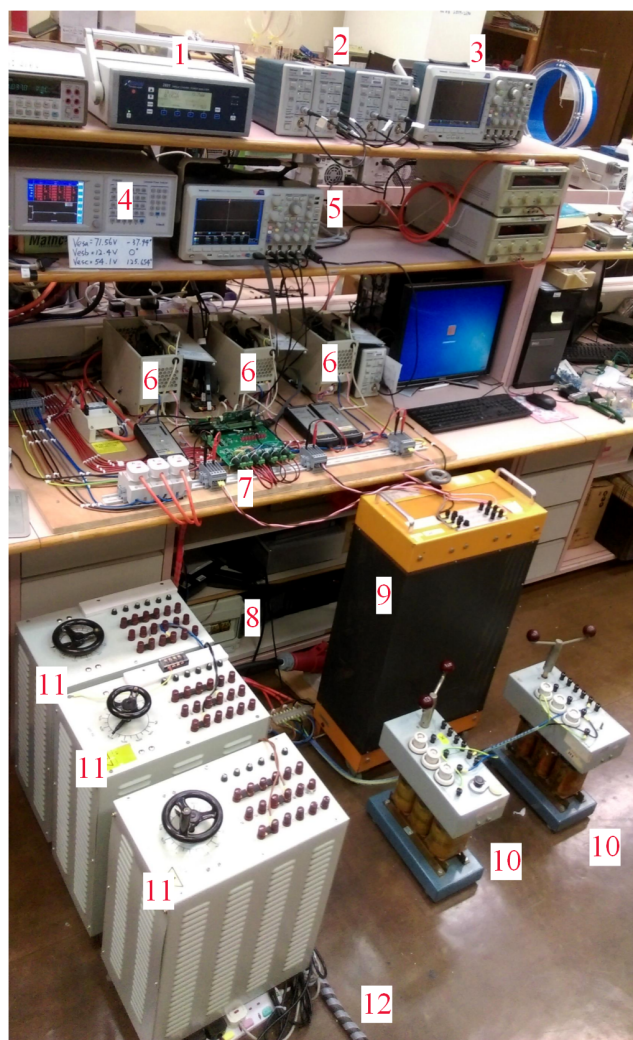


Fig. 19. The actual experimental setup. (1: DC bus power analyzer (XiTRON 2801), 2 & 3: system current measurement setup (Tektronix MSO-3034, Tektronix TCPA300 and Tektronix TCP312) , 4: system power analyzer (Voltech PM6000), 5: ES voltage measurement setup (Tektronix MSO-3034 and Pico Technology TA042), 6: three-phase electric springs, 7: DSP ES controller, 8: lead-acid battery bank, 9: resistive NC load banks, 10: inductive critical loads, 11: resistive critical load banks, 12: the power cable from the output of the AC power source (California Instruments CSW5550)).

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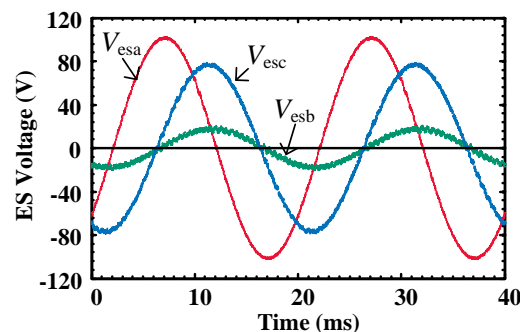
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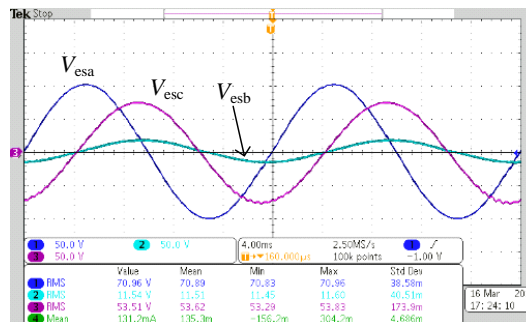
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(a) Simulation waveforms.



(b) Experiment waveforms.

Fig. 22. The simulation and experiment waveforms of the ES voltages determined by the proposed RCD approach in case A.

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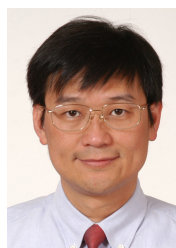
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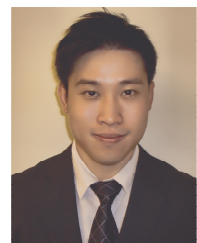
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