Direct Control of Three-Phase Smart Load for Neutral Current Mitigation

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***Abstract*—Electric Spring (ES), a power electronic based device, has been recently developed to improve various attributes of future power systems with high penetration of intermittent renewable energy sources. ES is connected in series with noncritical load to form an adaptive load, known as smart load. This configuration has been successfully used to mitigate voltage and frequency fluctuations, ensure demand side management, and improve power quality. It has also been used to reduce three-phase power imbalance and so the adverse effect of neutral current is eliminated. In this work a novel control scheme, based on run time impedance measurement, is proposed to mitigate neutral current from unbalanced three-phase system. Mathematical analysis is also given and corresponding simulations are carried out to substantiate the theoretical framework. Simulation results show the efficacy of presented technique under various unbalanced loading conditions.**

***Index Terms*—Electric spring, smart load, neutral current, unbalanced loads, smart grid.**

I. INTRODUCTION

Ever increasing demand of green energy has encouraged the renewable sources to play the pivotal role in power sharing of future power systems, so that not only the cost of per unit energy would be reduced but environmental friendly energy can also be produced. These benefits of such energy resources are accompanied with the drawback of dynamic behavior of power produced by them. Eventually, problems arise in power balance and its quality. Voltage fluctuations become common due to intermittent nature of wind energy. Under this situation, power electronic devices give rise to control methodologies which can propose promising solution to these problems. In present era of magnificent power demand, problems are not restricted to the intermittency of renewables.

Power imbalance in three phase four wire system due to unbalanced load is a major concern for sophisticated power systems. Neutral current, a direct consequence of unbalanced loads, has a deteriorating effect on key components of power system such as induction motors, electric drives and voltage source inverters [1]. Adverse effect of neutral current also includes increased system loss and reduced system efficiency [2]. Moreover, unbalanced line currents result in asymmetric voltage drops in the network, causing an overall reduction in power quality [3]. To resolve this major concern several methods have been used. Three-phase to single-phase static or rotary converter is sometimes used to feed single phase load. Another way to mitigate neutral current is to use rotating equipment to absorb negative sequence component. Three-phase to single-phase transformer is also used to serve this purpose. All these conventional methods are less efficient and costly [4]. With the advent of modern power electronic devices, new solutions are developed to improve power quality and reduce neutral current. Shunt active filter has been used as reactive power compensator to reduce load imbalance. A mixture of several techniques can be used, where active filter is used to redistribute real power, keeping total real power constant, on the other hand, positive, negative and zero sequence components are compensated independently or together. Such techniques are presented in [5]–[9].

ES is a power electronic device based on Hooke's law able to provide electric active suspension functions. It has been previously used for voltage regulation, demand side management and harmonic mitigation [10]–[16]. Reference [17] envisages the use of ES in reducing energy storage requirement. In [18]–[20] ES has been used to reduce three phase load imbalance. Reference [18], [19] presents an independent control of three phase ES with control parameters being evaluated using Genetic Algorithm (GA), whereas, in [20] three-phase ES is connected to system via isolation transformer in a built environment with a controller based on impedance estimation. GA based controller makes the system unnecessary complicated which results in reduced computational efficiency. Approach used in [20] is direct and convenient but it lacks depth and significant simulation results.

In this paper, a novel control scheme for three-phase ES is proposed and its mathematical basis is formulated. Loads are categorized as critical and noncritical loads on the basis of their operating voltage range. Theory of operation of proposed controller is illustrated by phasor diagrams. This controller will allow the ES to mitigate neutral caused by unbalanced three-phase loads. It is tested in a typical three-phase unbalanced power system to show its efficacy. The performance of proposed controller is also evaluated under dynamic loading condition.

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II. ELECTRIC SPRING CONFIGURATION

In analogy to mechanical spring, the concept of electrical spring has been introduced. Establishing its basis on the famous Hooke's law, electric spring provides the support, stability and storage capability as its mechanical counterpart. In the simplest form, ES is a power electronic based device in which a controller provides control signal to an inverter. The waveform of inverter is integrated to the power system in a manner that the whole topology presents the replica of mechanical spring.

Fig.1 is the depiction of smart load formed by embedding a noncritical load in series with ES. This noncritical load is very necessary for the operation of ES, as it acts as a damper. Noncritical load is a special type of load which can be operated within a range of fluctuating voltage. Examples of such loads include, refrigeration, air conditioning and lighting loads. These loads can withstand a wide range of voltage fluctuation (for a nominal voltage of 220V, such loads can be operated in a range from 180V to 265V). According to Hong Kong government's published data, air conditioning, heating and public lighting system (which are categorized as noncritical loads), make about 50% of the total power consumption in a typical commercial building. Fig. 2 shows the loads distribution in a pi-chart as published in [22]. ES when embedded with such loads offers multiple new features to improve power quality of power systems.

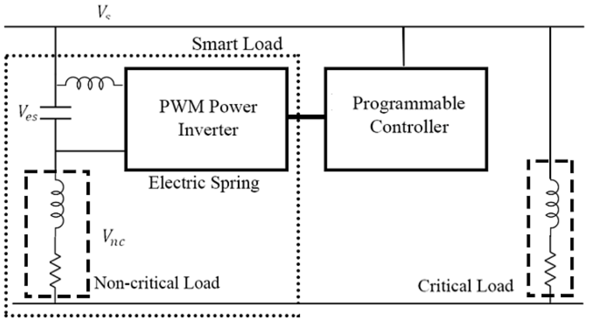


Fig. 1. Schematic of electric spring, smart load and non-critical load.

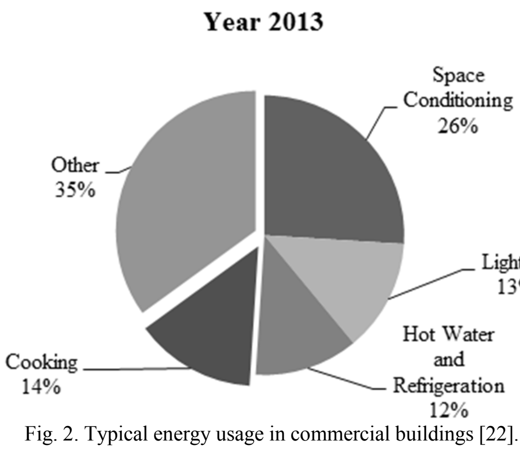


Fig. 2. Typical energy usage in commercial buildings [22].

So far, researchers have proposed three versions of ES. First version of ES has a capacitor on the DC side of inverter and hence it can only provide or absorb reactive power primarily to perform voltage regulation and demand side management [10]. In second version, capacitor is replaced by a DC source (for example regulated solar cell, electric vehicle battery, or a regular lead acid battery), which results in enhanced eight modes of operation of ES [11]. Active power exchange becomes possible in second version of ES. Active suspension concept, as provided by first two versions of ES, can be used with a shunt type ES. Basically, it is an input-feedback bidirectional grid connected power converter [21]. It does not need a noncritical load connected in series. Schematics of three versions of ES are shown in Fig. 3.

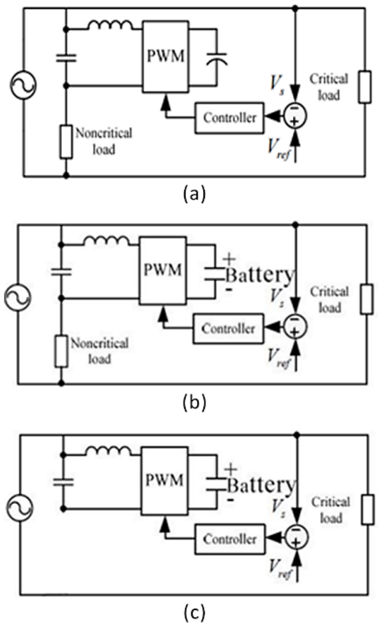


Fig. 3. Basic circuit implementation of (a) first, (b) second and (c) third version of ES.

Single phase ES can be extended to three-phase ES as shown in Fig. 4. Here placement of star connected noncritical and critical loads is illustrated in a typical three phase power system. A controller sends switching signals to three-phase inverter of ES based on the measurement taken from different nodes in the circuit. Controller can be programmed to achieve various tasks. In this paper, controller is programmed such that each phase of ES generates a voltage which brings the balance in overall impedance of the load. This control scheme is explained in next section.

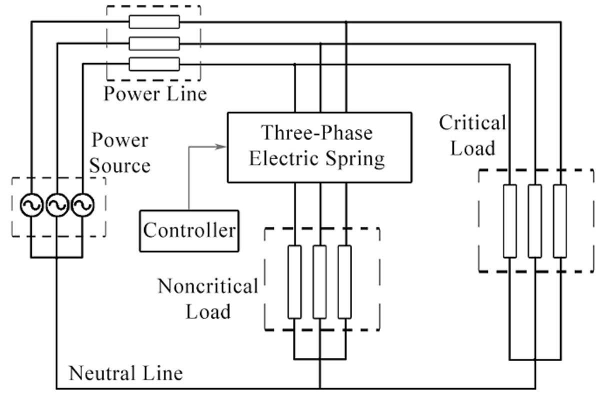


Fig. 4. Circuit diagram of typical three-phase power system with ES

III. THEORETICAL FRAMEWORK

In the following derivation, it is considered that critical loads tend to be unbalanced three-phase loads whereas noncritical loads always remain balanced. Neutral current will be mitigated if source sees same impedance for each of the three phases. Therefore, ES is required to balance the equivalent impedance of the network. In case of balanced noncritical loads, ES will not be operational and equivalent impedance as seen at the point of common coupling (PCC) is given by

$$Z_{eq_{a,b,c}} = Z_c || Z_{nc} \tag{1}$$

Where,

$$Z_c = Z_{c_a} = Z_{c_b} = Z_{c_c} \tag{2}$$

In above equations Z_{c_a}, Z_{c_b}, Z_{c_c} represents the critical load's impedance of phase A, phase B and phase C, respectively. Z_{nc} represents the phase impedance of critical load. In this analysis noncritical load will be a balanced load for all cases, therefore, each phase's impedance is indicated by Z_{nc}. For unbalanced case, when $Z_{c_a} \neq Z_{c_b} \neq Z_{c_c}$, it is suitable to determine the average impedance of unbalanced loads $Z_{c_{avg}}$.

$$Z_{c_{avg}} = \frac{Z_{c_a} + Z_{c_b} + Z_{c_c}}{3} \tag{3}$$

For unbalanced loads, ES will come into action and try to redistribute real power among each phase, such that the total impedance as seen by the source is balanced out. Now the equivalent impedance of each phase is given by:

$$Z_{eq_{a,b,c}} = Z_{c_{avg}} || Z_{nc} = Z_{c_{a,b,c}} || (Z_{nc} + Z_{ES_{a,b,c}}) \tag{4}$$

where $Z_{ES_{a,b,c}}$ is the impedance offered by ES in response to unbalanced loads for corresponding phases. Solving (3) for $Z_{ES_{a,b,c}}$ results in:

$$Z_{ES_{a,b,c}} = \frac{Z_{nc}^2 (Z_c - Z_{c_{a,b,c}})}{Z_{nc} Z_{c_{a,b,c}} + Z_{c_{avg}} Z_{c_{a,b,c}} - Z_{nc} Z_{c_{avg}}} \tag{5}$$

The vector voltage that has to be produced by ES (denoted by $V_{ES_{a,b,c}}$) in order to achieve load balancing is determined by voltage divider rule, as shown below:

$$V_{ES_{a,b,c}} = \left(\frac{Z_{ES_{a,b,c}}}{Z_{ES_{a,b,c}} + Z_{nc}} \right) V_{S_{a,b,c}} \tag{6}$$

where V_S is the corresponding phase voltage at point of common coupling.

Fig. 5 shows the phasor diagram of the proposed phenomenon.

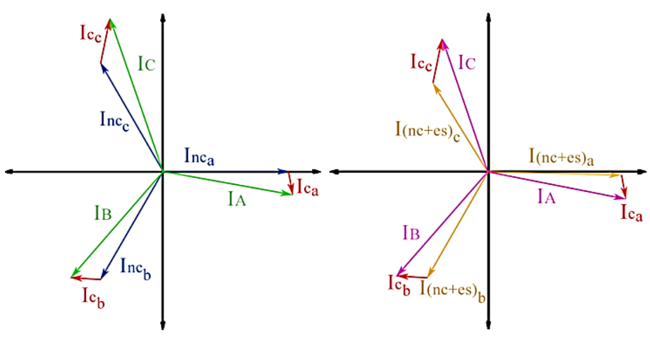


Fig. 5. Vector diagram of currents of an unbalanced system (a) without and (b) with ES.

Noncritical load is considered to be a balanced three phase load, whereas critical loads are unbalanced. This can be seen in Fig. 5a. Without ES, noncritical load phase currents $I_{nc_{a,b,c}}$ is equal in magnitude and symmetric in phase, on the other hand, critical load phase currents $I_{c_{a,b,c}}$ are unbalanced and hence causing an imbalance in net current $I_{A,B,C}$ When ES is connected with the system, it rearranges the real power distribution by controlling the current of noncritical load branch, which enables the net current vectors to be symmetric and balanced, eventually resulting in neutral current mitigation.

IV. Simulation Details

MATLAB Simscape Toolbox and Simulink environment is used for simulating a typical three-phase unbalanced power system and the designed controller on ES. Fig. 6 illustrates the steps of computations performed by the proposed controller. Based on current and voltage readings, impedance of each phase of noncritical load is estimated followed by determining average phase impedance. Impedance required to offer by each phase of ES is calculated using (5). Reference voltage of each phase of ES is set to the value computed by (6), which allows ES to offer impedance that balance equivalent three-phase impedance, and hence achieving neutral current mitigation.

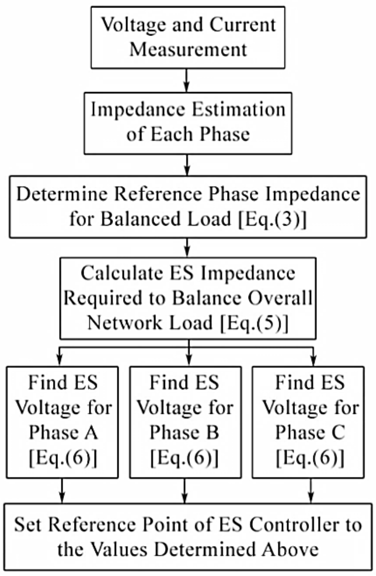


Fig. 6. Flow chart of control algorithm of three-phase ES

Simulated power system network's schematic is illustrated in Fig. 7. Both critical and noncritical loads are star connected with a stiff balanced source feeding the loads at 220V and 50 Hz. Detailed specifications of the balanced noncritical load and unbalanced critical loads are given in Table I. Sampling time of simulation model is 50μs.

V. Results and Discussions

In this work, two simulations scenarios are presented. First the impact of ES in the system is shown, followed by dynamic loading condition test. Effect of ES with proposed controller is shown in Fig. 8. Simulation is carried out for 0.4s in an unbalanced three phase circuit. For first 0.2s ES is bypassed using a bypass switch shown in Fig. 7. In Fig. 8a it can be seen that without ES, net current driving the load is unbalanced ($I_A = 115.7\angle 350.4°$ A, $I_B = 122\angle 229.7°$ A and $I_C = 138.6\angle 110°$A). Neutral current for initial 0.2s is given by $21.68\angle 124.34°$ and is shown in Fig. 8b. After 0.2s of simulation, bypass switch is opened enabling ES operation. Conforming to the theoretical analysis, neutral current is mitigated to $0.4\angle 8°$. It can be noted that in Fig 8a after 0.2s, all three phase currents have same magnitude with a phase difference of almost 120° ($I_A = 123\angle 348°$ A, $I_B = 123\angle 229°$ A and $I_C = 123\angle 108°$A).

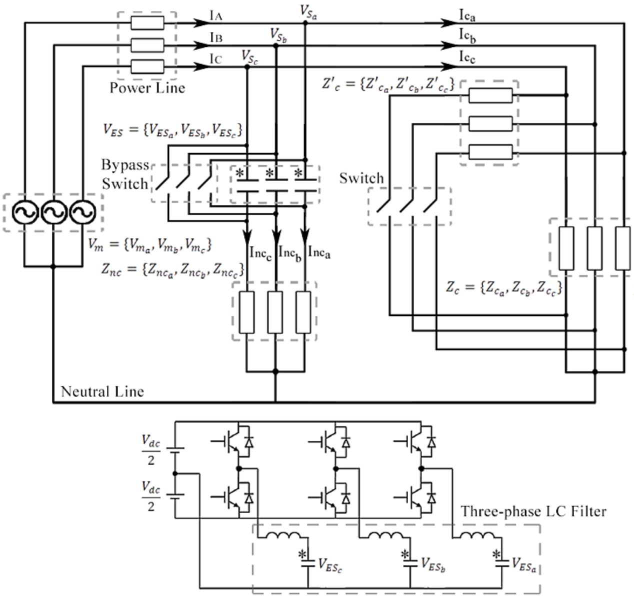
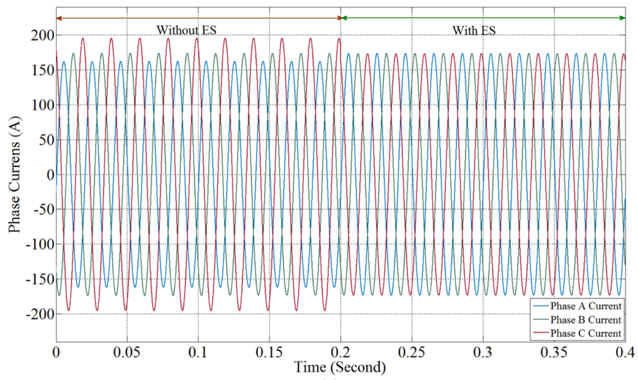


Fig. 7. Simulation diagram of power system with unbalanced critical load and dynamic loading.

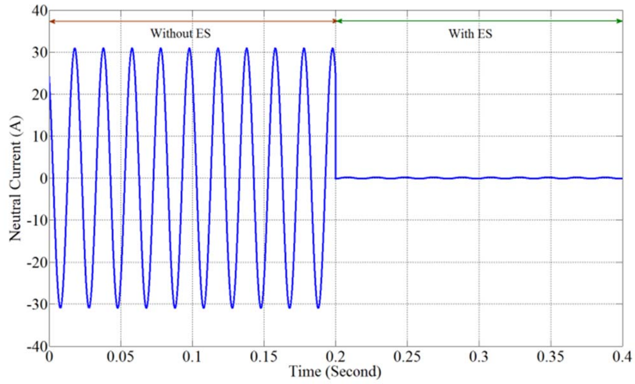
TABLE I. SYSTEM IMPEDANCE SPECIFICATIONS

	Phase A	Phase B	Phase C
$Z_c(\Omega)$	2+11.05j	4+8j	4.5+4j
$Z'_c(\Omega)$	1.5	1.2+3.1j	0.5+12.5j
$Z_{nc}(\Omega)$	2	2	2
V_S (V)	$220\angle 0$	$220\angle 240$	$220\angle 120$

Fig. 9 illustrates the waveform of voltages across ES and noncritical load. Voltage across each phase of ES terminals is approximately same as calculated by (6) (shown in Fig. 9a) The voltage at noncritical load, which is vector subtraction of $V_{ES_{a,b,c}}$ from $V_{S_{a,b,c}}$, is represented in Fig. 9b. It is important to note that after connecting ES, voltage across noncritical load is unbalanced and so is the current of each phase of that branch but net current is balanced and so neutral current is mitigated. In other words it can be said that ES redistributes power in each branch of noncritical load such that the adverse effect of unbalanced critical load is eliminated.

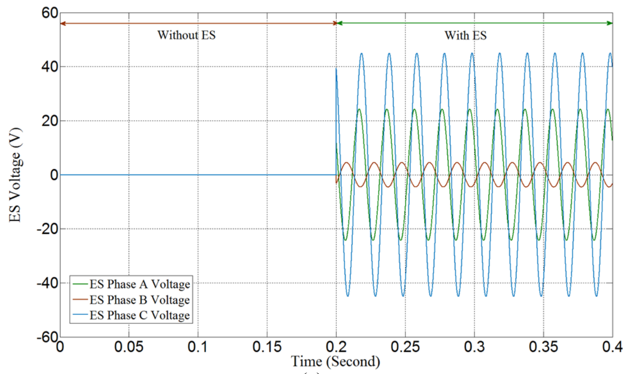


(a)

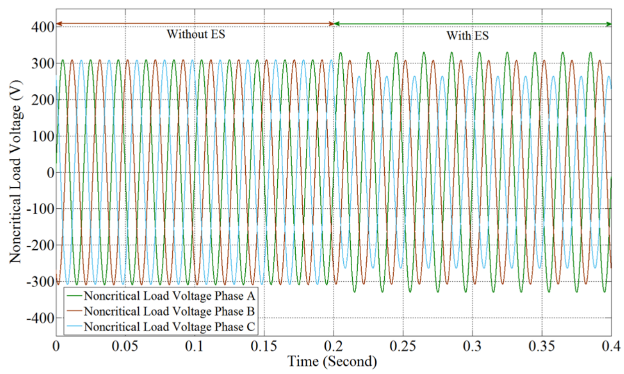


(b)

Fig. 8. (a) Supplied current waveform of each phase and (b) neutral current waveform before and after activating three-phase ES.



(a)



(b)

Fig. 9. Three-phase voltage of (a) ES and (b) noncritical load before and after activating three-phase ES

To test dynamic loading conditions and adaptability of ES to sudden load change, simulations are carried out for 0.8s, depicted in Fig. 10. For first 0.4s, system is simulated with same settings and therefore, similar results are obtained. After 0.4s an additional three-phase critical load Z'_c is connected in parallel to existing load as shown in Fig. 7. It increases the neutral current of the system from 21.68A to 89.19A. But after 0.6s, ES is again activated which brings the neutral current back to 0.72A. Basically, there are four intervals in the simulation time. First interval ranging from 0s to 0.2s in which ES is bypassed and only one three-phase critical load Z_c is connected to the system.

In second interval, which ranges from 0.2s to 0.4s, ES is operational to mitigate neutral current caused by unbalanced Z_c. Later, in third interval ES is bypassed again, and three-phase load is changed by connecting Z'_c in parallel with Z_c.

In last interval, ES is activated to mitigate the increased neutral current.

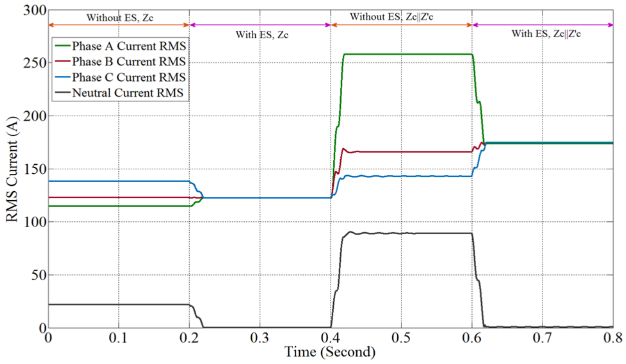
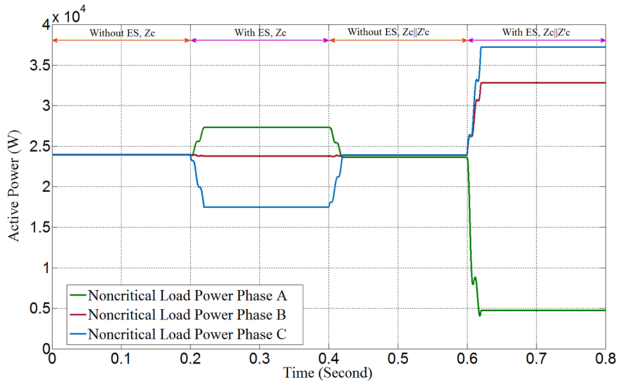
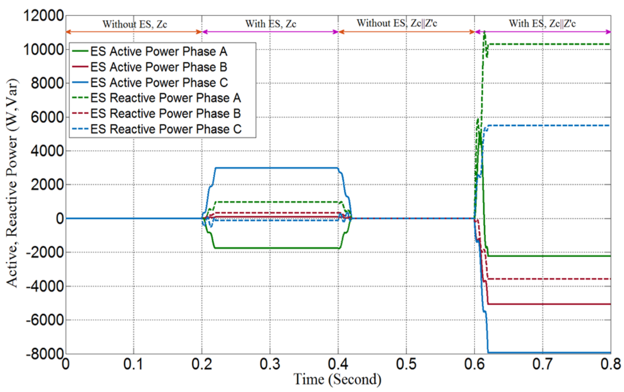


Fig. 10. RMS value of phase and neutral currents before and after changing three-phase critical load.

Under dynamic load changing, concept of active power distribution to mitigate neutral current is presented in Fig. 11. Active and reactive powers supplied and/or absorbed by ES during the simulation runtime is illustrated in Fig. 11a. Time intervals in which ES is bypassed have necessarily zero real and reactive powers, whereas, in remaining time intervals, real and reactive power is supplied and/or absorbed as determined by the control algorithm. As a result, each phase of noncritical load absorbs different real power when ES is operational. On the other hand, when ES is bypassed (0s-0.2s and 0.4s-0.6s), each phase of noncritical load consumes same real power of 24.2kW.



(a)



(b)

Fig.11. (a) Active and reactive power absorbed and/or supplied by ES and (b) active power absorbed by each phase of noncritical load.

VI. Conclusion

In this paper, a novel impedance estimation based control technique is developed to drive ES for neutral current mitigation. Concept behind this approach is presented first by mathematical equations and then explained by phasor diagram. MATLAB Simulink based simulations are performed under dynamic loading condition. It is found that proposed control approach is successful in balancing the unbalanced three-phase load. Under dynamic loading, smart load is able to detect the change and respond accordingly. Therefore, a same physical device can be used to perform wide range of tasks including voltage regulation, power factor correction and neutral current mitigation depending on the control algorithm used to operate ES.

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