Mitigation of Power Imbalance in Three Phase Power Systems Using Electrical Springs

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Abstract—Electric springs have been used previously in stabilizing mains voltage fluctuation in power grid fed by intermittent renewable energy sources. This paper describes a new three-phase electric spring circuit and its new operation in reducing power imbalance in the three-phase power system of a building. Based on government energy use data for tall buildings, the electric loads are classified as critical and noncritical loads so that building energy model can be developed. The proposed electric spring is connected in series with the noncritical loads to form a new generation of smart loads. A control scheme for such smart loads to reduce power imbalance within the building's electric power system has been evaluated initially with an experimental prototype and then in a system simulation study. The results have confirmed the effectiveness of the new three-phase electric springs in reducing powerimbalance and voltage fluctuation, making the building loads adaptive to internal load changes and external mains voltage changes. MATLAB/SIMULINK platform is used for simulation. The application of the proposed method has been investigated for different load conditions and the results are presented.

Index Terms— Adaptive systems, electric springs (ESs), power imbalance, smart grids, smart loads, PI Controller.

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1 INTRODUCTION

WITH increasing penetration of intermittent and distributed renewable energy sources such as wind and solar power, there has been rising concern on power system stability.To address those issues, many demand-side management Techniques have been proposed to ensure the balance between Power generation and consumption. Such techniques include: 1) Scheduling of delay-tolerant power demand tasks; 2) use energy storage to compensate peak demand; 3) real-time pricing; 4) direct load control or on–off control of smart load. Energy storage is a valid solution to cope with the instantaneous balance between power supply and demand. However, costs and limited energy storage capacity of batteries are practical issues. Therefore, new solutions that can reduce energy storage are preferred. In manufacturing plants, commercial and residential buildings, power is distributed through three-phase, four-wire (3P4W) systems. In these systems, single phase supply to loads is provided by one of the phase conductors and neutral wire. To balance the load on each of the phases, the loads are evenly distributed. Due to the unbalanced nature of the loads, a net current flowing through the neutral conductor.With linear loads, the neutral current is only due to imbalance between the phases.

The typical loads in a three-phase four-wire distribution system may be computer loads, lighting ballasts, small rating adjustable speeds drives (ASD) in air conditioners, fans, refrigerators and other domestic appliances etc. These non linear loads produce third harmonic components in the system. The inductive ballasts as well as electronic ballasts in fluorescent lighting also contribute to third harmonic currents. The third harmonic components in phase currents do not cancel each other even under balanced condition and are added up in the neutral line. Therefore, the total neutral current is contributed by the fundamental and harmonic components of the unbalanced load currents and thus results in the overload of neutral conductor in the three phase four wire distribution systems.

The excessive neutral current causes increased linelosses, deterioration of system voltage profiles, overload system phases overloading, mal-functioning of protective relays, saturation problem in the distribution power transformers, increased communication interference, deterioration of power quality, system security and reliability of the electric supply, etc**.**

2 RELATED WORK

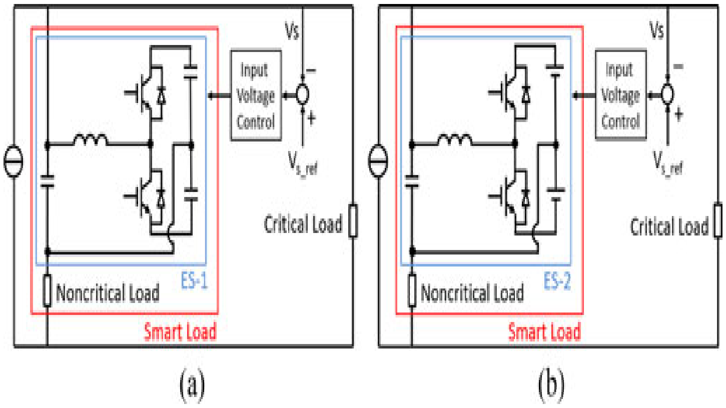
The aim of smart distribution system is on the efficiency enhancement by reducing distribution power losses, improving reliability, maximizing asset utilization and better power quality and integration of distributed energy resources. Therefore, modern distribution systems are gaining attention over several power quality issues such as poor voltage regulation, high reactive power, and harmonics current burden, phase unbalancing, excessive neutral line current, etc. There are various methods that deals with mitigation of neutral current.

Conventional passive and active power filters have been employed to solve the problems of harmonic currents and neutral-line current in three-phase four-wire distribution power systems [1]-[2]. The performance of passive filter is often significantly affected by the system impedance. The capacity and manufacturing cost of the power converter used in active filter is very high, thus limiting wide application of active power filters.

In comparison to the conventional passive and active filter methods, the electromagnetic filter is simpler, less expensive device, particularly for low voltage applications [3]. However, nonzero filter resistance, nonzero leakage flux, and nonideal magnetic coupling does not allow perfect filter performance. The zig-zag transformer is connected to the load in parallel, has been employed to attenuate the neutral-line current due to the advantages of low cost, high reliability and simplified circuit connection [4]. However, application of this method may result in the neutral voltage variation or raising the neutral voltage of the load side.

The electric spring is a new demand side management technology [5] . It can provide electric active suspension functions for stability of voltage and frequency in a distributed manner for future smart grid [6]. The change from output voltage control to input voltage control of a reactive power controller makes the electric spring suitable for future smart grid applications. For the compensation of neutral current, a new three-phase Electric Spring topology is proposed and its operating principle is explained.

The widespread use of non-linear loads causes, significant amounts of harmonic currents are being injected into power systems. Passive power filters (PPF) are generally used as traditional way for harmonic suppression which has made up of basic components like power capacitor, power inductance and resistance. It cannot filter the non-characteristic harmonics. The active power filter works on the operating principle by detecting harmonic current to calculate the amount of the compensating current needed for feeding back to the power system inorder to cancel the harmonic current [7]. There are various current control methods for such active power filter configurations, but for quick current control and easy implementation PI current control method has the highest rate among other current control methods such as sinusoidal PWM.



(a) (b)

Fig. 1. Practical power circuit implementation of ES. (a) ES version-1. (b) ES version-2.

3 METHODOLOGY

A three-phase Electric Spring is a three-phase inverter with a small battery storage on its DC link . The inverter output of each phase is connected to the primary side of an isolation transformer. The secondary sides of these isolation transformers are connected in series with three noncritical loads in star connection with the neutral line connected to the neutral point of three phase power source. The series connection of the electric spring and the non critical loads is collectively known as smart load. Critical loads in star connection are connected in parallel with this smart load. The neutral point of the critical load is also connected to the neutral point of power source.

A mechanical spring can expand and contract within a certain displacement only. Similarly an ES can regulate the line current within a certain range only [8] . Since the three-phase ES is typically a three-phase inverter with a constant DC voltage link, the output voltage of ES is limited by the DC link voltage. Thus the compensation voltage can vary in amplitude subject to the limitation of the DC link voltage *Vdc* and have a phase angle for 0° to 360° with respect to the reference vector which is usually the line voltage of phase A in a three-phase power system. The non-critical load is assumed as symmetric pure resistive and the critical load as symmetric resistive plus inductive load. In this system, it is considered that the critical loads are unbalanced among the three phases and the non-critical loads are balanced loads. The sum of power consumptions in the non-critical loads and critical loads represents the total power consumption. In the absence of compensation, the line currents are unbalanced due to the asymmetric load impedance of the critical loads and are given by

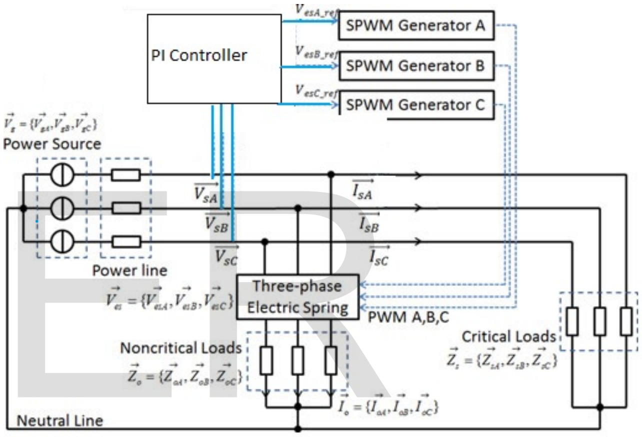


Fig.2 Implementation of Three Phase ES

$$\begin{aligned}\vec{I_A} &= \left(\frac{1}{\vec{Z_{sA}}} + \frac{1}{\vec{Z_{oA}}}\right)\vec{V_{sA}} - \frac{1}{\vec{Z_{oA}}}\vec{V_{esA}}\\ \vec{I_B} &= \left(\frac{1}{\vec{Z_{sB}}} + \frac{1}{\vec{Z_{oB}}}\right)\vec{V_{sB}} - \frac{1}{\vec{Z_{oB}}}\vec{V_{esB}} \qquad (1)\\ \vec{I_C} &= \left(\frac{1}{\vec{Z_{sC}}} + \frac{1}{\vec{Z_{oC}}}\right)\vec{V_{sC}} - \frac{1}{\vec{Z_{oC}}}\vec{V_{esC}}.\end{aligned}$$

The three-phase ES can be used to reduce the imbalance of a power system. From (1), it can be seen that the three-phase ES voltage *V*_es = *{ V*e_s*A, V*e_s*B , V*e_s*C }* can be controlled to actively alter the line currents both in amplitude and phase within its operating limits, in response to the changing states of the critical loads. The reduction of power imbalance can be illustrated by the reduction of neutral current, as large current results in unnecessary conduction losses in the cables of the building's power system. Thus, the equation of the neutral current (2) is a convenient and direct indication for the current imbalance

$$\begin{aligned}\vec{I_{\text{neutral}}} = &\left(\frac{1}{\vec{Z_{sA}}} + \frac{1}{\vec{Z_{oA}}}\right)\vec{V_{sA}} - \frac{1}{\vec{Z_{oA}}}\vec{V_{esA}}\\ &+ \left(\frac{1}{\vec{Z_{sB}}} + \frac{1}{\vec{Z_{oB}}}\right)\vec{V_{sB}} - \frac{1}{\vec{Z_{oB}}}\vec{V_{esB}}\\ &+ \left(\frac{1}{\vec{Z_{sC}}} + \frac{1}{\vec{Z_{oC}}}\right)\vec{V_{sC}} - \frac{1}{\vec{Z_{oC}}}\vec{V_{esC}}. \qquad (2)\end{aligned}$$

4 IMPLEMENTATION AND CONTROL OF ES

The proposed three-phase ES has been evaluated in both experimentaland simulation studies. Fig. 5 shows the schematic of the control system. The three-phase ES is simplified and expressed as three-phase compensation voltage: *V*es =*{ V*e_s*A, V*e_s*B , V*e_s*C }*.

The power inverter needs to operate in a special manner based on a few arrangements uniquely designed for three-phase ES for line current balance. Besides the power inverter, a PI controller, SPWM are also present. The input to the PI controller is a sinusoidal signal which is fed from the supply side,which consists of harmonics. In order to mitigate the distortion these signals are fed to the PI controller. This error controlled signal cannot directly fed to the power inverter. The required signal for the switching of electrical spring is fed from the SPWM. The three independentsinusoidal pulse-width-modulated (SPWM) generators, and The power inverter legs are operated independently as half-bridge inverters by receiving PWM signals from their respective SPWM generators.

4.1 PI Controller

To acquire better signals PI controllers are used by reducing steady state error. It will eliminate the forced oscillation of nonlinearity in three phase voltage .The input to the PI controller is a sinusoidal signal which is fed from the supply side,which consists of harmonics. In order to mitigate the distortion these signals are fed to the PI controller.

4.2 SPWM

The non linearity eliminated signals is fed to the power inverter through three independent sinusoidal pulse width generators. The SPWM generators compares the sinusoidal signal with the carrier signal. Sinusoidal signal is the reference signal and triangular signal is the carrier signal. Carrier signal has a frequency of 10 KHz. Whenever the reference signal gives the highest magnitude,and is fed to the power inverter for switching thyristors.

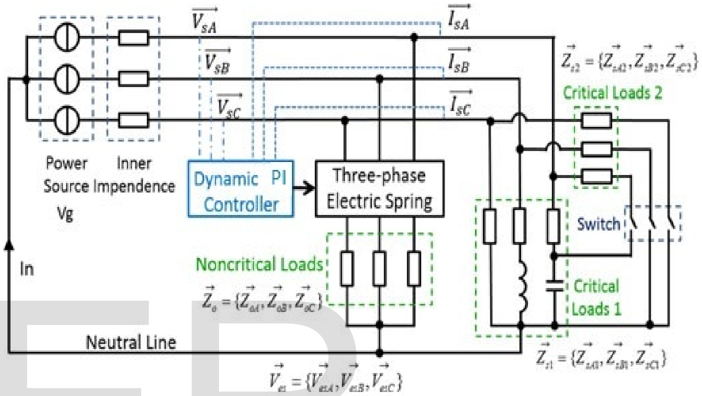


Fig.3 Experimental setup for testing for the Three phase ES

5 EXPERIMENTAL AND SIMULATION RESULT

In order to evaluate the performance of three-phase ES and the validity of proposed control methodology, a hardware prototype is first evaluated for a laboratory-based three-phase power system. Its characteristics are then modeled and incorporated into an electric energy model of a building (such as a hotel) for large-scale simulation study.

5.1 EXPERIMENTAL VERIFICATION

An experimental setup (see Fig. 3) has been used to test the power balancing function of the new three-phase ES. A threephase power system supplies power to a set of three-phase noncritical loads and two sets of critical loads. Noncritical loads are loads that can tolerate mains voltage fluctuation larger than the standard tolerance (typically ±5%). Examples of such noncritical loads in large buildings are the large-scale water heaters and large-scale cooling systems.

TABLE I
PARAMETERS OF THE EXPERIMENTAL SETUP

	Phase A	Phase B	Phase C
$\vec{V}_g$	$200\angle 0°$	$200\angle 240°$	$200\angle 120°$
$\vec{Z}_{s1}$ (Ω)	500 resistive	$250 + 115j$ resistive-inductive	$115 - 115j$ resistive-capacitive
$\vec{Z}_{s2}$ (Ω)	345 resistive	230 resistive	115 resistive
$\vec{Z}_{s2} // \vec{Z}_{s1}$ (Ω)	204 resistive	$119 + 21j$ resistive-inductive	$57.5 - 115j$ resistive-capacitive
$\vec{Z}_o$ (Ω)	200 resistive	200 resistive	200 resistive

These kinds of noncritical loads are assumed to be resistive and balanced in this study. Two sets of critical loads are used because one set will be used to evaluate the performance of the ES for the sudden load change. The parameters for the setup are tabulated in Table I.

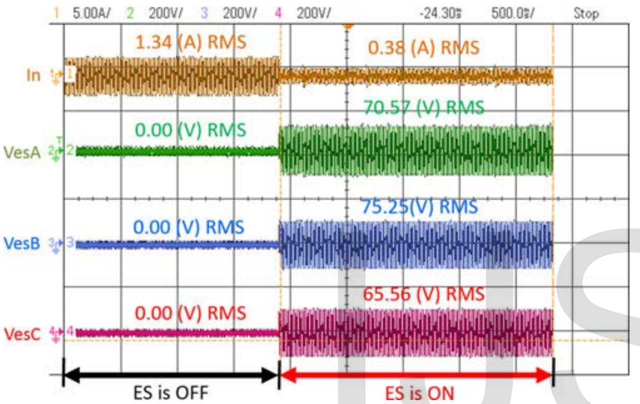
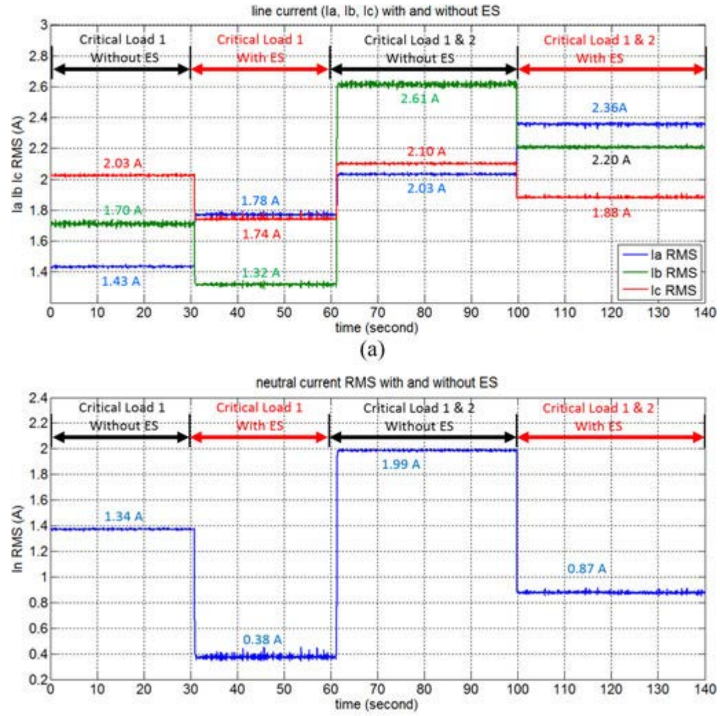


Fig.4 Measured waveforms of the neutral cureent and voltage of ES

Fig. 4 shows the recorded waveforms of the neutral current and the three-phase voltages of the ES before and after the ES is activated. It can be observed that, without the use of the ES, the neutral current is about 1.34 A. After the ES is activated, the neutral current is reduced by 72% to 0.38 A. It is noted that the three ES voltages are different, meaning that the phase load power consumptions of the balanced three-phase noncritical loads are not identical. Fig. 10(a) and (b) shows the three line currents of the noncritical loads before and after a tivatingthe ES, respectively. It can be seen that the three-phase ES is redistributing the line currents of the noncritical loads in order to reduce the power imbalance. For a noncritical load such as a large three-phase electric water heating system, the redistributed heating power within the system will be used to heat up the same tank of water.

In the second test, two different load conditions are used. Initially, only the first set of critical loads is used. Then, both sets of the critical loads are included. The ES is switched off in the interval so that the neutral currents under the two load conditions without activating the ES can be observed



(a)

(b)

Fig.6 (a) Measured line current and (b) Measured neutral current of the three phase system

Fig 6 (a) shows the three line currents of the three-phase powersupply.The corresponding neutral current is shown in Fig.5 (b). It can be seen from Fig. 6(a) that the line currents have been redistributed by the ES and from Fig. 5(b) that the neutral current can be reduced in both cases. In the first load case, the neutral current reduction has been illustrated in Fig. 4. In the second load case, the neutral current is reduced from 1.99 to 0.87 A. These experimental results therefore confirm that the new three-phase ES can be used to reduce power imbalance in a three-phase power system.

TABLE I
SPECIFICATIONS OF ELECTRIC MODEL OF A LARGE HOTEL

	Phase A	**Phase B**	**Phase C**
$\vec{Z}_s$ (Ω)	$0.075 + 0.425j$ (resistive plus inductive)	$0.157 + 0.298j$ (resistive plus inductive)	$0.171 + 0.171j$ (resistive plus inductive)
$\vec{Z}_o$ (Ω)	0.275 (resistive)	0.275 (resistive)	0.275 (resistive)

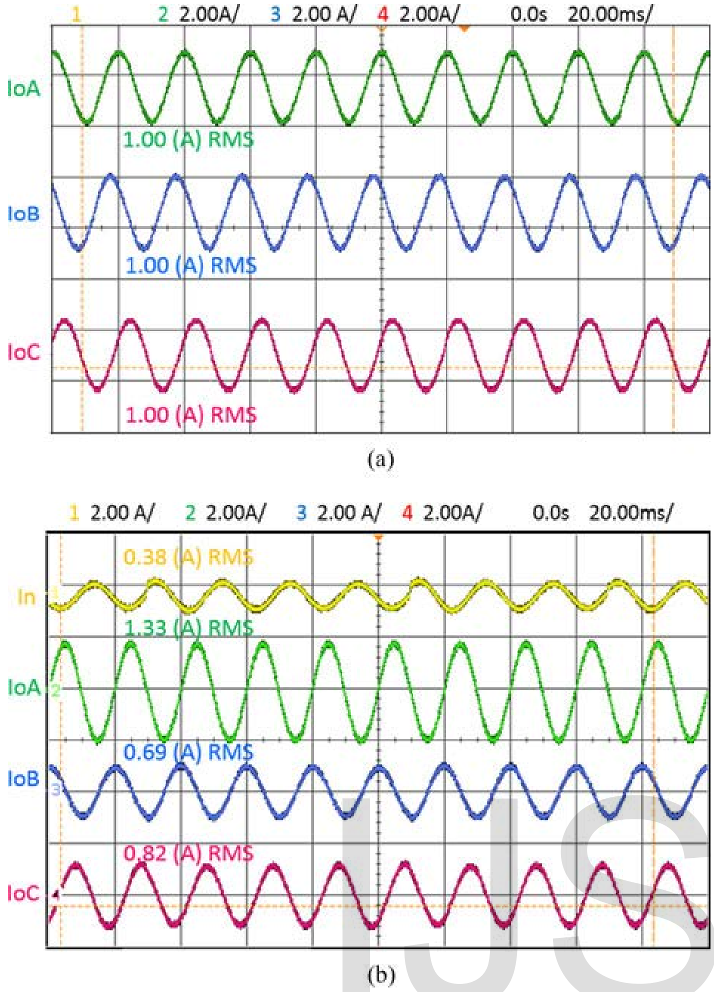


Fig.5 Measured line current of the three phase non critical load and the neutral current (a) before and (b) after activating the three phase ES

5.2 BUILDING ENERGY MODEL & SIMULATION STUDY

The building model built in this paper is based on recent publications on energy consumption research of large hotels. According to [9], in 2003, a large hotel in U.S.A. consumes 316 kW· h electric energy per meter square. Perez-Lombard *et al*. [18] point out that up to 68% of consumed energy is used for heating and lighting which can be considered as resistive loads (as lighting systems have power factor correction). Information reported in [9] shows that a typical large hotel has a total area of 122 116 ft2, which is equal to 11 345 m2. From the report released by ECS [19], the average power factor of a hotel usually remains between 0.80 and 0.92. The electric model of a typical hotel is suitable for the implementation of a three-phase ES. Since lighting and heating systems can be considered as resistive loads and are high tolerant to voltage and power fluctuation, they can be used as noncritical loads and be connected in series with the three-phase ES to form the smart loads. Specifications of the equivalent electric model of the three-phase critical and noncritical loads for the hotel building model are given in Table II.

1) Reduction of Current Imbalance: Fig. 7 shows the neutral current of the three-phase power system before and after activating the three-phase ES. The building model shows that the unbalanced loads causes a neutral current of 455 A. After activating the ES, the neutral current has been reduced from 455 A (rms) to 66 A (rms). The three line currents before and after activating the ES are shown in Fig. 8. Again, the current imbalance has been reduced. These results confirm the ability of the ES in reducing power imbalance in a three-phase powersystem.

The RMS values of three-phase line currents in Fig. 8 show that the current imbalance is reduced. According to the analysis in Section III, the introduction of compensation voltage *V_es = { Ve_sA, Ve_sB , Ve_sC }* can actively change the power consumption of the noncritical loads. The line currents are altered in the process without affecting the power consumption of the critical loads. Fig. 9 shows the phase voltages of the noncritical loads. It can be seen that the voltage amplitudes are not identical, implying that the noncritical load power consumptions among the three phases are nonidentical. In other words, the reduction of the current imbalance of the three-phase system is made possible by the ES in transferring the part of the power imbalance to the noncritical loads.

The constant power supply for the critical loads can be equivalently manifested by the mantainence of line voltage befor and after activating the three-phase ES, as shown in Fig.10.Although the ES does not change the profile of line voltage, the slight variation of mains voltage in RMS value can still be witnessed due to the existence of line impedance and the source impedance of the generator. An interesting byproduct worthmentioning is that the restoration of power balance, equivalently shown by the balance of line current, can help to improve the mains voltage balance. Results in Fig. 10 show that after the ES is turned on, the phase voltage differences among the three phases are reduced.

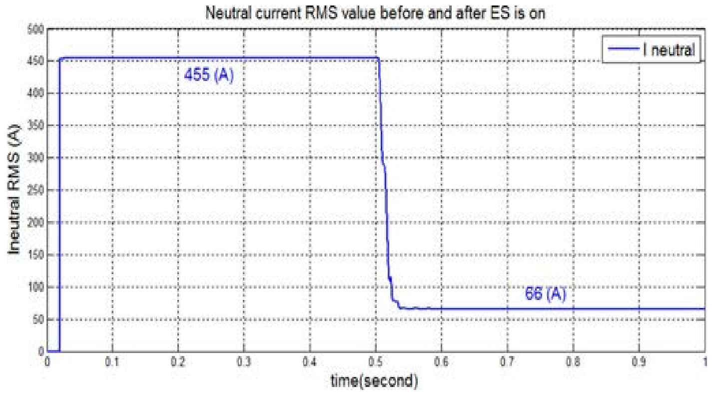


Fig.7 RMS value of neutral current before and after ES is turned ON

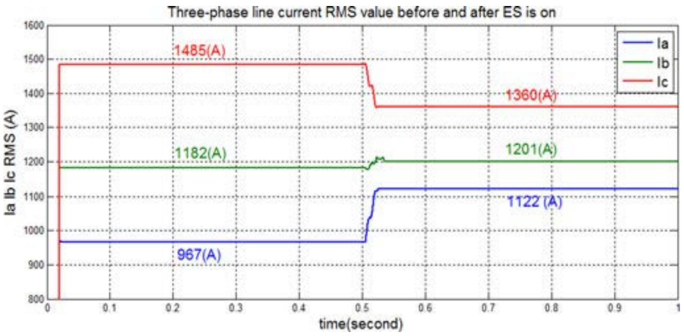


Fig.8 RMS value of three phase line current before and after turning on of ES

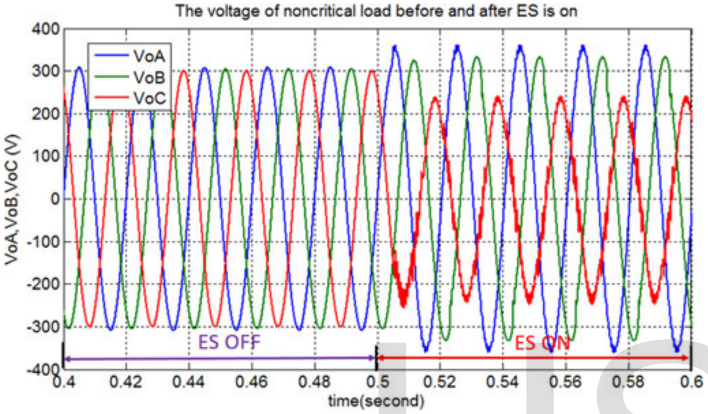


Fig.9 Steady state of non critical load voltage before and after turning on of ES

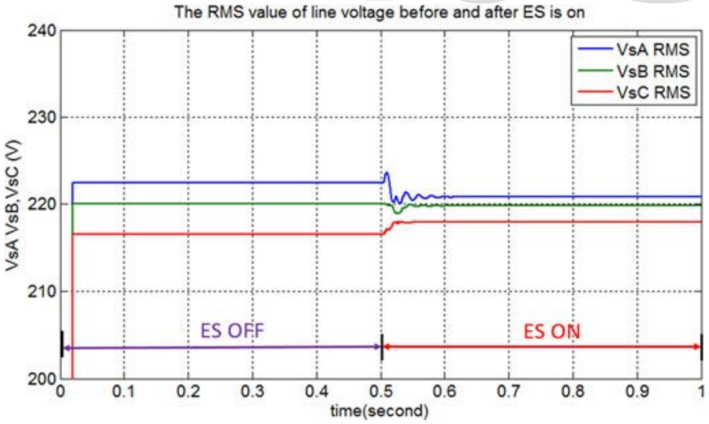


Fig.10 RMS value of mains voltage before and after ES is turned ON

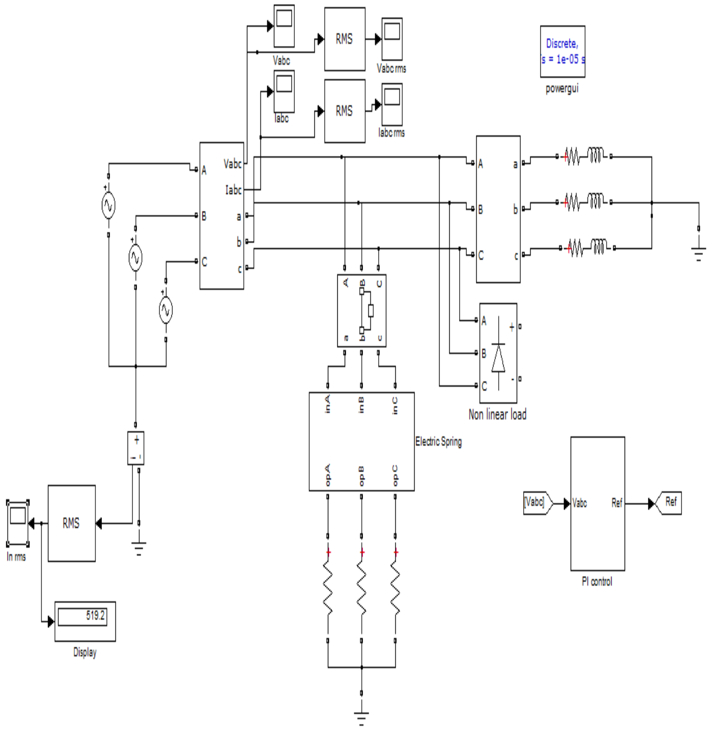


Fig.11 Simulation model of ES for reducing neutral current

6 CONCLUSION

The neutral current in a three phase distribution system is the result of unbalanced load and third harmonic currents. The excess neutral current in the conductor degrade the overall performance of a three phase secondary distribution system. A three phase Electric Spring circuit is introduced in to the three phase distribution system for reducing neutral current. A new three-phase ES circuit is introduced into the threephase power system of a building's electric power infrastructure for reducing power imbalance. This is the first study of its kind for smart or adaptive building energy usage. The use of ESs and-noncritical loads can form a new generation of smart load that is adaptive to future power supply with intermittent renewable energy sources. The ability of reducing power imbalance in the three-phase system using the three-phase ES has been experimentally verified. Its use with noncritical loads in a building has been successfully evaluated in a simulation study with the building's electric load treated as an adaptive load. The experimental and simulation results show that the ES is effective in reducing power imbalance through redistributing the power in the three-phase noncritical loads. In addition, it retains the power grid voltage regulating function of its single-phase counterpart. With the incorporation of ESs, the equivalent electric loads of buildings can form a new generation of adaptive electric loads that could interact constructively with the dynamically changing nature of future power grid.

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