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A brief review on hardware structure of AC electric spring

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ABSTRACT

Decarbonizing power generation and reducing greenhouse gas emissions require renewable energy sources. Intermittent nature of renewable energy sources can cause blackouts, fluctuation in voltage, grid-connected inverter usage, inability to predict power generation, fluctuations in voltage and frequency. It is possible to balance between the supply and demand of power to overcome these problems by using an electric spring (ES). It is necessary to study its work, types, and controlling actions for realizing the benefits of the electric spring. This paper reviews the hardware structure of an ES based on voltage-source inverter (VSI) and current-source inverter (CSI) topologies, in single-phase and three-phase AC power distribution systems with renewable energy sources. The structure, control strategies, operating modes, advantages and disadvantages of each ES topology are elaborated to make it a suitable alternative for resolving different power quality issues caused due to the high penetration of renewable energy sources.

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1. INTRODUCTION

In modern electric grid, the integration of power into grid is obtained by using renewable energy sources, electric and hybrid vehicles, different types of linear and non-linear devices and power electronics converters. This integration provides a path for up-gradation of the existing electric grid without making any drastic changes and makes it a smart grid. A smart grid should fulfil the following requirements: good power quality, advanced control, real time control, optimal operation, communication, and advanced protection [1].

The power quality is a major parameter of a smart grid because it impacts the reliability of the equipment. Common observed disturbances like voltage sag, swell, and fluctuations can disturb the power quality. These types of disturbances are responsible for the harmonics in the voltage and current. The power electronics devices like DC-AC converters, AC-DC converters, linear and non-linear loads add to such disturbances and reduce the reliability of the system [2].

An increase in the use of the power electronic devices for the renewable energy utilization will cause a harmonic increase in the system. The power electronics devices like D-FACT, DVR, STATCOM and SSSC are used for regulating the voltage, reactive power compensation, grid voltage control, current control and power factor improvement [3]. The Active power filters are used for harmonics elimination and the reactive power control [4].

A recent invention of advance power electronic based instantaneous power balancing device is done by Dr. Ron Hui named as the electric spring [5]. The electric spring is used for voltage regulation and as a demand side management technique. It is a power electronics inverter (single phase or three phases) connected in series with the non-critical load to maintain the rated voltage at the critical load. The electric spring works similarly as a flexible AC device or an active filter, but it uses the input voltage control instead of the output voltage control. It controls the balance between the generation and the load demand. This characteristic of the electric spring makes it a suitable candidate for further research in the electric grid to have more utilization of renewable energy sources.

In technical literature of the electric spring, several research lines are highlighted regarding: its hardware structure [6], control strategies [7], their steady state [8] and dynamic characteristics [9]–[11], optimization [12]–[17] and application in electrical distribution network [18]. Due to its new features, different method of controlling voltage, variety of applications, it is required to review the electric spring ES thoroughly to recognize the potential application in electric grid with the intermittent renewable energy source [19]. The available literature of the ES helps to understand, how it evolved by applying simple analogy of the mechanical spring in [20]. The objective of this paper is to review all the available ES topologies in the AC system to solve the power quality issues which arises due to the penetration of renewable energy sources. Robert Hooke in 1660 discovered the law of elasticity and proposed a concept of mechanical spring which exhibits elastic behavior; mathematically it is expressed as (1) [20].

$$F = kX \tag{1}$$

Where: F is the applied Force; X is the displacement in length; K is constant whose value depends on shape and dimension of elastic material. Potential energy associated with mechanical spring can be mathematically expressed as (2):

$$P.E. = \frac{1}{2}kx^2 \tag{2}$$

Where: P.E. is the potential energy.

The Mechanical spring provides the mechanical strength, reduces the mechanical oscillations, and stores the mechanical energy. The concept of the Electric spring is based on the Hooke's law which was discovered in [5] with its practical realization. An analogy of the mechanical spring and the electric spring, under three different conditions such as: voltage boosting, neutral and the voltage suppression are elaborated in the Figure 1.

The Electric spring is analogous to a mechanical spring. It provides voltage support, reduces electric oscillation, and stores electrical energy. The analogous equation to (1) can explain the function the electric spring which can be expressed as (3)-(5):

$$q = cVa \text{ Inductive Mode} \tag{3}$$

$$q = -cV_a \text{ Capacitive Mode} \tag{4}$$

$$q = \int idt \tag{5}$$

Where: q is the stored charge in capacitor having capacitance C; V_a is the voltage across capacitor; i is the current flowing through capacitor having capacitance C.

In (3) and (4) indicates, the voltage enhancing and the voltage suppression function of the electric spring are controlled by the stored charge, and the (5) indicates that the charge can be controlled by utilizing the controlled current source. Thus, the electric spring is addressed as a current-controlled voltage source.

- Problem statement

Electrical energy generation using non-renewable energy sources causes the emission of greenhouse gases such as carbon dioxide, sulfur dioxide, and mercury. These emissions are responsible for the coastal flood, heat waves, acid rain, soil contamination, and so on. The cost to generate power from non-renewable sources is also increasing and the dwindling availability of such sources is causing economic crises and conflicts. Hence, it is needed to gradually increase power generation by using abundant renewable energy sources such as solar, and wind. The use of RES decreases electricity costs for all types of electricity consumers, increases job opportunities in the power generation sector, and is healthier for the general environment. Despite all these advantages, renewable energy sources are intermittent which causes issues like power quality deterioration, fluctuations in voltage, and power factor reduction. To overcome these problems a power electronics-based instantaneous power balancing device was invented by Dr. Ron Hui named an Electric spring which uses input voltage control and reduces issues arising due to the use of RES.

- Objectives

i) To encourage the use of renewable energy sources which are: better for the environment, better economic development of economies dependent on imported power, and healthier flora and fauna.

ii) To discourage the use of fossil fuels that causes pollution in the environment and protection of fragile ecologies.
iii) To settle all problems caused due to nonrenewable energy sources by electric spring in connection with the non-sensitive electric load

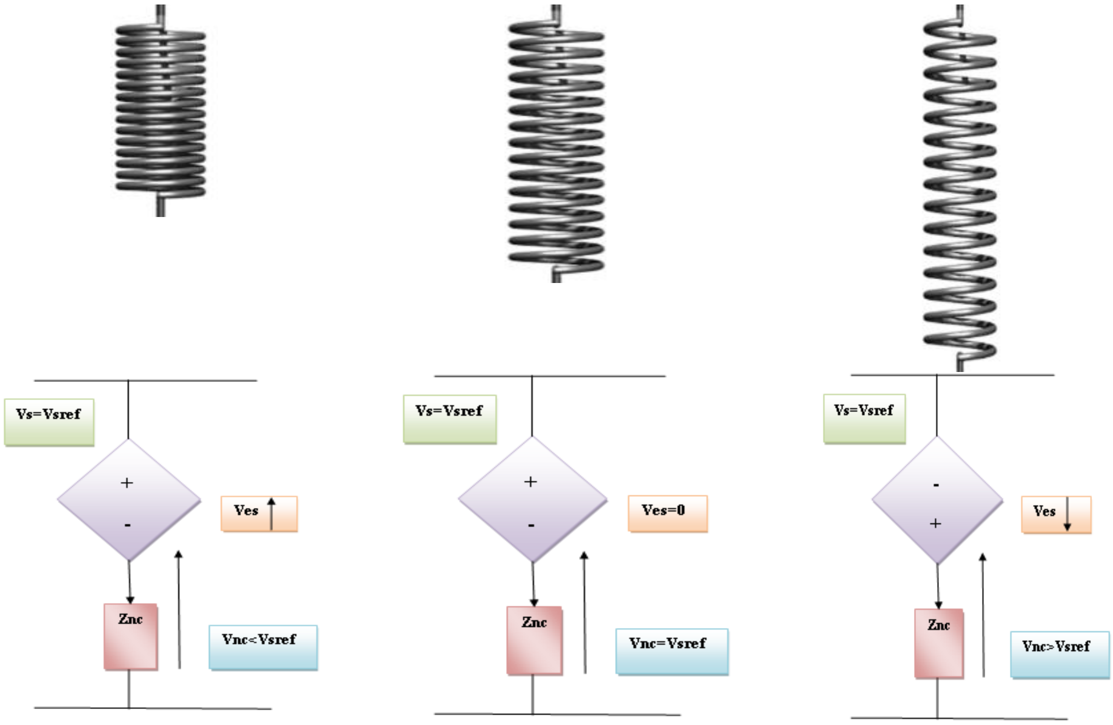


Figure 1. Analogy of electric spring with mechanical spring: (a) compressed, (b) neutral, and (c) expansion

2. PROPOSED SOLUTION

The encouragement for the use of renewable energy sources is to reduce their intermittency. Hence the concept of an electric spring is introduced [5] in the power distribution network to reduce voltage fluctuations caused by renewable energy sources. The Figure 2 shows the structure of electric spring for describing its working principle. Electric spring has arisen in [5] as a unique demand side management technique which uses input voltage control. To regulate voltage of sensitive load, ES injects voltage perpendicular to current flowing through the non-sensitive load. While doing this non-critical load has to sacrifice power stability. To overcome this the concept of the switchable smart load was introduced [21] using indirect voltage control. The electric spring does not require, a communication network but with use of a communication network with ES can drastically reduce the power instability [22]. In microgrids for unplanned islanding operations, ES stabilizes the voltage across critical loads [23]. The ES uses energy storage devices such as capacitors, batteries, and PV systems. For different energy storage devices, the compensation range of ES is also different. The use of energy management system [19] and use of controller such as PID, Fuzzy, and ANN with ES is used to reduce voltage fluctuation [24].

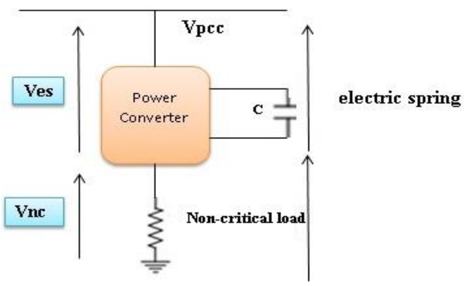


Figure 2. Structure of electric spring

3. ELECTRIC SPRING TOPOLOGIES

Electric spring is one of the advance reactive power compensator in electrical power distribution network having presence of the intermittent renewable energy sources. Topologies of ES are classified, on the basis of: type of energy storage devices used, type of supply (single phase/three phase), type of power converter used, type of converter topologies (VSI/CSI/ZSI) used and utilization of distributed generation [25].

3.1. Hardware structure of single-phase electric spring (SPES)

Electric spring has emerged as a facility provider to resolve the problems happening due to the intermittent nature of the renewable energy sources. The type of power compensation depends on hardware structures of the electric spring. In a power grid, ES is used with a capacitor; it provides reactive power compensation only, ES used with battery provides both the active and reactive power compensation and ES used with back-to-back converter strictly regulates the grid voltage. The ability of ES to compensate both active and reactive power makes it unique.

The Figure 3 shows the schematic for the SPES. From this diagram it can be observed that ES is connected in series with the non-critical load in the presence of renewable energy sources. A low pass filter used with power converter which forms the structure of the ES. This filter reduces the harmonics [26] as well as keeps the fundamental frequency of output voltage of ES. This filter may be L, LC or LCL type depends upon application of ES. Non-critical load can be: resistive, capacitive, inductive or customer loads like water heater [26], air conditioning unit [27], and thermal storage [28]. It can tolerate the voltage fluctuation. The critical load is a load which cannot tolerate voltage fluctuations for example: medical instrument and other sensitive equipments. The controller is the heart of the ES; it provides the pulses for the operation of ES and it defines the operating mode of the ES depending upon the version of the ES.

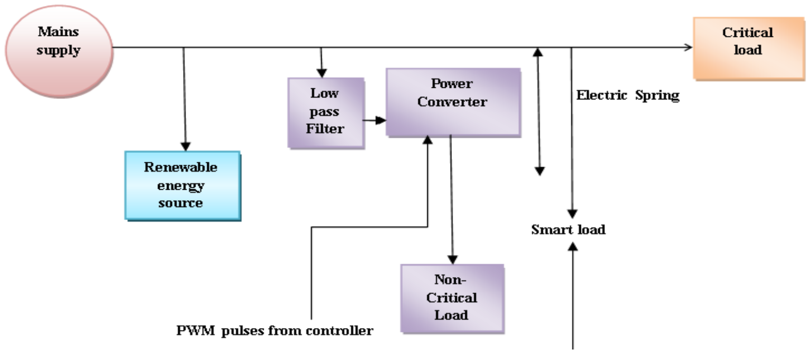


Figure 3. Schematic of single-phase ES

According to the research studies, four versions of ES are available i.e., SPES with capacitor, battery, back-to-back converter, photovoltaic system, combination of battery and capacitor for single phase ac system. For three phase AC systems, there are two versions of ES available i.e., TPES with capacitor and TPES with battery. The different topology can be applied for ES by using different types of power converter, different types of low pass filter, controller and control strategies according to its configuration. The working principle of ES remains same in every combination among these.

3.1.1. Single phase electric spring with capacitor (SPES-C)

Single phase electric spring with capacitor is a special type of reactive power compensator first proposed in [5]. It uses PWM inverter in series with non-critical load and capacitor as energy storage device. It is best suitable for reactive power compensation. Different topologies of SPES-C are proposed based on protection for switching device used in power converter, types of inverters, type of application and type of material used for capacitor.

SPES-C with undeland snubber circuit is proposed in [29] or providing current protection and reducing switching losses of power converter. The Figure 4(a) SPES-C uses half bridge inverter and has two switches and two capacitors for power supply. The SPES-C using full bridge inverter is shown in Figure 4(b). It uses four switches & four diodes and it gets energy from the capacitor. It uses PWM commutation techniques to produce two or three voltage levels. Modified five level packed U-cell topology of SPES-C is shown in Figure 4(c) [30] to improve the THD of the ES output without using any additional controller. Modified seven level packed U cells is shown in Figure 4(d) [31]. This topology of SPES-C is an advancement of modified five level packed U-cell topology of SPES-C which improves the power density of electric spring by applying finite control set model predictive current (MPC) control. It has been observed that by replacing the electrolytic capacitor of the SPES-C with DC link film capacitor of less capacitance value [32], range of DC link voltage can be increase and provides a reliable operation. The SPES-C is used with the fuel cell [33]to reduce the load transients, it provides voltage regulation and increases efficiency of system. Five level neutral point clamped based SPES-C is shown in Figure 4(e) [34]. It is used with the IPD modulation to reduce the THD to 1.84%. Figure 4(f) shows the diode clamped MLI based SPES-B [35]. It uses the carrier-based modulation technique of SPWM to reduce THD to 1.27%. The Table 1shows summary of the single-phase ES with the capacitor considering parameters like: modification in hardware structure features and hardware implementation.

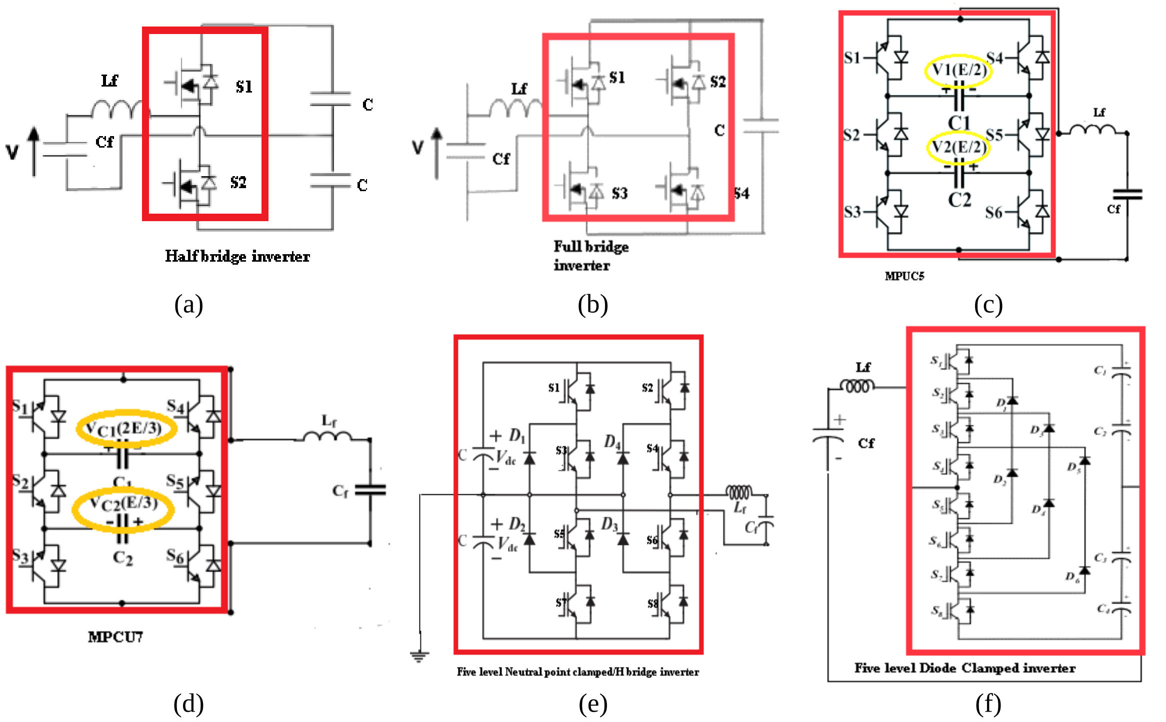


Figure 4. Topologies of SPES-C: (a) half bridge inverter, (b) full bridge inverter, (c) MPCU-5, (d) MPCU-7, (e) five level NPC/H bridge inverter, and (f) five level diode clamped inverter

Table 1. Summary of hardware structure of SPES-C

References	Modifications in hardware structure	Features	Hardware implementation
[29]	It uses Undeland snubber circuit, IRFP31N50L MOSFET and iron-based Metglas amorphous alloy for LC filter	- Provides current protection, reduce switching loss of switches - Reduction in electromagnetic interference problem	Y
[30]	It uses of modified five level packed U cell inverter	- Lower rating of low pass filter and switches - No need of additional controller for balancing voltage and power - Requires half DC link voltage - Reduces THD - Applicable for high power application	Y
[31]	It uses of modified seven level packed U cell inverter	- Controllable switching frequency - Uses non-linear control - Medium voltage and power application	Y
[32]	It uses DC link film capacitor instead of electrolytic capacitor	- Minimum power loss of ES - Requires smaller value of capacitance	Y
[35]	It uses five level diode clamped inverter	- SPWM scheme - Reduces THD	N
[34]	It uses of five level neutral clamped inverter	- Less stress on switches, low harmonics - Uses IPD modulation - Applicable in industrial drives of medium voltage	N

The Figure 5 shows the construction and the control structure of the SPES-C with renewable energy source ‘Ir’. It consists of four switches S1, S2, S3 and S4 for full bridge inverter, one capacitor as energy source and a low pass filter as shown in Figure 5(a). There are two operating modes of SPES-C: inductive and capacitive shown in the Figures 5(b) and 5(c) SPES-C operates only in these modes, hence providing reactive power compensation. The Figure 5(b) shows the ES voltage leads the current through NCL by 90° in inductive mode. Figure 5(c) shows the ES voltage lags the current through NCL by 90° in capacitive mode. Voltage across NCL is decreases in inductive mode and increases in capacitive mode. It is observed that for the reactive power compensation, the ES voltage must be perpendicular to the current flowing through the NCL.

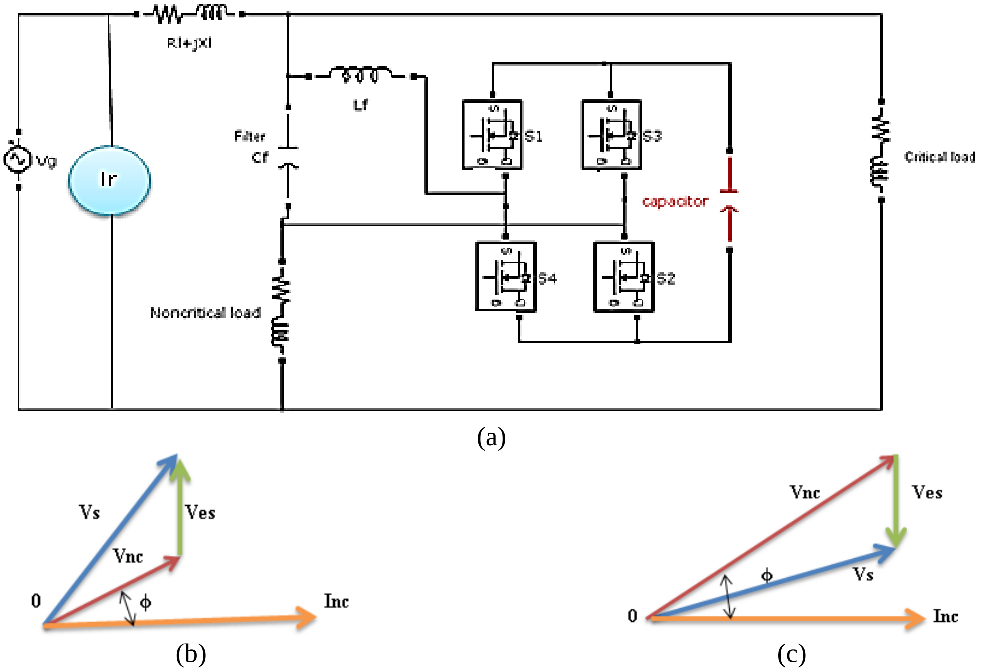


Figure 5. Construction and control structure of SPES-C: (a) hardware structure, (b) inductive mode, and (c) capacitive mode

3.1.2. Single phase electric spring with battery (SPES-B)

The single-phase electric spring with battery has the same structure as SPES-C but it uses battery as energy source instead of capacitor. This version of ES is illustrated in number of research articles. It is experimented in [36], [37] with half bridge and full bridge inverter. SPES-B provides both the active and the reactive power compensation. It is configured with: different MLIs, split storage capacitor, multiport transformer and without non-critical load.

The Figure 6(a) shows SPES-B with three level cascaded H bridge inverter which consist of four switches S1, S2, S3 and S4 with Filter parameter L_f and $C_{f.}$,it reduces the THD with 1.64% [38]. In MLI, the number of levels and the THD are inversely proportional to each other. Increasing levels demands more complex control. Hence the seven level MLI with reduced switch count is proposed in [39] and shown in Figure 6(b) .It reduces THD to 0.44% in main voltage. The packed E cell based SPES-B is shown in Figure 6(c), it uses the artificial neural network (ANN) based controller with features like: reduced number of components, more switching states and spectacular dynamic performance during transients [40]. The Figure 6(d) shows the SPES-B without the non-critical load. It is also called the fractional order ES which is integrated with the resonant filter. The key feature of this ES is that its operating range does not depend on the NCL in improving the power factor but it shows poor performance in the voltage regulation of critical load during high power applications [41].

Different topologies of the SPES-B are available based on number of ports used for the single-phase transformer. The SPES-B with the two port transformer is shown in the Figure 6(e) [42]. It uses the refined delta control to change the voltage of the non-critical load in the direction of the line voltage. The Figure 6(f) and the Figure 6(g) show isolated topologies of the SPES-B with the three and four port transformers respectively. This isolated topology fulfill all the voltage requirements of critical load and provides safer environment for its application but these configurations of ES add extra cost of the transformer [43].

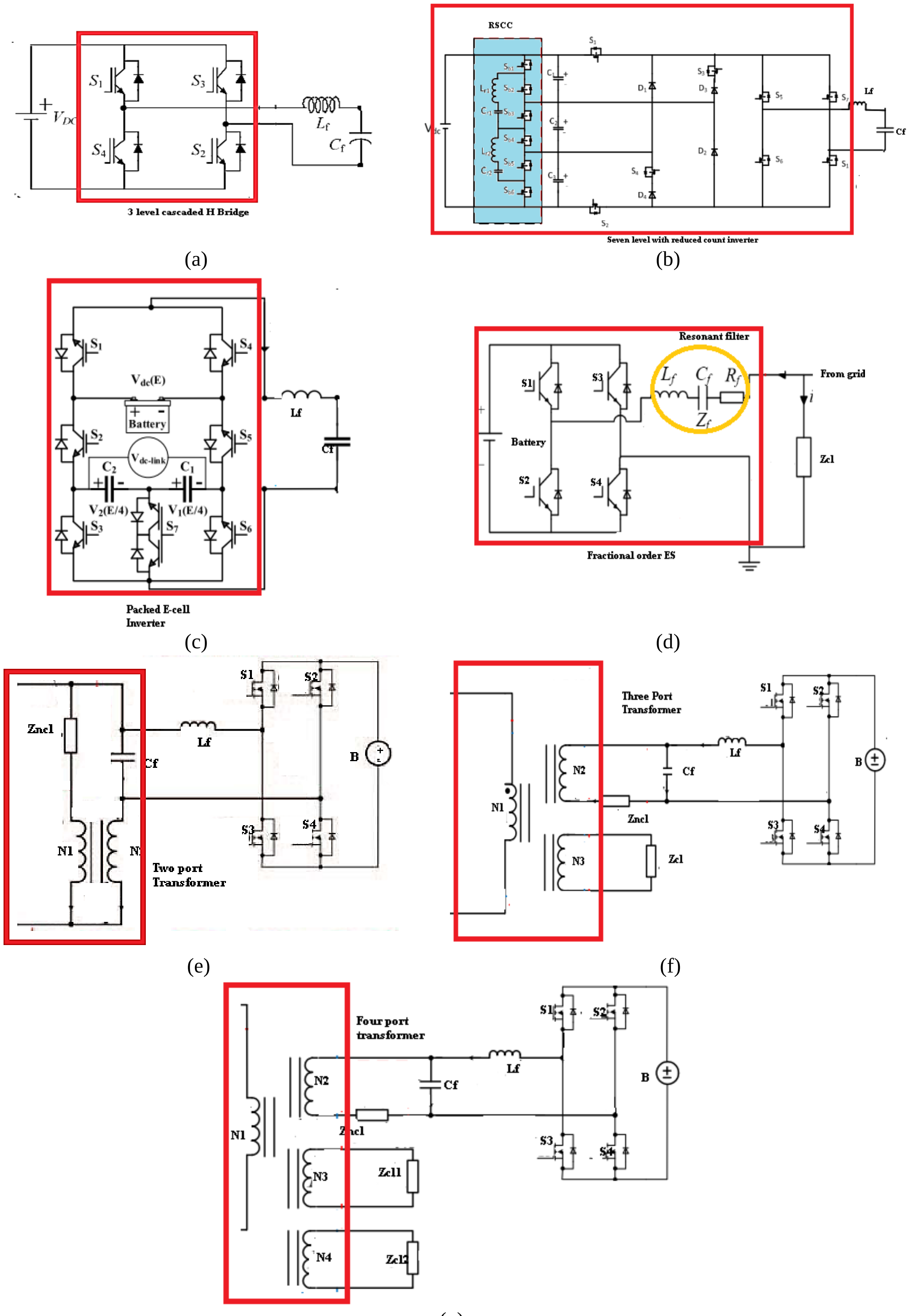


Figure 6. Different topologies of SPES-B: (a) 3 level cascaded H Bridge, (b) 7 level with reduced count inverter, (c) Packed E-cell inverter, (d) Fractional order ES, (e) SPES-B with 2 port transformers, (f) SPES-B with 3 port transformers, and (g) SPES-B with 4 port transformers

The Figure 7 shows the construction and the control structure of the SPES-B. The use of battery makes it capable to provide: real and reactive power compensation, power factor improvement and voltage regulation. SPES-B operates in eight operating modes, namely: capacitive, inductive, resistive, negative resistive, inductive plus resistive, capacitive plus resistive, inductive plus negative resistive and capacitive plus negative resistive. To understand the working principle of SPES-B it is assumed that non-critical load is purely resistive and supply voltage is constant for all operating modes.

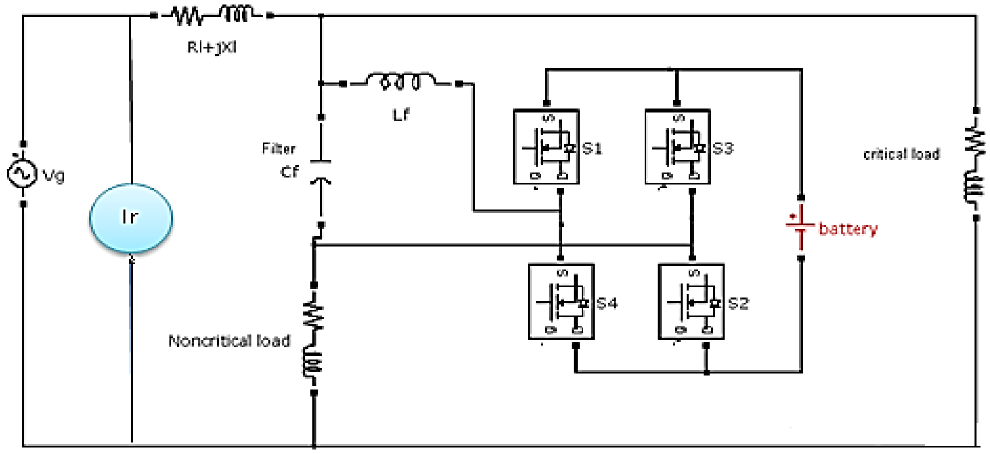


Figure 7. Construction and control structure of SPES-B

The Figure 8(a) and the Figure 8(b) show the capacitive and the inductive mode. The phase angle between the non-critical load voltage and the ES voltage is $-90°$ for the capacitive and $90°$ for the inductive mode. The Figure 8(c) and Figure 8(d) shows the positive and the negative resistive modes. In these operating modes, the phase angle between the non-critical load voltage and the ES voltage is same and exchanging only the active power between power grid and ES. $\theta es = 0°$ and $180°$ for the positive resistive mode and the negative resistive mode respectively. The Figure 8(e) and 8(f) shows the inductive plus resistive and the capacitive plus resistive mode. These operating modes exchange both active and reactive power by ranging the ES angle, $90° > \theta es > 0°$ for inductive plus resistive and $-90° < \theta es < 0°$ for capacitive plus resistive. The Figure 8(g) and the Figure 8(h) show the inductive plus negative resistive and the capacitive plus negative resistive modes. It delivers the active power and consume the reactive power by ranging the ES angle, $180° > \theta es > 90°$ and delivers both power by ranging the ES angle, $0° > \theta es > 180°$. The Table 2 shows summary of single-phase ES with the battery considering parameters like: modification in hardware structure features and hardware implementation.

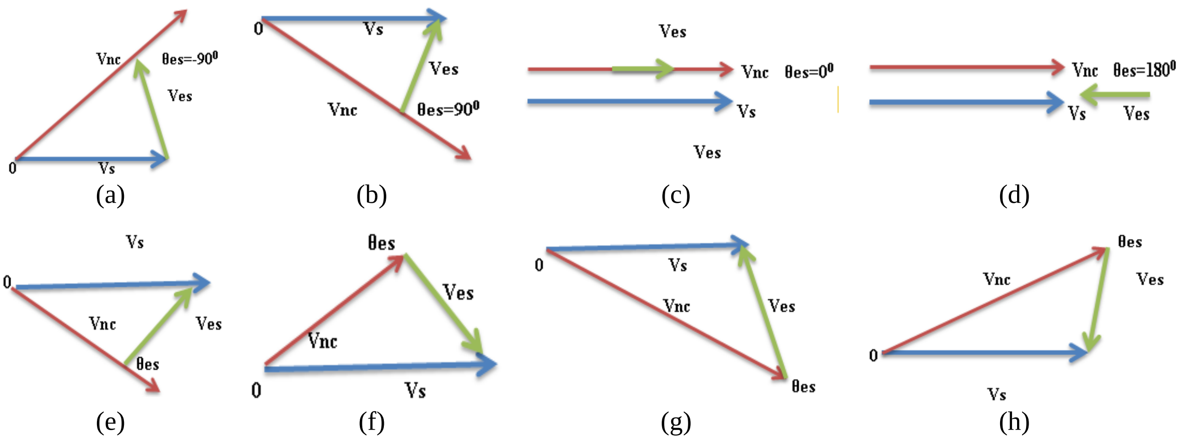


Figure 8. Phasor diagram for operating modes of SPES-B: (a) capacitive, (b) inductive, (c) resistive, (d) negative resistive, (e) inductive plus resistive, (f) capacitive plus resistive, (g) inductive plus negative resistive, and (h) capacitive plus negative resistive

Table 2. Summary of hardware structures of SPES-B

References	Modifications in hardware structure	Features	Hardware implementation
[38]	It uses three level cascaded H bridge inverter	- Reduces THD	N
[40]	It uses packed E-cell inverter	- Uses switches of half voltage rating - Applicable in high power application - Operational during faulty condition - Uses ANN control	Y
[44]	It uses seven level multilevel inverter and resonant switched capacitor inverter	- Reduces voltage unbalancing - Reduces THD	N
[45]	It uses full bridge inverter with split storage capacitor and battery	- Provides flexible power flow and control for battery SOC - Reduces storage capacity of battery	Y
[41]	It uses VSI and resonant filter	- Operating range not depend on non-critical load and it is related to line impedance & maximum capacity - Applicable to low power factor consumer	Y
[43]	It uses three port and four port transformers of isolated topology	- Provides safety - Provides high power quality - Adds extra cost of transformer	Y
[42]	It uses two port transformers	- Uses delta control for non-critical voltage	N

3.1.3. Single phase electric spring with back-to-back converter (SPES-B2B)

The Figure 9 shows the construction and the control structure of single phase electric spring with back to back converter [46]. It consists of two converters; shunt ES and series ES. The shunt ES is connected to grid via L_{sh1}, Lsh2 and C_{sh1} and the series ES is connected to grid via L_{se1} and C_{se1} via transformer. This version of ES does not use the non-critical load in series connection as used in SPES-C and SPES-B. The controller of SPES-B2B uses reference DC voltage and supply voltage as the input signals.

The Figure 10 shows the operating modes of the SPES-B2B. To understand the operating mode, it is assumed that noncritical load is resistive. The Figure 10(a) shows voltage supportive mode in which $V_{series\ ES}$ is in phase with supply voltage V_s. The compensation voltage provided by the series ES decreases the voltage and the power of the non-critical load to regulate the supply voltage at reference value. The Figure 10(b) shows the voltage suppressive mode in which $V_{series\ ES}$ is in out of phase with the supply voltage V_s. The compensation voltage provided by the series ES, increases voltage and power of the non-critical load. This in turn increases the voltage drop in the distribution line to regulate the supply voltage at the reference value. It is seen that the operating range of the SPES-B2B depends on the rating of the series ES and the shunt ES [47].

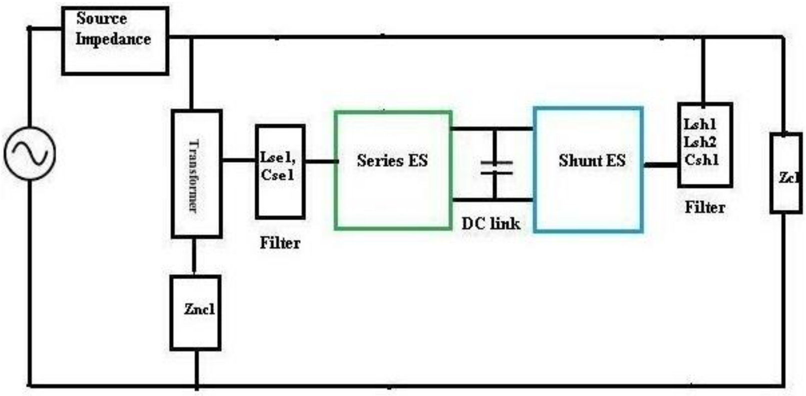


Figure 9. Structure of the single phase ES with back to back converter

Figure 10. Operating modes of SPES-B2B: (a)voltage supportive mode and (b)voltage suppressive mode

The Figure 11 shows the SPES-B2B without the use of transformer which provides: independent control for DC link voltage, active and reactive power [48]. The Figure 12 shows the SPES-B2B with the additional converter in [49] to help in the active power compensation provided by the series converter without need of the energy storage device. Its structure resemble the structure of UPQC except one converter of it, is connected in series with the non-critical load and another converter is connected parallel to supply for maintaining DC link voltage [19]. The Table 3 shows summary of single-phase ES with back-to-back converter considering parameters like: modification in hardware structure features and hardware implementation.

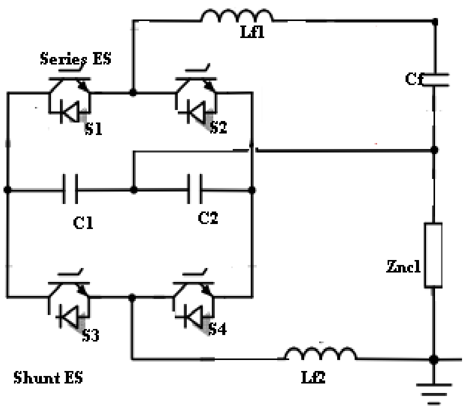


Figure 11. Transformer less ES

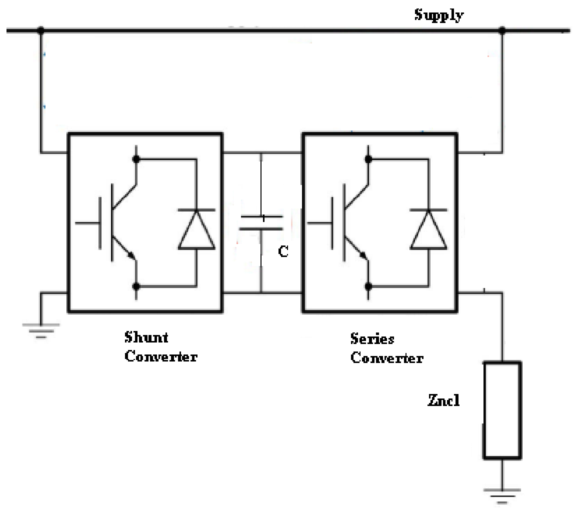


Figure 12. Smart load with back-to-back converter (SLBC)

Table 3. Summary of hardware structures of SPES-B2B

References	Modifications in hardware structure	Features	Hardware implementation
[48]	It doesn't use transformer	- Controls P,Q and DC link voltage independently - Supports frequency regulation	Y
[49]	It uses additional shunt converter	- Provides flexible control to smart load without energy storage - Low cost - Suitable for high power application	N

3.1.4. Photovoltaic single phase electric spring (PV-SPES)

The photovoltaic single phase electric spring is another version of the electric spring which has same structure as that of the SPES-B only difference is that the photovoltaic system is added on the DC bus as shown in the Figure 13. The operation of PV-SPES is based on the radial chordal method proposed in [50] shows that the power consumed by smart load is not depend on the variations in the photovoltaic power. The Figure 14 shows the phasor diagram for the operation of the PV-SPES with the radial component of ES voltage as V_{esr} and the chordal component as V_{esc}. The current through the smart load and the non-critical load is same. The V_{esr} is parallel to the V_{nc} and V_{esc} is perpendicular to $V_{nc.}$ The operation shows that the power consumed by the smart load is not depend on the power variations in the photovoltaic system.

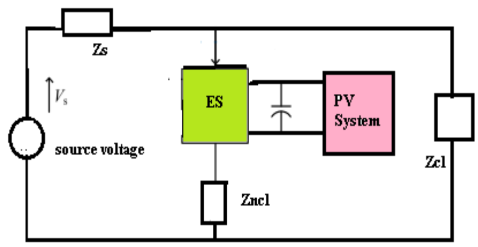


Figure 13. Photovoltaic electric spring

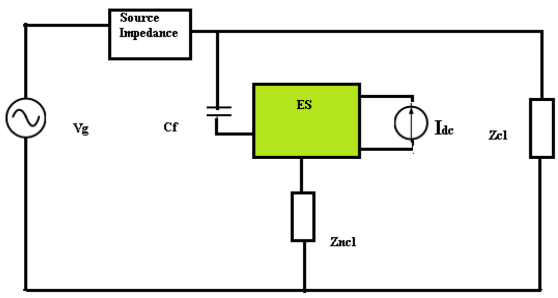


Figure 14. Current source inverter based electric spring

3.1.5. Single phase ES with current source inverter (SPES-CSI)

The single-phase ES based on current source inverter is shown in the Figure 14. It consists of DC current source as an energy storage, four switches, and single capacitor as a filter. The working of the SPES-CSI is similar to the active power filter. The voltage control strategies used for the recent VSI based ES, reduces the total harmonic distortion. It can be again improve with the SPES-CSI using the direct current control method [51].

3.1.6. Single phase ES with output voltage control (SPES-OVC)

This version of ES has structure similar to the SPES-C only difference is; it uses the output voltage control. ES with the input voltage control is a peculiarity of it. In the core concept of ES, it regulates the voltage across the critical load by sacrificing voltage at the non-critical load but in the practical application of it, the majority of customers were not satisfied. Hence the SPES with output voltage control is implemented in [52]. The output voltage control is divided in three sections: the DC voltage regulation, the voltage regulation at load and the selection of operating mode. While regulating the voltage across critical load, it maintains the voltage at the non-critical load also. The SPES-OVC requires less reactive power as compared to the traditional SPES, this leads to more economical solution.

3.1.7. Single phase ES with battery and capacitor (Hybrid ES)

The hybrid ES uses the battery and split storage capacitor with renewable energy generation. The Figure 15 shows the SPES-B with the split storage capacitor [45]. This configuration of electric spring provides cost effective solution for industrial use, it prevents the charging and discharging of the battery by changing the non-critical load.

3.2. Hardware structure of three phase electric spring (TPES)

The power fluctuations are more common in the three-phase system due to unbalance loads. It impacts on the power quality and give rise to the power quality issues like unbalanced line current, excessive and neutral current. To provide the solution for these issues, the three-phase electric spring is implemented in [53] to reduce the three-phase power imbalance. The Figure 16 shows the schematic of the three-phase electric spring (TPES). Similar to the SPES, every ES of three phase system is connected in series with its respective the non-critical load to form the smart load for regulating voltage across the critical load of each phase. On the basis of energy storage devices, the TPES is classified as TPES with the capacitor and TPES with the battery.

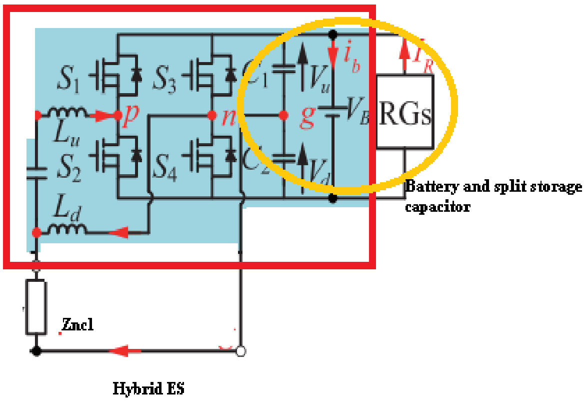


Figure 15. Hybrid ES

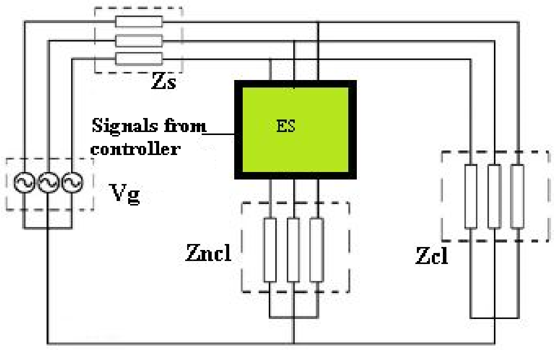


Figure 16. Schematic of three phase electric spring

3.2.1. Three phase ES with capacitor (TPES-C)

The Figure 17 shows the three phase ES with the capacitor. It consists of six switches, three legs with group of inductors and capacitors connected to the grid via a three-phase transformer. This topology of ES provides the balance and equal voltage to the critical load, it requires large requirement of voltage injection for a very small change in grid voltage. This in turn increases the rating of the switches. Thus nine switch converter topology of TPES-C is proposed in [54]. It performs all power compensation for all operating modes without the need of additional energy storage requirement. It provides the active power transfer from the grid to the ES and the ES to grid hence provides full control for the phase angle of injected voltage. The unified topology of the TPES-C is proposed in [55] operates as: series, series to shunt and shunt to compensator. It consists of combination of series and shunt converter. The LCL filter is connected on the supply side and the LC filters across the non-critical load. It also provides all type of power compensation but with additional features like reduced cost of manufacturing, issues related to isolation transformer and energy storage devices.

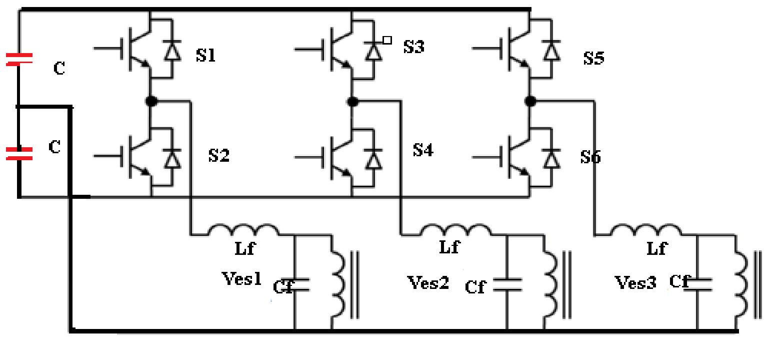
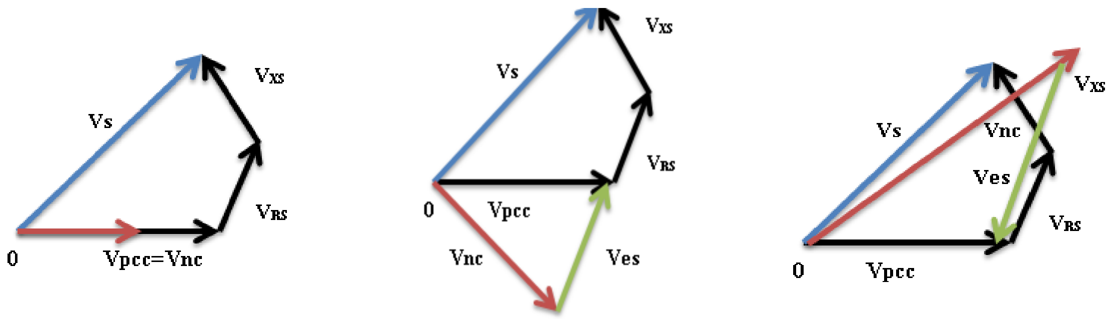


Figure 17. Three phase electric spring with capacitor

The Figure 18 shows the operating modes of TPES-C with phasor diagram. The Figure 18(a) shows Vpcc is at the reference value. The voltage across the non-critical load coincides the voltage at point of common coupling (PCC). Here the ES is bypassed hence voltage across the non-critical load and the critical load is same. The Figure 18(b) shows the unbalance between the power generation and the power consumption which changes the voltage at PCC. The ES voltage leads the non-critical load voltage to regulate the voltage at PCC. The Figure 18(c) shows the generation is more than the consumption. This changes the voltage at PCC and it goes beyond the reference value. The voltage of ES lags the voltage of the noncritical load to regulate the voltage at PCC.



(a) (b) (c)

Figure 18. Phasor diagram of TPES-C with phasor diagram: (a) Vpcc is at the reference value, (b) unbalance power generation and power consumption, and (c) generation is more than the consumption

3.2.2. Three phase electric spring with battery (TPES-B)

Three phase electric spring has a structure similar to the TPES-C, only difference is; it uses battery instead of the capacitor. This version of the TPES has the capability to convert the smart load into an adaptive load and can transform them to fulfill all power compensation requirements during the transient state. It can simultaneously compensate the grid voltage and the current flowing through the critical load [56]. It is used in smart buildings to convert conventional thermal load into an adaptive load to reduce voltage and the frequency deviation [28]. It reduces voltage and load imbalance by using the independent delta control [57]. It reduces the total harmonic distortion of the main voltage [58]. The TPES-B performs multiple functions like: voltage regulation at PCC, frequency regulation, active and reactive power compensation, power factor improvement at the same time using instantaneous power theory [59]. In unplanned island type grid, the TPES-B regulates the voltage across the critical load without neutral connection [23]. It provides a more practical application and changes the modes of operation by the addition of extra transformer [60]. It has eight operating modes similar to SPES-B, namely: capacitive, inductive, resistive, negative resistive, inductive plus resistive, capacitive plus resistive, inductive plus negative resistive and capacitive plus negative resistive. The Table 4 provides summary of all single phase and three phase electric spring considering parameters such as: energy source, characteristic, power controllability, type of compensation, different types of controllers, advantages and disadvantages.

Table 4. Summary of all AC electric spring

Parameters			VSI based			CSI based
	SPES-C/ TPES-C	SPES-B/ TPES-B	SPES-B2B	PV-SPES	SPES-OVC	SPES-CSI
Energy source	Capacitor	Battery	DC link	DC source and photovoltaic system	Capacitor	Current source
Characteristics	With non-critical load	With non-critical load	Without non-critical load	With non-critical load	With non-critical load	With non-critical load
Power controllability	Coupled	Independent	Independent	Coupled	Coupled	Independent
Types of compensation	Reactive power compensation	Active and Reactive power compensation	Active and Reactive power compensation	Active and Reactive power compensation	Reactive power compensation	Reactive power compensation
Name of Controller	PI controller	P, PI, PR, fuzzy controller	PI controller	PI, PR and RCD controller	PI controller	PR and P controller
Operating Range	Less	More	More	Moderate	Less	Moderate
Advantages	Uses simple converter topology	Exchange of active and reactive power	-provide frequency regulation, -no need of additional energy source	Use of renewable energy source on DC bus	- Provides voltage stability at critical and non-critical load. - Requires less reactive power, - Provides economical solution	- Only a single capacitor worked as filter - Provide reliable operation, - Adjustable value of input current - Easy understanding of ES concept
Disadvantages	Provides only reactive power compensation	Voltage regulation level is restricted by DC voltage source	-Complex structure, -Voltage regulation level depends on rating of converter	Voltage regulation level is restricted by DC voltage source	Operating mode selector is required to avoid overcompensation	- Not applicable for inductive load - For low power application, give poor performance and raise stability issues
Application	Purely reactive power compensation	All possible compensation	All possible compensation	All possible compensation	Purely reactive power compensation	- Application requires CSI as an input

4. RESULT AND DISCUSSION

After reviewing the literature on the AC electric spring, it has been observed that this concept is applied to both three-phase and single-phase AC systems. It is applied for improving power factor, regulating voltage across sensitive loads, reducing power imbalance, and reducing neutral current mitigation using different converter topologies such as VSI, CSI; different types of low filters, and using different control strategies with different controllers such as PI, PR, hysteresis, fuzzy, and ANN for single ES and droop control, and consensus control. for multiple ES using energy storage elements such as a capacitor, battery, and photovoltaic system. Results among all these combinations of ES show that the electric spring has more potential as a reactive power compensator as compared to other devices such as active power filter and FACT devices like SSSC, and STATCOM and reduce the power quality issues.

A theoretical analysis shows that AC electric spring can become an advanced demand-side management technique in electric power distribution networks with distributed generation. This requires: the ES to be used with a well-structured communication network, the use of a low-cost & compact design of an inverter associated with it, and the use of control strategies that are simple and cost-effective.

5. CONCLUSION

An electric spring is an alternative for reducing voltage fluctuations caused due to the penetration of renewable energy sources. In this paper, a comprehensive review of the VSI based and CSI based ES is carried out for the single phase and the three-phase ac system. Contributions are classified into three main sections such as; hardware structure, operating modes and the type of controller in power distribution network are elaborated in detail. It has been observed that evolutionary steps in hardware structure of ES are subjected to energy source and type of controller. ES is provided with energy sources like battery, capacitor, and renewable energy source alone or in combination. An appropriate design for control parameters gives exact power exchange in grid and ES, improves power factor, increases reliability and capability to increase voltage regulation of the sensitive load in the presence of renewable energy sources

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