

# Electric Spring and Smart Load: Technology, System-level Impact and Opportunities

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**Abstract**— Increasing use of renewable energy sources to combat climate change comes with the challenge of power imbalance and instability issues in emerging power grids. To mitigate power fluctuation arising from the intermittent nature of renewables, electric spring has been proposed as a fast demand-side management technology. Since its original conceptualization in 2011, many versions and variants of electric springs have emerged and industrial evaluations have begun. This paper provides an update of existing electric spring topologies, their associated control methodologies, and studies from the device level to the power system level. Future trends of electric springs in large-scale infrastructures are also addressed.

**Index Terms**—Electric Spring, smart load, distributed renewable generations, demand response, demand-side management

## NOMENCLATURE

AC-ES	AC electric spring
BTB	Back-to-Back
CL	Critical load
DCES	DC electric spring
D-FACT	Distributed flexible AC transmission
D-Statcom	Distributed Static VAR Compensator
DSM	Demand-side management
ES	Electric Spring
EV	Electric vehicles
EWB	Electric water heater
H-DCES	Hybrid DC electric spring
HVAC	Heating, ventilations and air-conditioning
LV	Low voltage
NCL	Noncritical load
PLL	Phase-locked loop
$P_{CL}$	Power of critical load
$P_{NCL}$	Power of noncritical load
PV	Photovoltaic
RCD	Radial-chordal decomposition
R/X	Resistance/Reactance
SL	Smart load
SOC	State-of-charge
TCL	Thermostatically controlled loads
$V_s$	AC mains voltage
$V_{ES}$	Voltage across the electric spring
$V_{NC}$	Voltage across the noncritical load

## I. INTRODUCTION

The rapid contraction of sea ice in the Arctic [1] and Antarctica [2], huge bush fires in Amazon forest [3] and Australia [4], atmospheric CO<sub>2</sub> concentration passing 400 ppm, and continual rising of acidity of seawater, sea level and global temperature [5] have prompted urgent needs to address climate change issues. Renewable energy, clean energy conversion, energy storage, nuclear energy, carbon capture and sequestration, replacement of combustion vehicles with electric ones, and sustainable building designs are parts of existing solutions to combat climate change. Based on the 2019 data provided by the International Renewable Energy Agency (IRENA) [6], solar power (94GW; +24% over 2017) and wind power (49GW; +10% over 2017) are the top two dominant renewable energy capacities installed in 2018.

The increasing use of wind and solar power of intermittent nature pose new challenges to power system stability, which requires an instantaneous balance of power supply and load demand. In fact, intermittent renewables will not only lead to power system collapse [7], the instability problems may even be exported to neighboring countries with power networks connected to the same super grid [8]. Traditional power systems adopt the centralized generation principle with the control paradigm of “power generation (supply) following load demand” and unidirectional power flow from the power stations to the load centers. With increasing capacities of distributed renewable energy generation, control paradigm for centralized power generation is no longer valid for the future power grid. Distributed renewable energy generation in the load centers implies bidirectional power flow in the power networks and renewable power generation has stochastic nature. Therefore, for an emerging power grid, there is a need for a radical change in control paradigm to “load demand following power generation” in order to achieve power balance for system stability. Key differences between traditional and emerging power grids are highlighted in Table I.

Table I Key differences between traditional and emerging power systems

Traditional Power Generation	Emerging Power Generation
Centralized	Distributed
Unidirectional power flow	Bidirectional power flow
Traditional Control Paradigm	New Control Paradigm
Power generation (supply) follows load demand	Load demand follows power generation (supply)

Demand response or demand-side management is not a new concept [9]. Power companies have been using traditional demand response methods such as (i) scheduling of deferrable loads (e.g. washing machines, dishwashers) [10], (ii) energy storage [11], real-time pricing [12] and direct on-off control of noncritical loads [13] in order to alleviate peak demands. Although these methods have their advantages, they have inherent limitations. For example, load scheduling can only be achieved days or hours ahead and cannot provide instantaneous demand response and direct on-off control of customers' loads may cause user inconvenience. Moreover, traditional demand response methods may not offer solutions even if the overall system power supply and load demand are balanced. For example, excessive PV power injection in local distribution line could cause transient overvoltage [14]. Therefore, fast and distributed demand-response methods deserve more attention.

Modern power electronics provides the technology to develop fast demand response solutions to cope with fast fluctuation of renewable power injection into the power grid. This paper addresses recent developments in Electric Springs (ES) technology that has been proposed to enable effective demand response with very fast response time in the order of tens of milliseconds (i.e. almost instantaneous for the power systems at mains frequency of 50Hz or 60Hz). Starting with a brief explanation of ES concept, this paper describes various types of ES topologies and their variants reported since 2012 for smart grid applications. For AC power systems, these functions include voltage and frequency regulation, power quality improvement, reduction of power imbalance, reduction of energy storage and enhancing power system resilience. Electric springs can also be applied to DC power grid and the research and developments so far are summarized. Different control schemes corresponding to their circuit topologies proposed by several research groups are then explained. Besides individual control, droop and distributed control of a large group of distributed ESs are explained. After the ES device aspects have been addressed, recent investigations of ES applications to power systems will be covered. Future trends of ES research are discussed before the conclusion section.

## II. CONCEPT OF ELECTRIC SPRING

A mechanical spring is an elastic device that can be used to (i) provide mechanical support, (ii) store mechanical energy and (iii) damp mechanical oscillations. When compressed or stretched, it exerts an opposite force proportional to its change in displacement. Potential energy ( $PE$ ) is stored in the mechanical spring when the length of the spring deviates from its natural length. The principle of the mechanical springs has been described by Robert Hooke in 1678 [15]. Hooke's law states that the force of an ideal mechanical spring is:

$$\mathbf{F} = -k\mathbf{x} \quad (1)$$

where  $\mathbf{F}$  is the force vector,  $k$  is the spring constant and  $\mathbf{x}$  is the displacement vector. The potential energy ( $PE$ ) stored in the mechanical spring is:

$$PE = \frac{1}{2}kx^2 \quad (2)$$

Analogous to a mechanical spring, an electric spring is an electric device that can be used to (i) provide voltage support, (ii) store electric energy and (iii) damp electric oscillations (Fig.1). Analogous to (1), the basic physical relationship of the electric spring is expressed as:

$$q = \begin{cases} C v_a & \text{inductive mode} \\ -C v_a & \text{capacitive mode} \end{cases} \quad (3)$$

where  $q$  is the electric charge stored in a capacitor with capacitance  $C$ ,  $v_a$  is the electric potential difference across the capacitor and  $i_c$  is the current flowing into the capacitor (Fig.2). The energy storage capability of the electric spring can be seen from the potential electric energy stored in the capacitor:

$$PE = \frac{1}{2} C v_a^2 \quad (4)$$

So the capacitor  $C$  serves as the energy storage element for the electric spring and the voltage  $v_a$  can be considered as the voltage of the electric spring  $V_{ES}$ .

The first paper on electric spring was published in 2012 [16]. Fig. 1 depicts the similarity between a mechanical spring and the simplest form of an ES, in which ES is represented with a voltage block generating a compensating voltage  $V_{ES}$  and connected in series with a noncritical load  $Z_{NC}$ . When the mains voltage  $V_S$  deviates from its reference value  $V_{S\_ref}$ , ES can operate in different modes to restore  $V_S$ . In voltage boosting mode, ES generates a supporting voltage to boost the mains voltage while in voltage suppression mode ES provides a suppressing voltage to reduce the mains voltage. In this way, ES functions as a dynamic voltage restorer damping electric oscillations.  $V_{ES}$  can be generated dynamically by controlling the current in a capacitor as shown in Fig.2.

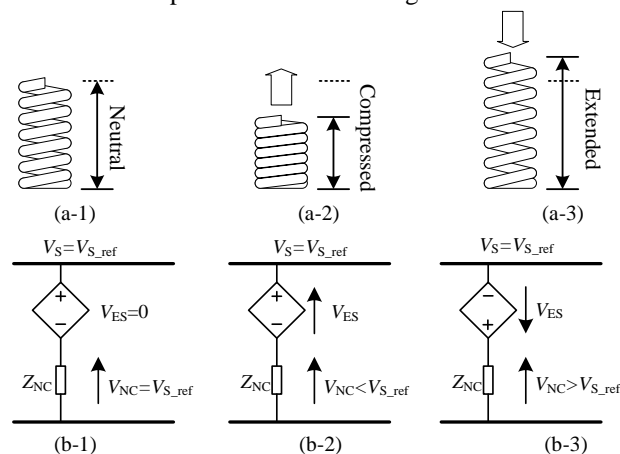


Fig. 1. Similarity between a mechanical spring and an electric spring. (a) Neutral mode. (b) Boosting mode. (c) Suppression mode. [16]

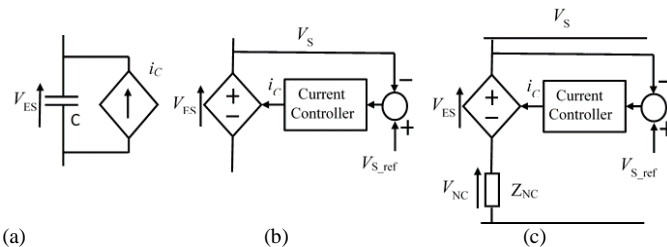


Fig.2 (a) An electric spring in form of a capacitor fed by a controlled current source; (b) Schematic of an electric spring with input-feedforward and input-voltage control; (c) An electric spring in series with a dissipative load for energy storage, voltage support and damping.

Two important points about ES should be noted:

(i) Various forms of ES have emerged over the last few years. The basic form of ES provides a *standard* ac mains voltage well-regulated within its nominal voltage tolerance (e.g.  $\pm 5\%$ ) and an *adaptive* ac mains voltage possibly with a higher voltage tolerance (e.g.  $+10\%/-20\%$ ). In this case, the standard mains will be used for critical loads ( $Z_C$ ) (that require tight voltage regulation) whilst the adaptive mains for noncritical loads ( $Z_{NC}$ ) (that are tolerant to relatively large mains voltage fluctuation).

(ii) However, recent research of ES indicates that, if the adaptive mains voltage is controlled within the nominal voltage tolerance (e.g.  $\pm 5\%$ ), distributed ES can still offer significant active and reactive power compensation as well as virtual inertia for mitigating mains voltage and frequency fluctuation on a power system level [17][84]. In this case, there is no need to differentiate electric loads as critical and noncritical. Readers of this paper should remember this important point, although the following discussions will start by assuming the critical load and noncritical load classification.

For ES technology, the electric load  $Z_{NC}$  in series with the output of the ES. The ES and its associated noncritical load (NCL) can be considered as a type of smart load, which can consume power in an adaptive manner to stabilize the power grid. Such a noncritical load is used for two reasons. Firstly, the NCL voltage  $V_{NC}$  is a necessary component of the dynamic voltage compensation according to Kirchhoff voltage law (KVL) shown in (5).  $V_{ES}$  and  $V_{NC}$  have to change simultaneously in order to maintain  $V_S$  to the nominal value within its tight voltage tolerance. Secondly, NCL consumes controllable power adaptively based on the variation of the output voltage of ES (i.e. the adaptive mains voltage). The NCL power changes adaptively to absorb the fluctuating power generation in order to regulate  $V_S$ . The vectorial relationship of the mains voltage, ES voltage and NCL voltage is:

$$V_S = V_{NC} + V_{ES} \quad (5)$$

Generally, electric loads can be classified into two categories: (i) critical loads (CL), e.g. computers and medical equipment, which require tightly regulated supply voltage and (ii) noncritical loads (NCL), e.g. electric heaters, lighting loads etc. which can tolerate a certain amount of voltage and power variation without significant adverse impact on the loads and consumers. The power consumption of NCL is dependent on its supply voltage. Therefore, it is possible to adjust their power consumption by controlling the voltage. They are suitable candidates to work with ES.

Noncritical loads are widely distributed on the demand side and take a relatively high percentage of electricity usage. The electricity consumption by end-use in Hong Kong [18] in 2016 as shown in Table II reports that thermostatically controlled loads (TCL), which includes HVAC loads (e.g., heating, ventilation, and air-conditioner), electric water heaters, and refrigerators, account for 27% to 57% of total electricity usage in residential, commercial and industrial consumption. Similar

NCL percentage range has been reported in Singapore [19].

Fig.3 illustrates the instantaneous power balancing concept of power supply and demand using the ES technology. The ES regulates the standard AC mains voltage for the CL and its output becomes an adaptive AC mains voltage for NCL. The NCL consume power ( $P_{NCL}$ ) adaptively to follow the fluctuating power generation profile in real time.

TABLE II ELECTRICITY CONSUMPTION BY END USE IN HONG KONG.

End use	Residential	Commercial	Industrial
Cooking	9%	7%	---
Air conditioning	35%	29%	27%
Hot water & Refrigeration	22%	8%	---
Lighting	9%	15%	10%
Equipment	15%	6%	41%
Others	10%	35%	22%

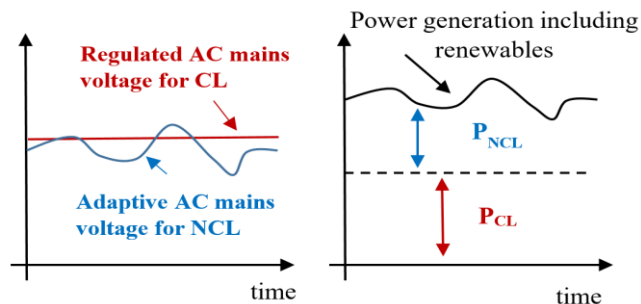


Fig.3 ES technology for balancing power supply and demand

### III. CLASSIFICATIONS OF AC ELECTRIC SPRING

Since the first ES concept appeared in [16], different versions of ES have been proposed. Generally, they can be classified into five categories according to their configurations, namely, (i) the first version of Electric Spring (ES-1), (ii) the second version of Electric Spring with battery storage (ES-2), (iii) ES with bidirectional power flow control of battery having nominal state-of-charge (SOC) of 0.5 (ES-3), (iv) the back-to-back Electric Spring (BTB ES), and (v) ES integrated with photovoltaic (PV) panel and other variants. Single-phase ES versions can also be extended to three-phase ES.

#### A. The first Electric Spring (ES-1)

The original Electric Spring (ES-1) is proposed as a local mains voltage regulator for the power grid with intermittent renewable source generation [20]. Fig. 4 shows a simplified schematic diagram of ES-1 which is implemented with a DC/AC PWM inverter with capacitors,  $C_1$  and  $C_2$ , on the DC link and an LC filter at the output. The PWM inverter can be either a half-bridge or a full-bridge converter. ES-1 and NCL work together as a smart load (SL). In voltage regulation mode, the voltage error between the mains voltage  $V_S$  and its reference  $V_{S\_ref}$  is fed to the ES controller to change the ES voltage  $V_{ES}$  until the mains voltage is regulated at its desired value.

The anti-parallel diodes of the inverter act as a rectifier to provide a DC voltage across the capacitors  $C_1$  and  $C_2$ . ES-1 can

provide reactive power compensation. Therefore, ES-1 voltage vector  $V_{ES}$  must be perpendicular to its current vector  $I_s$  in the ideal case when the power loss of the ES converter is ignored.  $V_{ES}$  can either lead or lag  $I_s$ . Correspondingly, ES-1 operates in two modes consuming different reactive power  $Q_{ES}$ :

- 1) Inductive mode,  $V_{ES}$  leads  $I_s$  by  $90^\circ$  ( $+Q_{ES}$ ).
- 2) Capacitive mode,  $V_{ES}$  lags  $I_s$  by  $90^\circ$  ( $-Q_{ES}$ ).

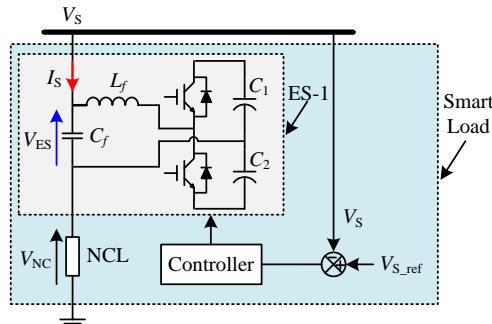


Fig. 4. Schematic diagram of the initial Electric Spring (ES-1) based on Input Voltage Control.

Fig. 5 illustrates the electric vector diagrams of ES-1 in different operation modes with a resistive-inductive NCL.  $\theta_z$  is the load impedance angle. In inductive mode,  $V_{ES}$  leads  $I_s$  by  $90^\circ$  and the NCL voltage vector  $V_{NC}$  is suppressed lower than  $V_s$ . The NCL power is reduced to boost  $V_s$  to  $V_{s\_ref}$ . While in capacitive mode,  $V_{ES}$  lags  $I_s$  by  $90^\circ$  and  $V_{NC}$  is boosted higher than  $V_s$ . NCL power is increased to suppress  $V_s$ .

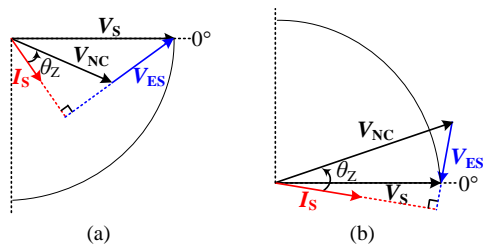


Fig. 5. Vector diagrams of ES-1 in different operation modes. (a) Inductive mode ( $+Q_{ES}$ ). (b) Capacitive mode ( $-Q_{ES}$ ).

In the inductive mode,  $V_{NC}$  can be controlled to be substantially lower than  $V_s$ . In the capacitive mode,  $V_{NC}$  can be controlled to be slightly higher than  $V_s$ . Therefore, besides reactive power compensation, ES-1 has some active power compensation capability for balancing power supply and demand. However, its ability to reduce the active power of NCL is larger than that to increase it. Also, the active power control and reactive power control of the smart load are coupled.

ES-1 has the advantage of system simplicity and has been demonstrated as a fast demand-side management technique for mitigating voltage fluctuations [16][19][21] and both voltage and frequency fluctuations in power grid [22]. Because the switching frequency of the power inverter of the ES is typically higher than 20 kHz, the bandwidth of the LC filter is typically one-tenth of the switching frequency. So the response of ES is very fast and is in the order of milliseconds. Reference [23] confirms that ES-1 can be applied to resistive, capacitive and inductive loads. Although original works of ES-1 were based on the single-phase version, 3-phase ES-1 has been investigated for reducing unbalanced 3-phase power system within a

building [24]. Both single-phase and three-phase ES-1 systems have been evaluated independently by Guangdong Power Company with positive results [25]. The work of ES-1 in [26] and that of BTB ES in [17] show that operating the adaptive ac mains within  $\pm 5\%$  can ensure frequency stability.

### B. The Second Electric Spring with Battery Storage (ES-2)

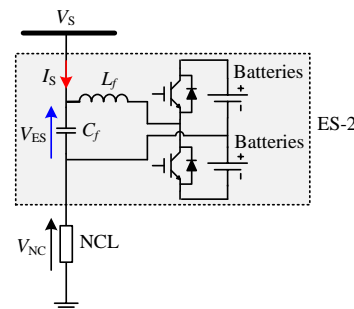


Fig. 6. Schematic diagram of the ES-2 with battery storage and an NCL.

The second generation of ES (ES-2) is reported in [27] to enhance the capability of ES. As shown in Fig. 6, its configuration is the same as that of ES-1 except that batteries are added to the DC link and act as energy storage components. The charging and discharging control circuits of batteries are omitted in the diagram. With batteries on the DC link, ES-2 can compensate active and reactive power independently. The voltage vector of ES-2 is no longer limited to be perpendicular to its current vector. The operation of ES-2 is more flexible compared to ES-1. Besides inductive and capacitive reactive power, ES-2 can also provide positive or negative active power. In general, ES-2 has eight operation modes with different combinations of active power  $P_{ES}$  and reactive power  $Q_{ES}$ :

- 1) inductive power ( $+jQ_{ES}$ ) compensation
  - 2) capacitive power ( $-jQ_{ES}$ ) compensation
  - 3) positive real power ( $+P_{ES}$ ) compensation
  - 4) negative real power ( $-P_{ES}$ ) compensation
  - 5) inductive and positive real power compensation ( $+jQ_{ES}+P_{ES}$ )
  - 6) inductive and negative real power compensation ( $+jQ_{ES}-P_{ES}$ )
  - 7) capacitive and positive real power compensation ( $-jQ_{ES}+P_{ES}$ )
  - 8) capacitive and negative real power compensation ( $-jQ_{ES}-P_{ES}$ )
- where  $j$  refers to an imaginary number.

The vector diagrams of ES-2 in mode-5 to mode-8 are depicted in Fig. 7 (a)-(d) respectively. The NCL is considered to be a resistive-inductive load. ES-2 expands its operating range into four quadrants with a phase difference between  $V_{ES}$  and  $I_s$ . In Fig. 7 (a) and (c) for resistive modes,  $V_{ES}$  leads or lags  $I_s$  less than  $90^\circ$  and  $V_{NC}$  is suppressed. ES-2 absorbs active power and batteries are charged. For negative resistive modes in Fig. 7 (b) and (d),  $V_{ES}$  leads or lags  $I_s$  more than  $90^\circ$  and  $V_{NC}$  is boosted. ES-2 generates active power and batteries are discharged. Compared to ES-1, even in the case of purely resistive NCL, NCL power can be increased or decreased with the use of ES-2.

It is important to note that the suppression of  $V_{NC}$  does not necessarily result in the reduction of total active power and the boost of  $V_{NC}$  does not ensure the increase of total active power.



For example, in Fig. 7 (c)  $V_{NC}$  is suppressed and the active power of NCL is reduced. Meanwhile, ES-2 absorbs more active power than the power reduction of NCL. As a result, the total active power of the smart load increases even though the power of NCL decreases. On the contrary, in Fig. 7 (b)  $V_{NC}$  is boosted and the active power of NCL is increased. At the same time, ES-2 delivers more active power and some of the active power is fed back to the grid. So the total active power is reduced while NCL power of NCL increases.

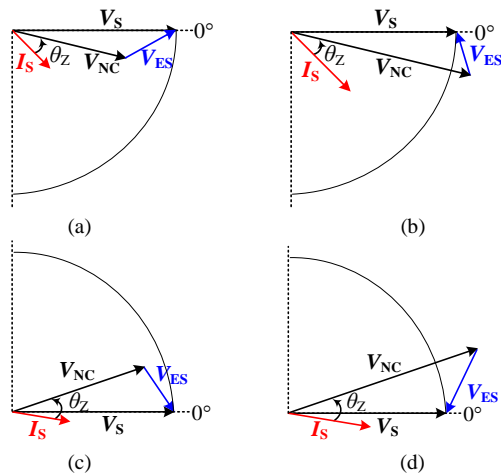


Fig. 7. Vector diagrams of ES-2 in different operation modes. (a) Inductive plus resistive ( $+Q_{ES} + P_{ES}$ ) mode. (b) Inductive plus negative resistive ( $+Q_{ES} - P_{ES}$ ) mode. (c) Capacitive plus resistive ( $-Q_{ES} + P_{ES}$ ) mode. (d) Capacitive plus negative resistive ( $-Q_{ES} - P_{ES}$ ) mode.

Benefiting from the use of batteries, ES-2 can perform independent active and reactive power compensation in four quadrants. Both NCL power and the total power depends on ES-2. Different from ES-1, the total active power and reactive power of load associated with ES-2 can be controlled independently. The additional flexibility of ES-2 is realized at the expense of the batteries and auxiliary circuits. However, if distributed energy storage is considered as part of future smart grid strategy, the use of distributed ES-2 will form a simple solution to cope with primary frequency control in the power grid. Research sponsored by State Grid of China [28] indicates that distributed ES-2 can be used to optimize the operations in a distribution network such as reducing losses and achieving voltage regulation.

### C. Electric Spring based on Bidirectional Converter and Coordinated Battery Management Control (ES-3)

ES-2 can further be modified by using a coordinated battery management scheme in association with a bidirectional AC/DC converter as shown in Fig. 8. Due to the limited capacity and lifetime of a battery, it is necessary to consider the state-of-charge (SOC) variation so that the battery will not be overcharged or over-discharged. This third version of ES [29] has two distinct differences from ES-2. Firstly, ES-3 does not need to work with NCL. Secondly, the SOC of the battery is set nominally at 0.5 so that the battery has the capacity to either absorb or release energy within a range of SOC that can preserve battery life. Second-life batteries can be reused for this purpose.

In the control scheme, an instant SOC signal ( $SOC_f$ , which is normalized from 0 to 1) is introduced. A SOC reference of  $SOC_{ref} = 0.5$  is set as a long term target to maintain the battery at 50% SOC so that it is readily available to either absorb or deliver the active power for the power grid regulation purpose. There are two factors to determine the active power reference of the ES-3, namely  $P_f$  and  $P_{SOC}$ .  $P_f$  is a signal that controls the amount of active power delivered or adsorbed for the regulation of utility frequency while  $P_{SOC}$  is a signal that controls the SOC of the battery storage system.

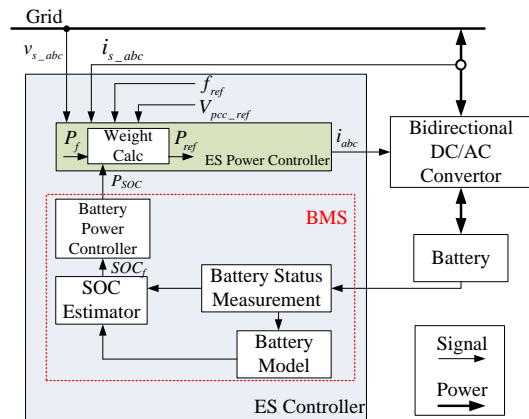


Fig. 8 Schematic of ES-3 with coordinated battery management control with the need for a NCL [29]

The actual active power reference signal  $P_{ref}$  is the weighted sum of these two signals. Hence,

$$P_{ref} = aP_{SOC} + (1 - a)P_f \quad (6)$$

where  $a$  is the weighted factor. The adaptive weighted factor  $a$  provides a way to coordinate between the battery management and the frequency regulation process, which is defined as a function depending on the absolute SOC error signal ( $SOC_e = SOC_{ref} - SOC_f$ , i.e. the deviation between the SOC reference and the instant SOC status). It can be expressed as

$$a = f(k, |SOC_e|) = \frac{e^{2k|SOC_e|} - e^{-k}}{1 - e^{-k}} \quad (7)$$

where  $k$  is a parameter which determines the profile of  $a$  as shown in Fig. 9. This function ensures that the charging and discharging of the battery can be performed exponentially in a way that the charging/discharging rate is relatively faster when the absolute SOC error is large while it is slower when the instant status of the SOC approaches the reference value  $SOC_{ref}$ . The choice of  $k$  depends on the configuration of the system and the design requirements. A higher value of  $k$  results in a wider range of the SOC error, as well as a more aggressive charging/discharging manner when the SOC is getting closer to the upper and lower limits of the working region. The proposed method not only provides an adaptively weighted priority between the mitigating of grid fluctuation and maintaining the storage system within the healthy SOC range, but also avoids abrupt change of output power for SOC control during transient operations. For ES-3, the SOC of the battery will be controlled gradually back to 0.5 after the stability of the mains voltage and/or frequency has been regained.

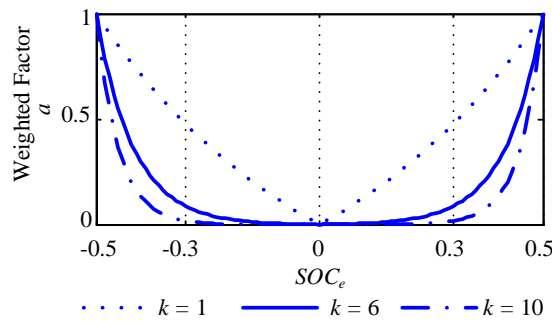


Fig. 9. The weighted factor  $a$  versus the  $SOC_e$  with different values of  $k$ .

#### D. Back-to-Back Electric Spring (BTB ES)

The back-to-back converter topology can be incorporated into ES technology as the bidirectional DC-AC power converter to form the BTB ES [30][31] in order not to use any battery in the DC voltage link. Fig. 10 (a) shows the schematic diagram of BTB ES. It consists of two PWM converters sharing a common DC voltage bus. One is a half-bridge converter with an LC filter. Its output is connected in series with NCL through an isolation transformer. The other is a half-bridge converter directly connected to the mains through an LCL filter. Fig. 10 (b) shows the equivalent circuit of BTB ES which consists of a series ES and a shunt ES.

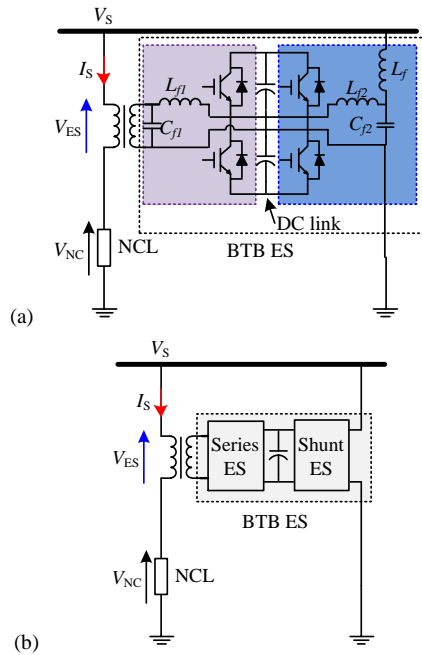


Fig. 10. Schematic diagram of BTB ES. (a) Circuit diagram of BTB ES. (b) Equivalent Circuit of BTB ES.

Compared to ES-2, BTB ES uses an additional shunt ES to replace the batteries on the DC link. The series ES operates in the same way as ES-2 and provides independent active and reactive power in four quadrants. Through changing the output of the series ES, NCL power can be changed. The shunt ES is used to balance the active power exchange between the series and shunt ES to maintain a constant DC voltage. Without the limitations of batteries, the operating range of BTB ES is greatly extended. An isolation transformer is necessary to decouple the output of the series and shunt converters of the

original BTB-ES as shown in Fig.10. However, a recent research paper [32] confirms that the bidirectional power converter of the BTB-ES can be formed with a three-phase power inverter module without the need for an isolation transformer. This new circuit has a similar operating range with that of the original BTB-ES, but has the advantages of high compactness, low cost and no transformer power loss.

#### E. Other ES variants

##### 1) PV-ES:

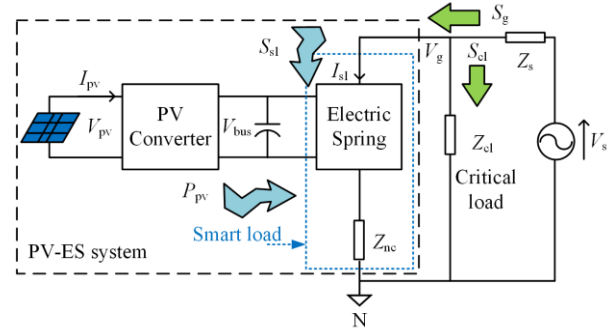


Fig.11 A simplified schematic of a PV-ES system [33] (IEEE copyright)

In addition to the above four ES, there are other ES variants, there are other ES variants. One ES variant integrating Photovoltaic (PV) panel and Electric Spring (PV-ES) has been reported in [33] and [34]. Its schematic is shown in Fig. 11. Energy is harvested by the PV system, the dc output of which is connected across the DC link capacitor of the DC voltage link of the ES. As pointed out in [27], the DC voltage source used in ES-2 allows decoupled active and reactive power control. The availability of the DC voltage source provided by the PV converter can play the same role and also allows the solar power flow via the PV converter. The concept of PV-ES is later generalized to link the ES with a range of renewable energy sources in [35].

##### 2) Three-phase ES:

Three-phase ES has been explored for reducing power imbalance [36] and conduction loss of circulating current [37] in the three-phase power system of a building (Fig.12). It is also used for extra functions such as active power filter in [38]. For distribution lines with relatively high resistance, a three-phase nine-switch matrix power converter (Fig.13) has been evaluated [39]. It allows the three-phase ES-1 to exchange bidirectional active power with the grid and perform the critical load voltage compensation with a minimal magnitude of injected voltage. Also, it relaxes the limitation of the quadrature relationship of the ES voltage and current.

The ES variants are derivatives of the four ESs (e.g., ES-1, ES-2, ES-3 and BTB ES) which demonstrate the basic structures of ESs. A comparison between the basic ES versions in terms of configuration, power controllability, and operating range is conducted and summarized in Table III. Generally speaking, more components an ES has, more flexibly it provides. ES-1 has the simplest configuration with the least components while its power controllability and operating range are limited. Energy storage components like batteries enable ES-2 to operate flexibly with decoupled P & Q power control

but increase the cost and weight. ES-3 works primarily with energy storage and can be independent of NCL, although its coordinated control with NCL power control can reduce the energy storage requirement. The trend of increasing acceptance of distributed energy storage favors ES-2 and ES-3. BTB ES has the highest operating range without batteries. Its latest version can function without an isolation transformer [32]. While most of the ESs reported so far use voltage-source inverter, the use of a current source inverter is also a possibility [40].

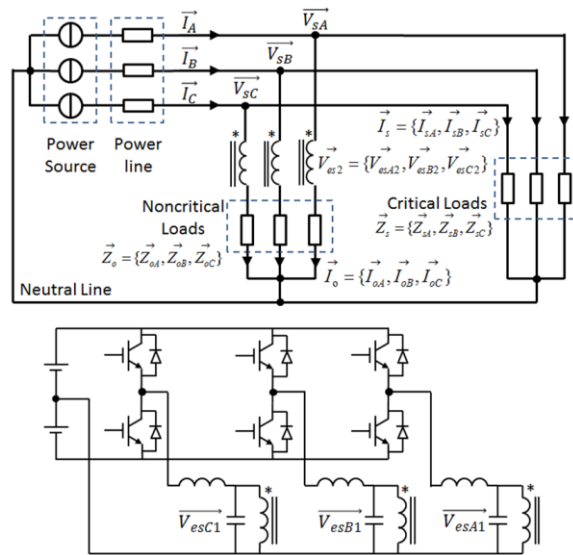


Fig.12 Schematic of a 3-phase ES-2 [24] (IEEE copyright)

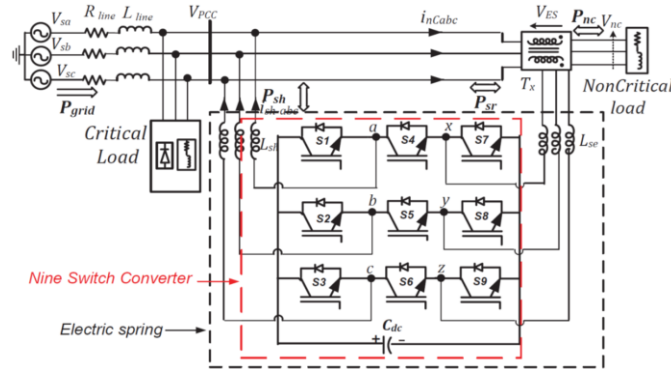


Fig.13 Schematic of a 3-phase E-1 based on a nine-switch matrix converter [39] (IEEE copyright)

It is important to note that the selection of ES topologies should depend on application requirements. ES-1 system is a good choice when space, weight and cost are critical issues. The performance of ES-2 system is comparable to BTB ES system while the power handling capacity of ES-2 is smaller than BTB ES. The transformer-less and lightweight design of ES-2 makes it compact and suitable for integration with PV panels. BTB ES system is able to provide outstanding performance while space and weight are not critical issues. The above information provides a basic guideline for engineers to design their ES systems according to different specifications.

TABLE III COMPARISON OF ESS.

ES versions and variants	No. of converters	Battery	Transformer	Power controllability	Operating range
ES-1	1	No	No	Coupled	Smallest
ES-2	1	Yes	No	Independent	High
ES-3	1	Yes	No	Independent	High
BTB ES	2	Yes	No with new version [32]	Independent	Highest
PV-ES	1	No	No	Coupled	Medium
3-phase ES-2	3	Yes	Yes	Independent	High
Matrix Converter ES	1	No	Yes	Independent	High

### F. Comparison between ES and D-FACTS

FACTS devices have been applied as power electronic-based systems to improve the capability and stability of the power grid for at least 2 decades. While both ES and FACTS devices are based on power converters, ES is different from FACTS at least in three aspects. (i) FACTS are typically installed on the transmission level in a centralized form while ESs are deployed in the distributed network (although some FACTS can be installed on the distribution level as D-FACTS). (ii) FACTS are controlled to regulate their ‘output’ voltages at points of connection regardless of the input change. Each ES adopts ‘input’ control to maintain the input voltage (i.e. the ac mains voltage) and let the output voltage fluctuate. (iii) Most ESs are operated with NCL to form smart loads. They work together to contribute the active and reactive power compensation. Even without battery on its DC link, ES-1 and BTB ES with NCL can still provide active power compensation. Table IV tabulates some differences between ES and D-FACTS.

Table IV Comparison of ES and DVR/D-STATCOM

Configuration	ES	DVR/D-STATCOM
Series		
Shunt		
Series-Shunt		

A comparative case study conducted in [41] to control the voltage using ES and D-STATCOM reveals that a group of distributed ESs achieve better voltage regulation at various buses with significantly less total reactive power capacity than D-STATCOM. D-STATCOM can only tightly regulate the voltage at the point where it is installed. The effectiveness of distributed ES also depends on the noncritical loads. The higher the portion of the noncritical load, the higher the ability for voltage control.

#### IV CONTROL OF ELECTRIC SPRING

The control methods applied for ES in the distributed network are generally classified into two types.

##### A. Control of Single ES

###### 1) Basic voltage control

The initial ES (ES-1) is proposed to mitigate the voltage fluctuation caused by intermittent renewable source generation [16]. The basic voltage control diagram of ES-1 is illustrated in Fig. 14. To regulate the mains voltage, the voltage error between  $V_S$  and its reference  $V_{S\_ref}$  is fed to a proportional-integral (PI) controller to produce the magnitude of ES voltage  $|V_{ES}|$ . Meanwhile, to maintain a constant DC voltage, the DC voltage error is used to adjust the phase of ES voltage  $\theta_{ES}$  through another PI controller.

In practice, the ES voltage is not strictly perpendicular to its current because a small amount of active power should be consumed to meet the power loss of the ES converter. With obtained magnitude and phase information, one can get the desired ES voltage reference  $V_{ES\_ref}$  and generate the PWM signal. This is a very simple method directly derived from the initial idea of ES-1 and easy to be implemented practically. Even  $|V_{ES}|$  and  $\theta_{ES}$  are controlled by two control loops, they are inherently correlated. Each  $|V_{ES}|$  has only one corresponding  $\theta_{ES}$  and the active and reactive power are coupled together.

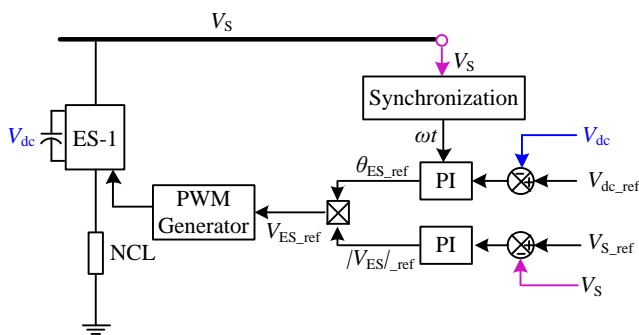


Fig. 14. Basic voltage control diagram for ES-1 [16]

###### 2) dq control

For ES-2 with diversified operation modes, its controllability is also enhanced. A dq control method can be used to decouple the active and reactive power control, which is based on the direct-quadrature (dq) transformation as shown in (7) [42]. A sinusoidal quantity could be decomposed into a direct and quadrature components. Taking  $V_S \angle 0^\circ$  as the synchronized direct axis reference, the current of the smart load will be

decomposed into active and reactive currents.

$$\begin{cases} d = \frac{2}{T} \int_{T_n}^{T_{n+1}} A \sin(\omega t + \theta) \sin(\omega t) dt = A \cos \theta \\ q = \frac{2}{T} \int_{T_n}^{T_{n+1}} A \sin(\omega t + \theta) \cos(\omega t) dt = A \sin \theta \end{cases} \quad (7)$$

A dq controller for ES-2 is illustrated in Fig. 15, which can regulate the mains voltage and control the power angle of the smart load simultaneously. The mains voltage  $V_S$  is controlled by adjusting the current of the smart load. With desired power angle  $\theta_S$ , both the reference current  $I_{S\_ref}$  and the feedback current  $I_S$  are decomposed into  $d$  and  $q$  components and sent to independent  $d$  and  $q$  control loops to generate the ES voltage reference. This method decouples the active and reactive power control through dq transformation. It can be used for harmonics reduction and extended to BTB ES and three-phase ES as well. The disadvantage is that it uses three PI controllers and increases the control complexity.

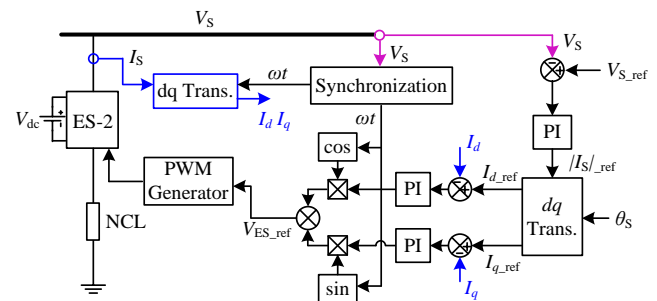


Fig. 15. dq control diagram for ES-2.

###### 3) delta control

Fig. 16 shows the  $\delta$  control for ES-2 to regulate the mains voltage by controlling the phase angle  $\delta$  that local mains voltage lags the generator voltage [43]. With  $\delta$  obtained through the  $\delta$  control block, the local mains voltage reference  $V_{S\_ref}$  is generated and sent to a PR controller to get the current reference  $I_{L\_ref}$  for the inner current loop which controls the inductor current  $I_L$  of ES converter.

With  $\delta$  control, ES-2 takes different types of NCL into consideration and automatically determines its operation mode. However, the  $\delta$  control block requires all the parameters of the system including the impedance of CL and NCL, the impedance of transmission line, the generator voltage and the local mains voltage. Such information is usually unavailable in practice.

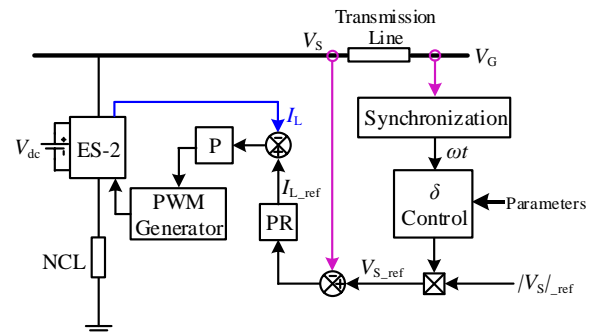


Fig. 16.  $\delta$  control diagram for ES-2.



#### 4) RCD control

Another control scheme for ES-2 is called radial-chordal decomposition (RCD) control in which ES voltage is decomposed into a radial component  $V_{ESR}$  and a chordal component  $V_{ESC}$  as shown in Fig. 17 [44]. Different  $V_{ESR}$  results in different load voltage  $V_{NC}$ . Consequently, the current and apparent power of the smart load change with  $V_{ESR}$ . As for  $V_{ESC}$ , it determines the power angle  $\theta_o$  between the mains voltage  $V_s$  and the load voltage  $V_{NC}$ . The power angle of the smart load  $\theta_s$  can be obtained using  $\theta_s = \theta_o + \theta_z$ .

Fig. 18 depicts the RCD control scheme for ES-2. The mains voltage  $V_s$  is regulated by changing  $V_{ESR}$  through a PI controller. The power angle of the smart load  $\theta_s$  is controlled by changing the power angle  $\theta_o$ . Then, the radial and chordal components of ES voltage can be obtained through the RCD control block. RCD control decouples voltage and power angle control and greatly simplifies the control. Compared to  $dq$  control, only one PI controller is needed when the load impedance angle  $\theta_z$  is known.

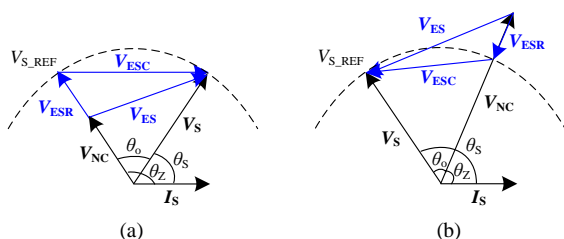


Fig. 17. Phasor diagram of RCD. (a)  $V_{NC}$  leading  $V_s$ . (b)  $V_{NC}$  lagging  $V_s$ .

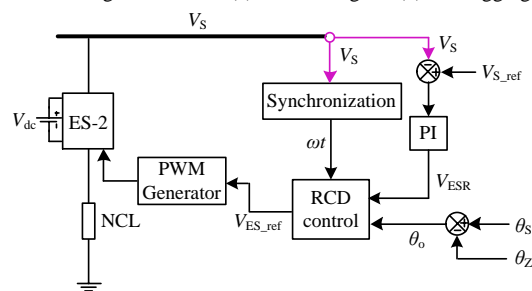


Fig. 18. RCD control diagram for ES-2.

#### 5) Modified Simple Power Decoupling (SPD) method

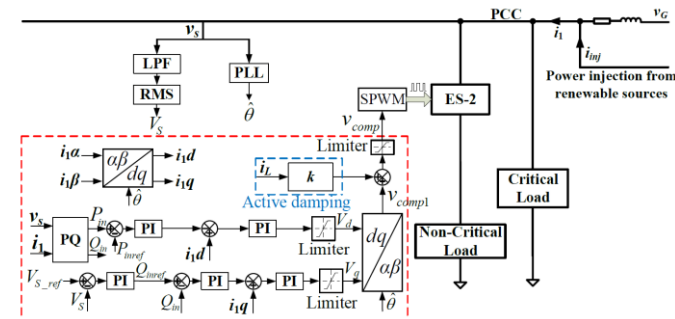


Fig. 19 Schematic of the modified SPD scheme [45] (IEEE copyright)

The initial SPD method [44] has several limitations that key members of the same research group published a modified SPD method in [45]. The modified SPD control scheme is designed without needing the values of circuit parameters and simultaneously offering a faster transient response over the original SPD scheme. It is achieved by using two current loops

that regulate the line current drawn by the load on the d-axis and q-axis separately as shown in Fig. 19. An active damping control is needed in this scheme. Despite that the circuit parameter values are not needed, this modified SPD method requires the ES output current in the control scheme to achieve a damped response. The authors of [45] stress that this control cannot work effectively without the ES output current information.

#### B. Control of a Group of Distributed ES

All control methods described previously are applied to a single ES. The contribution of a single ES is limited due to its limited power capacity. Similar to the array of mechanical springs under a mattress, a large group of distributed ES can be installed in the distribution network for providing robust stability support for the power grid. For now, there are two types of control methods introduced for distributed ES to enhance their effectiveness, namely, droop control and consensus control.

##### 1) Droop control

Droop control is widely used for traditional power generators cooperation [46][47]. The droop concept is firstly applied to multiples ES-1 in [48] for voltage control and prevents competition among ES at the same time. The mains voltage reference  $V_{Sx\_ref}$  for the ES installed at the distance  $x$  is automatically adjusted by a droop constant so that the ES far away from generation will not be overload.

Another droop control method for BTB ES is proposed for voltage control in [49]. As shown in Fig. 20, the mains voltage references for all ES are the same, but the voltage error is updated by the active and reactive power change of smart load. Droop gains  $D_{VP}$  and  $D_{VQ}$  are designed to share the droop effect between active and reactive power. Updated voltage error is fed to a PI controller and weighted to derive the required active and reactive power change of the smart load ( $\Delta P_s$ ,  $\Delta Q_s$ ). Then the smart load model can be used to calculate the required ES voltage. This idea can also be applied to frequency regulation [50] in which only one droop gain ( $D$ ) is used to update the frequency with the active power change of smart load.

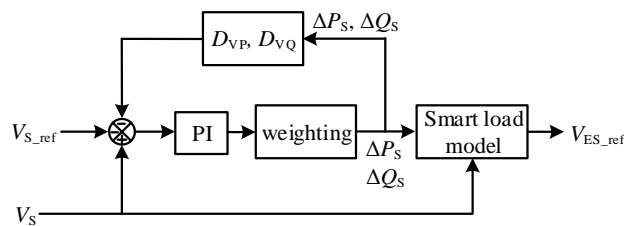


Fig. 20. Droop control for distributed smart load using ES.

Droop control modulates the nominal value of the voltage reference (e.g. 1.0 pu) to share the burden and thus ensure that ESs do not fight against each other. However, droop gains are highly dependent on the resistance/reactance (R/X) ratio of the network and the location of ES. Therefore, it is difficult to tune the droop gains. Good cooperation and work sharing are barely acceptable without reasonable droop gains and control structure.

## 2) Consensus control

The consensus algorithm is also commonly used for multi-agent systems and has been introduced to control generators, plug-in electric vehicles, and energy storage systems in the power grid [51]-[53]. It is applied to multiple ES and practically verified for the first time in [54]. The basic idea is each ES behaves as an agent and shares its local information state with neighboring ES agents. Through an appropriate algorithm, each ES acts to update its information state so that the information states of all the ES converge to a consensus. In Fig. 21, the local information is the reactive power  $Q_{ES}$  of each ES. There are three ES in the network, and they share the information of  $Q_{ES}/Q_{ES\_MAX}$  with their neighbors. The consensus algorithm is designed to regulate the mains voltage with equal reactive power sharing which generates a compensation adjustment value to the primary voltage set point.

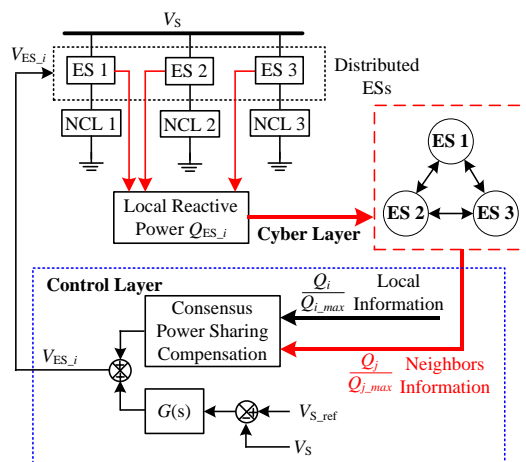


Fig. 21. Consensus control of distributed ES for voltage regulation.

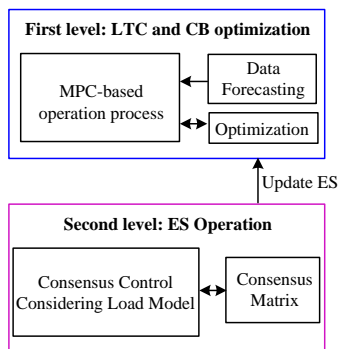


Fig. 22. Two-level voltage control scheme using ES.

Consensus control is also introduced to enable distributed ES to achieve voltage and frequency regulation with sharing active and reactive power respectively in [22]. Compared to droop control, consensus control can accurately control the responsibility of each ES. These two methods are complementary and used together for voltage control. Fig. 22 shows a two-level voltage control scheme is developed to optimize critical bus voltage at chosen locations [55]. The upper level adopts a model predictive control (MPC)-based method to determine the optimal cooperation of load tap changer (LTC) and capacitor banks (CB). Then, in the lower level, critical bus voltage is regulated through responsibility sharing among ES

via consensus control. In case of communication failure, either the droop control or the top-level control could act as a safety guard to ensure safe operation.

The outstanding feature of consensus control is that responsibility sharing with high consistency can be implemented. However, local communication is necessary for consensus control. The time delay and coupling strength between neighboring agents need careful consideration to ensure stability and satisfactory convergence rate, especially when the number of agents increases. Recently, the droop control and consensus control are practically implemented in real-time in a distributed ES system [56]. When the cyber layer is in normal condition, consensus control takes actions for the distributed ES to provide voltage and frequency stability. When the cyber layer is attacked or not available, the control will be reverted to droop control.

All the control methods for ES are classified into two categories and summarized in TABLE V. Basic voltage control,  $dq$  control,  $\delta$  control, RCD control and modified SDP control are developed to control single ES while droop control and consensus control are designed to coordinate a group of distributed ES.

TABLE V SUMMARY OF CONTROL METHODS FOR ES.

Category	Control method	Application	Features
Single ES	Basic voltage control	ES-1 Matrix Converter ES	Simple PQ Coupled
	$dq$ control	ES-2 BTB ES 3-phase ES-2	PQ decoupled
	$\delta$ control	ES-2	Difficult implementation
	RCD control	ES-2 PV-ES	PQ coupled
Distributed ES	Modified SDP	ES-2	PQ decoupled
	Droop control	All ES	Droop gain No communication
	Consensus control	All ES	Responsibility sharing Local communication

\*PQ-Active and reactive power

## IV. DC ELECTRIC SPRINGS IN DC MICROGRIDS

The proliferation of the information and communication technology (ICT), electric vehicles and energy storages has led to the growing use of DC appliances. This makes the DC microgrids increasingly feasible in delivering cost-efficient electricity than its AC counterparts. Meanwhile, the industries are replacing their energy sources with renewables for reducing the greenhouse gas emission so as to alleviate the global warming issue. Multinational corporations such as Facebook, Microsoft, Apple and Google, have committed to achieve “100% renewables” in their global operations of data centers, cloud services, manufacture, and etc. Spurred by growing interest on the migration of AC power systems to DC power systems, the DC Electric Springs (DCES) was proposed as a means to tackle the possible instability issues of the DC power systems and

microgrids, in relation to the use of more intermittent renewable resources. With respect to the recent research findings on DCES, the physical operating principles, hardware circuit topologies, control and applications of the DCES will be summarized in this section.

### A. Series and Shunt DCES

A typical unipolar DC grid integrated with the DCES is depicted as shown in Fig. 23. Under such a configuration, the supply-demand power imbalance, the relatively long-distance (low-voltage) power delivery through distribution lines, the possible occasional faults (e.g. faults  $F_L$  and  $F_U$  in Fig. 22), and the integration of appliances with harmonic pollution sources (e.g. single-phase AC-DC conversion) to the DC grid, can potentially render the voltage instability issues of (i) DC voltage variation, (ii) voltage droop, (iii) voltage flicker and (iv) harmonic voltage, of which the corresponding waveforms are illustrated as shown in Fig. 24. Irrespective of its hardware circuit topology, the DCES is essentially a decentralized demand-side management (DSM) unit, which is massively scattered in DC power systems, such as that shown in Fig. 23 for addressing the aforementioned instability issues in a distributed manner [57].

The DCES can be categorized into series and shunt types. The basic configuration of the series type DCES in a DC grid is shown in Fig. 25. In terms of circuitry, it is a controllable bipolar voltage source which is connected in series with a non-critical load (NCL). Similar to the AC counterpart, such a configuration enables a smart load branch. The active attenuation of the smart load power can be achieved by adjusting the voltage of DCES. The power quality of the critical loads (CL) can be guaranteed with the smart load compensating these voltage instability issues. The general operating principles of the series type DCES is firstly reported in [57], in which the steady-state operating modes of the series type DCES associated with (i) positive constant-resistive loads, ii) negative constant-resistive loads, iii) positive constant-power loads, and iv) negative constant-power loads have been analysed, respectively.

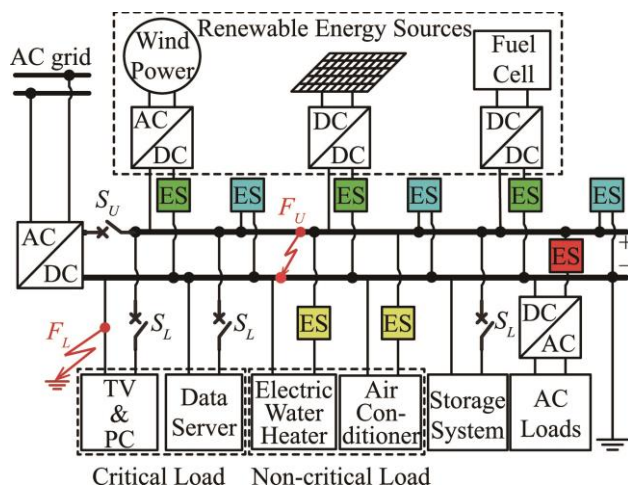


Fig. 23. A DCES-integrated unipolar DC grid.

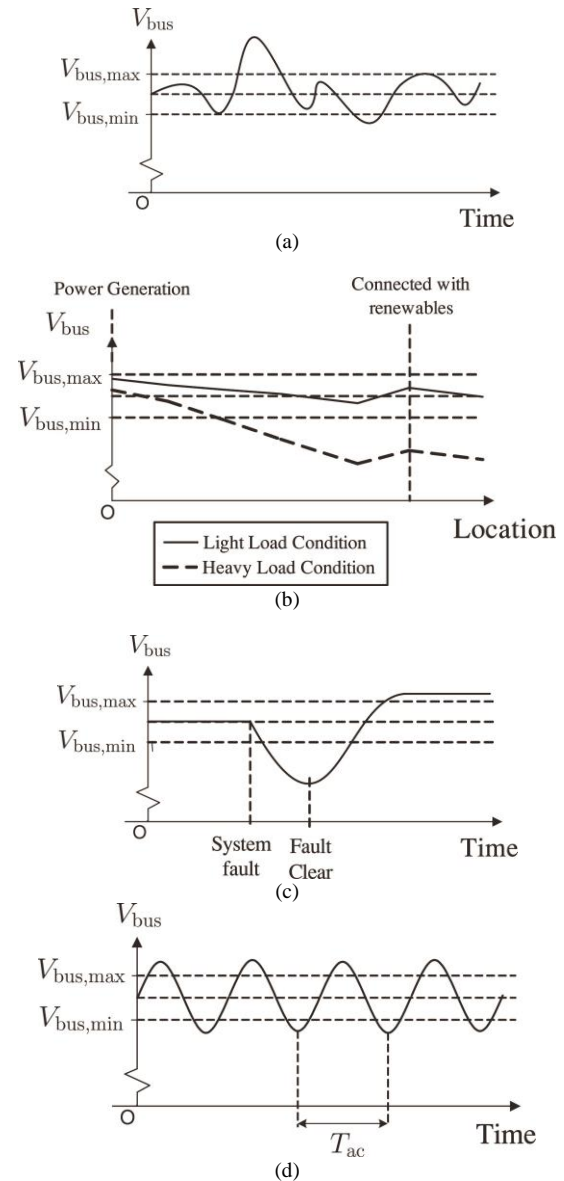


Fig. 24. Different voltage issues in DC power systems. (a) DC voltage variation, (b) droop effect, (c) voltage flicker and (d) harmonic voltage.

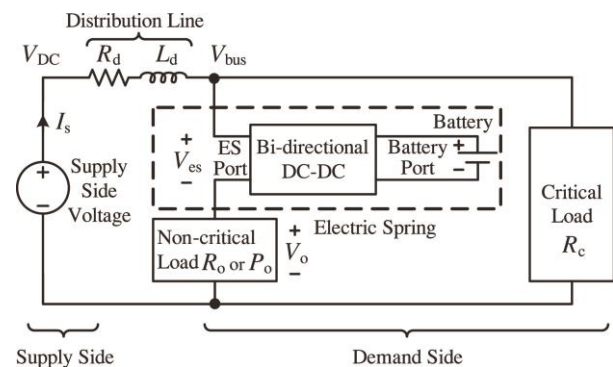


Fig. 25. Basic configuration of the series type DCES.



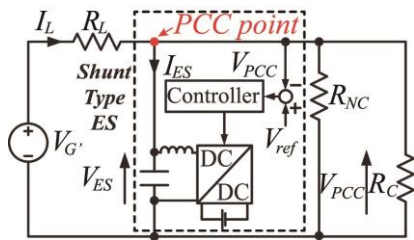


Fig. 26. Basic configuration of the shunt type DCES.

In the event that the appliances of DC microgrids are generally critical, i.e., few NCL can be connected to the series type DCES, the shunt type DCES can be alternatively used for the bus voltage regulation. The basic circuit model of a shunt type DCES incorporated to the DC grid is illustrated in Fig. 26. The shunt type DCES is essentially a controllable bidirectional current source. It is directly connected to the DC bus and does not associate with any NCL [58]. In [58], a systematic comparative study is performed between the series and shunt type DCES. With respect to different applications, the advantages and disadvantages of both types of DCES are summarized as shown in Table VI.

TABLE VI COMPARISON OF SERIES- AND SHUNT-TYPE DCES

	Series Type	Shunt Type
<b>Dynamic response</b>	× Slow × NCL-dependent	√ Fast
<b>Supply-demand balancing</b>	√ Real-time load manipulation √ Storage reduction	× Incapable of load manipulation
<b>Harmonic cancellation</b>	× Power consuming × NCL-dependent	√ Consume little power
<b>Providing fault-ride-through support</b>	× Slow × Affect NCL	√ Fast

### B. Hardware Topology of DCES

In the reported research works [57] and [58], the half- and full-bridge DC-DC converters are applied to achieve the DCES functions. These conventional circuit topologies provide a coupled relationship between the harmonic power and DC power of the DCES batteries in the concurrent operations of supply-demand balancing and harmonic cancellation. This can lead to a low energy efficiency and a short lifetime of the batteries. In [59], a hybrid DCES (H-DCES), which is essentially a DC-split full-bridge DC-DC converter, is proposed to address this issue.

The schematic diagrams of the H-DCES and the corresponding equivalent circuit are shown in Fig. 27. Compared with the series-type (Fig. 24) and shunt-type (Fig. 25) ES, the H-DCES has a split DC-link capacitor branch, which bypasses the DC-link batteries and the NCL from the harmonic current path. The harmonic power and DC power can be stored in split DC-link capacitors and batteries, separately.

Besides this non-isolated topology of H-DCES for achieving the decoupling of the harmonic and DC powers, a three-port isolated topology of DCES (Fig.28) has been reported in [60] for isolating the DC power supply, NCL and CL. The circuit topology comprises a three-port isolated dual active full-bridge

DC-DC converter and a bidirectional boost converter (BBC). The DC power supply, NCL and CL are connected to the three ports, respectively. The batteries are connected to the CL via the bidirectional boost converter. Essentially, the NCL is operated to consume the disruptive part of the renewable DC power supply, while the batteries are controlled to compensate the power imbalance between the loads and the DC power supply. Although the power flows of NCL, CL and DC power supply can be independently controlled in this topology, it involves the use of considerable power electronics, i.e. 14 active switches and a high-frequency three-port transformer.

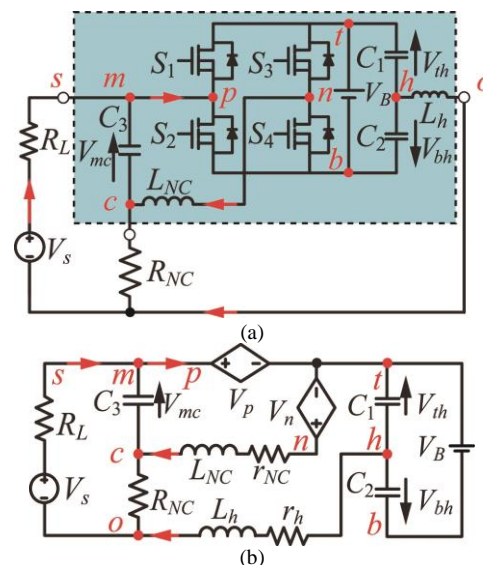


Fig. 27. Schematics of (a) H-DCES and (b) the corresponding equivalent circuit.

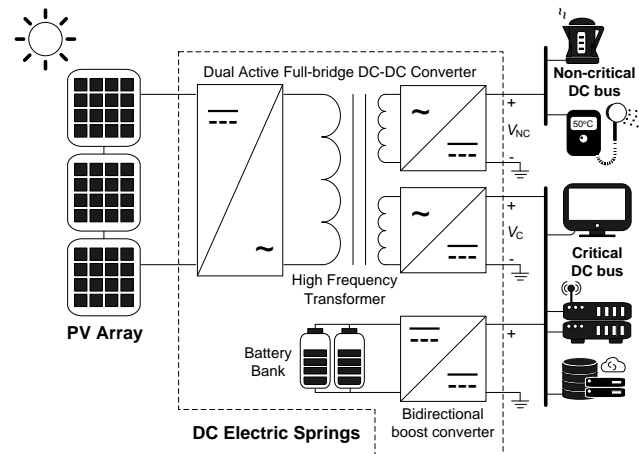


Fig.28 Schematic of a three-port DCES system [60] (copyright IET)

### C. Control and Application of Multiple DCES

The schematic diagrams of a DC distribution grid and a series-type DCES integrated DC microgrid are shown in Fig. 29(a) and (b), respectively. In order to achieve the cooperative and optimum operation of the DC power grid, the centralized, decentralized and distributed control methods can be applied to various DCES in the system.

In [61], a centralized model predictive control scheme is proposed to operate the series-type DCES in DC distribution grids. In this work, a dual-objective cost function is formulated to minimize the nodal bus voltage deviation and the distribution



line loss. In the prediction of the optimum bus voltage references, the nodal voltages are discretized for enabling an enumerative evaluation of the penalty cost. Then, the series-type DCES will be operated by the local voltage controller to regulate the nodal voltage according to the calculated voltage reference. Although this centralized method can achieve a reasonably guaranteed global optimal condition, it demands synchronized measurements, real-time data communication and a significant amount of computation. Considering the cost of the communication infrastructure, this method may be more suitable for small distribution systems rather than large ones.

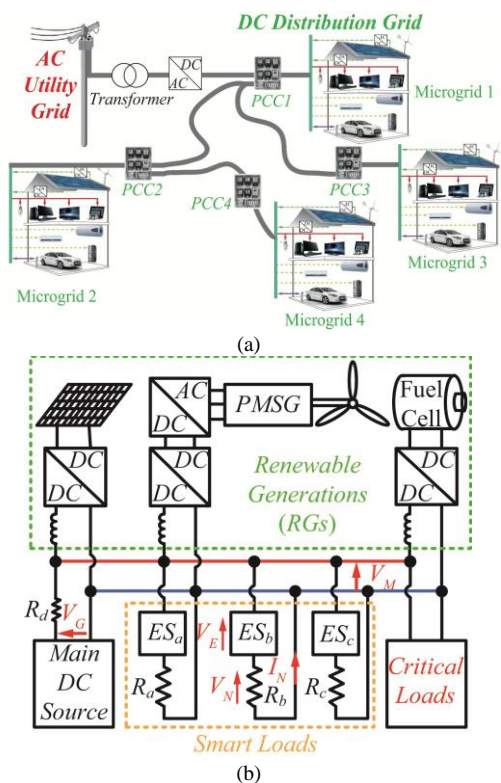


Fig. 29. Illustration of (a) a DC distribution grid and (b) a DC microgrid integrated with multiple series type DCES. [62]

In order to regulate the bus voltage against the intermittent renewable generation with reduced storage capacity, a decentralized droop control scheme is proposed in [62] for coordinating the operation of multiple series-type DCES in DC microgrids. The investigated system topology is shown in Fig. 29(b). In this work, the smart load branches share a common DC bus. The proposed droop control scheme can operate the series type DCES to achieve the minimum charging and discharging power to cope with the voltage sag and overvoltage, respectively. In this way, the overall energy deviation of the DCES batteries, as well as the required storage capacity, can be reduced. This method is practical and independent of the communication network. However, it cannot eliminate the DC bus voltage deviation. The line impedance between different series-type DCES will affect the performance of the controller. In [63] and [64], a distributed cooperative control scheme is applied on the three-port DCES [60] and the shunt-type DCES to achieve the unanimous regulation of bus voltages and battery states of charge (SOC). This control scheme consists of a primary droop controller and a secondary consensus controller.

With local and neighbouring measurements, this control scheme eliminates the impact of line impedance on the load sharing of DCES and the bus voltage regulation. Thus, it has a better voltage regulation than the conventional droop control scheme and a lower requirement on the communication system than the centralized control scheme, which makes it suitable for implementation in large power systems.

Besides the applications of DCES in unipolar DC grids, the unbalanced voltage suppression of the DCES in bipolar DC distribution grids is reported in [65]. In the work, the coupled relationship between the positive-pole and negative-pole voltages are mathematically derived and it is demonstrated that the investigated DCES-integrated bipolar DC grid is a coupled two-input-two-output system. In order to enhance the dynamic performance of the system in restoring the respective pole voltages and reducing the neutral current, decoupling control variables are introduced and fed forward to eliminate the coupling between the two control inputs. With this decoupling control method, the original two-input-two-output system is transformed into two independent single-input-single-output systems.

## V. SYSTEM-LEVEL IMPACT

A precursor to studying the system-level impact of ES is to develop its dynamic model which is compatible with large-scale power system simulation model. Modelling of ES for power system studies is discussed first in this section followed by its effectiveness towards voltage regulation, frequency control, power quality improvement, system restoration and also impact on stability.

### A. Modelling of ES for System Studies

A dynamic simulation model of ES appropriate for voltage and frequency control studies at the power system level is reported in [66]. The case studies show a close match between simulation and experimental results confirming the accuracy of the proposed model. Slight discrepancies are attributed to the absence of the DC link voltage control loop which, if included, will drastically slow down the simulation with little improvement in the accuracy. In [67], a dynamic and modular ES model is presented that can incorporate the controller design and the dynamics of the power electronic circuits. Experimental results are used to reduce the order of this dynamic model to suit both circuit and system simulations. The modular approach allows the circuit and controller of the ES model and the load module to be combined in the d-q frame. The performance of the ES model is validated on IEEE 13-node power system and a microgrid.

A linearized state-space model of the distribution network with multiple ES-1s with vector control is developed in [68] which is extendible to include inverter-interfaced DGs, energy storage, active loads, etc. The state-space model is utilized to analyze the impact of distance of an ES from the substation, the proximity between adjacent ESs and the R/X ratio of the network on small-signal stability and compared against the case with equivalent DG inverters. This state-space model of vector-controlled ES-1 could be incorporated into the stability models of microgrids to study how droop control of ES impacts the overall stability.

## B. Voltage Regulation

### 1. Distribution Network

The effectiveness of distributed voltage control using ES is compared against the traditional single-point control with STATCOM in [41]. A case study on a part of the distribution network in Sha Lo Wan Bay in Hong Kong shows that a group of ESs achieves better total voltage regulation than STATCOM with less overall reactive power capacity as shown in Fig. 30. In [49], SLs with BTB ES are shown to mitigate voltage problems caused by photovoltaic (PV) generation and electric vehicle (EV) charging in low-voltage distribution networks more effectively than ES-1 especially, under the over-voltage condition. Reference [33] reports the use of ES to maximize PV power and simultaneously ensure supply-demand balance obviating (or reducing) the need for battery storage. In [30], the effectiveness of BTB ES in suppressing the mains voltage compared to ES-1 is demonstrated with a weak power system.

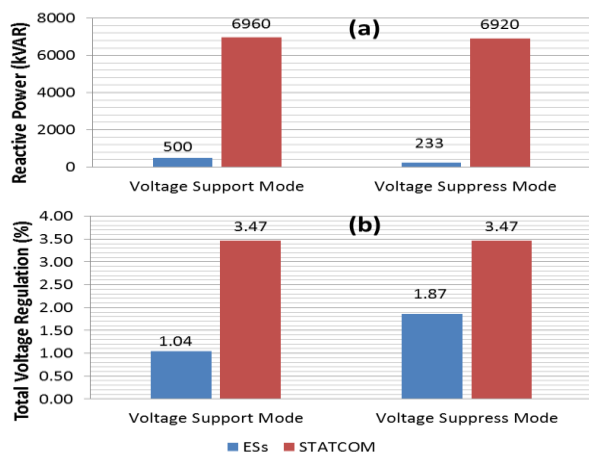


Fig.

30 Reactive power required and total voltage regulation achieve collectively by all the distributed ESs and the STATCOM under voltage support and suppress condition for the Sha Lo Wan Bay case study in [41].

A specific situation of overvoltage prevention using ES with storage-type electric water heaters (EWHs) is considered in [69]. A case study on the Sha Lo Bay residential LV network in Lantau Island, Hong Kong demonstrates that the effectiveness of the proposed approach in absorbing excess PV power to prevent overvoltage. In [70], BTB ES in output voltage control mode is used to tackle under- and over-voltage problems enabling larger PV and EV penetration. Both load- and feeder-level approaches are effective in accommodating PV generation and EV charging but the former requires overall higher converter capacity than the latter and produces better voltage regulation at the load terminals with larger demand response provision. Moreover, higher PV throughput is achieved with load-level ES despite higher losses in the feeder and the ES itself but the feeder-side voltage could exceed the stipulated upper limit.

In [55], a two-level voltage management scheme with load tap changer and capacitor banks at the upper level and ES at the lower level is demonstrated using consensus control allowing different voltage regulation devices to work together to maintain the voltage of critical buses by sharing the responsibility. Reference [71] also uses a consensus algorithm to coordinate multiple ESs for maintaining critical bus voltage

in distribution systems with ultra-high renewable penetration. This yields similar voltage suppression capability as the conventional ES but better voltage support with the ESs sharing the burden using limited communication.

A risk-limiting approach to ES planning method is reported in [72] to obtain the optimal ES configuration (number, locations, capacities, and types) to mitigate the voltage violations considering the uncertainties in renewable generation. An optimal voltage control method for an active distribution network with ES is presented in [73]. The critical bus voltage is regulated with minimum ES voltage is a distributed but coordinated fashion for which the load parameters are estimated in real-time using non-intrusive load monitoring. A decoupled dual functionality of ES is demonstrated in [34] by combining feeder voltage regulation and injection of roof-top PV power with drastic changes in solar irradiance. In [74], the performance of ES is evaluated operationally and economically using a backward/forward sweep method for optimal power flow and the real price and load data of the ISO-NE market. The results of the case study confirm the ES improves power loss, voltage profile, power factor, and stability while it reduces the operation cost. In [75], a hybrid method for ES control combining the data-driven and analytical models is demonstrated for voltage control in IEEE 15-node distribution network. Three data-driven models based on the extreme learning machine are built which are shown to be more accurate than the analytical model in predicting system states.

### 2. AC Microgrid

In [76], ESs in conjunction with water heating system as non-critical loads are used to regulate the critical load voltages in an islanded microgrid with intermittent renewables. The temperature constraint of the water heating system and the ramping constraint of a diesel generator are managed using the model predictive control. Smart loads having the ES in series with the critical load are considered in [77] to mitigate voltage fluctuations in low-inertia nanogrids. This is shown to reduce the burden on energy storage depending on the percentage of the loads that are converted to smart loads. In [78], several interconnected microgrids with ES are shown to form a transactive energy system. An optimization model and solution method are presented to determine the optimal operating points for multiple ESs in the microgrid to minimize the total voltage deviation.

A hybrid ES integrated with renewable generation and noncritical load is used in [35] power control and reduction of battery storage capacity in AC microgrids. This achieves an extended operating region for power control compared to the conventional way of using battery storage and ES. Moreover, the hybrid ES prevents over-charge and over-discharge of the battery by limiting its state-of-charge within a predetermined critical region to preserve the lifetime.

Overall, BTB ES has been found to be the most flexible and effective for voltage regulation in AC distribution network and microgrids, in general, unless specific situations such as PV or EV integration and/or the need for distributed energy storage favor other ES types. This is true irrespective of whether a distinction is made between critical and non-critical loads. By complementing the voltage support, the ES can not only reduce the need for battery storage but can also improve the

management of the batteries to extend their lifetime. Use of distributed control with minimal reliance on communication is crucial for voltage regulation with ES.

### 3. DC Microgrid

Regulation of DC microgrid bus voltage using DC-ES is demonstrated in [58]. Both series- and shunt-connected DC-ES are considered for DC bus voltage regulation, double-line frequency harmonic compensation, and fault-ride-through support. Faster dynamic response capability of the shunt ES is utilized for FRT support to tackle the stability problem in DC microgrids with intermittent renewable energy sources. In [61], model predictive control (MPC) with both adaptive and non-adaptive weighting factors is used to coordinate multiple DC-ESs to regulate DC bus voltage and reduce power loss on the distribution lines. Use of MPC with adaptive weighting factor results in less power loss than the non-adaptive version. A 48 V 5-bus DC microgrid experimental set up is used to validate DC bus voltage regulation in the above two references.

A distributed cooperative control is used in [64] for multiple DC-ESs with DC/DC three-port converter, bi-directional buck-boost converter and battery. Allocation of the primary and secondary control duty among multiple DC-ESs is exercised using droop and consensus, respectively while balancing the state-of-charge of the batteries associated with the DC-ESs. In [69], an energy management system (EMS) for the above DC-ES is presented which controls the operating mode transition of the buck-boost converter, changes the operating status of the battery and realizes multiple charging and/or discharging mechanism. Thus, the EMS can regulate the voltage of the DC microgrid and also maintain the state of charge (SOC) of the battery within a reasonable range to extend the battery life.

## C. Frequency Control

### 1. Primary Frequency Control

In [50], the effectiveness of the SLs with ES-1 in improving mains frequency regulation with a little relaxation in mains voltage tolerance is demonstrated through a case study on the IEEE 37 bus test distribution network. Sensitivity analysis is included to show the effectiveness and limitations of SLs for varying load power factors, the proportion of SLs, and system strengths. In order to achieve primary frequency control with ES-1, the mains voltage regulation is compromised slightly (still staying well within acceptable limits) which can be overcome with BTB ES. A control strategy based on the relationship between the active power of non-critical load and voltage of critical load is used in [26] to show that the ES can stabilize frequency fluctuations.

Reference [79] studies both automatic generation control and load-side control using a switched distributed controller designed for each load bus in a transmission network. Selection of control gains and design of the switching signal and the communication network for the load-side controller is discussed. The local stability criterion of the system with the proposed controller is established using linearization techniques. The effectiveness of the proposed controller for grid frequency control is demonstrated using the modified WSCC 9-bus test system with a single control area and the IEEE 39-bus test system with two control areas.

The concept of ES aggregators is used in [80] to achieve the required coordinated active power response to regulate grid

frequency and maintain the bus voltages within the acceptable limits. A distributed leader-following consensus algorithm is adopted for ES aggregators to obtain the updated active power set points and achieve the required active power response in a coordinated way. Simulation results show that ES aggregators can cooperatively provide the required active power response in time and regulate the frequency more effectively than the traditional automatic generation control while keeping the bus voltages within the admissible range.

### 2. Frequency Control in Isolated Microgrids

An ES with a bi-directional grid-connected power converter with a battery bank is used in [29] to reduce both voltage and frequency fluctuations in an isolated microgrid. A modified dead zone control circuit with a hysteresis band embedded on the existing active-reactive power decoupling control scheme for ES is used. Both simulation and experimental results are presented to illustrate the monitoring, charging/discharging management, and output power control. In [56], consensus control with a circular communication link at the cyber layer is used for a cluster of ESs to provide local voltage and system frequency regulations in a microgrid. Droop control (without communication) and consensus control (with the communication) are shown to be complementary. The latter achieves better power-sharing with local communication but can revert to droop control when local communication is not available. Fig.31 shows the practical measurements of the grid frequency after a sudden load increase of 20% with and without the use of distributed ES. It can be observed that the ES can quickly restore the grid frequency of the microgrid after the load disturbance.

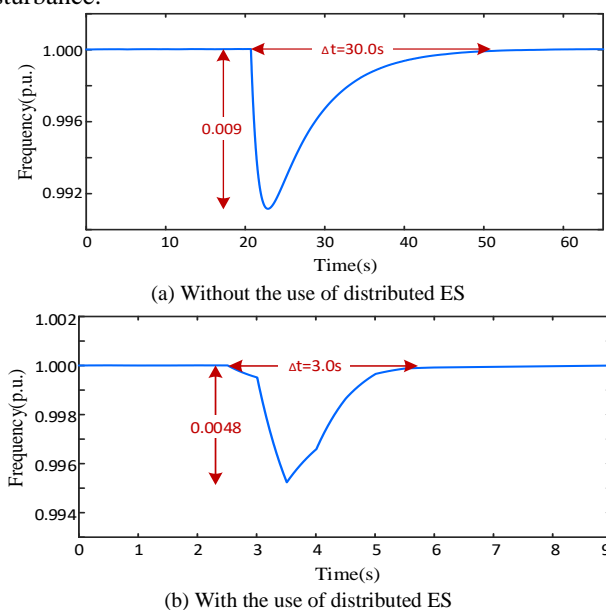


Fig.31 Frequency of a microgrid after a 20% load change (a) without and (b) with the use of distributed ES [56]

### D. Demand Response through Point-of-Load Voltage Control

The most common way to exploit the voltage dependence of loads for peak demand reduction is by decreasing the operating voltage of the distribution feeders, known as the Conservation Voltage Reduction (CVR) [81][82]. In practice, this is usually done through transformers at the primary substation but equivalent power electronic solutions such as a ‘Smart Transformer’ [83] at the secondary substation and mid-feeder

compensation [70] have been reported as well. They are effective as long as there is sufficient room to manoeuvre the voltage without violating the stipulated voltage limits at the far end of the feeders. However, during high loading and/or non-uniform loading across parallel feeders, the available margin for changing the voltage from the substation (or at some point on the feeder) could be very limited necessitating distributed point-of-load voltage control through ES.

The collective contribution of both static and motor type smart loads to aggregated demand response provision is demonstrated in [31] through a case study on the Great Britain (GB) transmission system. The study shows that the smart loads collectively offer a short-term power reserve which is comparable to the spinning reserve in the GB system, and thus can ensure acceptable frequency deviation and its rate of change following a large infeed loss. Reference [17] quantifies the aggregate demand reduction through distributed voltage control at the supply point of a cluster of domestic customers. This is shown to be more effective than voltage control at substations (VCS) especially, under high loading. A high-resolution stochastic demand model and the aggregate power-voltage sensitivity of individual domestic customers are used for the study. The rating of the voltage compensators required for PVC is evaluated to weigh the benefits against the required investment. Virtual inertia contribution through fast demand response capability of PVC using ES is quantified in [84]. For the first time, this paper has shown that the demand side could play a significant role in complementing the depleting inertial contribution from the supply side which has inherent limitations as well. For instance, the virtual inertia contribution from wind turbines is limited by the recovery phase (depending on the prevailing wind speed), the rated capacity of the grid interface power converters and the mechanical stress on the turbine components and the associated impact on lifetime. For solar photovoltaic (PV), virtual inertia can be provided by operating below maximum available power (i.e. part-rated operation) which could be expensive. This is where smart loads could complement the existing solutions as an additional source of virtual inertia.

Available demand response capability through point-of-load voltage control would vary with time of the day depending on the incidence of different types of voltage-dependent loads and also the voltage profile across the feeders. It is important for the grid operators to know the aggregate power reserve from the voltage-dependent loads during different times of the day in order to schedule other forms of reserves accordingly. Reference [85] presents such a methodology to estimate such power reserve from the measured power and voltage at the bulk supply points without knowing the actual distribution network topology and/or load profile of individual customers. This is applied to estimate the time variation of the aggregate reserve offered by the voltage-dependent loads within the domestic sector in Great Britain.

Fast response time of ES enables them to collectively contribute to frequency control over a range of timescales from inertial to fast frequency response (< 1 s) to primary frequency regulation (<10 s). Similar to the case of voltage regulation, ES can effectively complement energy storage for frequency control. However, the challenge is to provide accurate system-wide quantification of the aggregate response capability of the

ES/SL which the system operators can rely on whenever it is necessary.

### E. Harmonics Reduction

Effectiveness of ES-2 for harmonic reduction and power factor correction is demonstrated experimentally on a small-scale power grid in [42]. Coordinated operation of ES-2 for harmonics reduction and power factor correction and ES-1 for voltage regulation with input current control is demonstrated experimentally on a single-phase hardware setup. An ES with current-source inverters (CSI) is used in [40] for harmonic suppression. The harmonic distortion is shown to be reduced with CSI and direct current control. The harmonic components of the critical load voltages can be suppressed further with the direct current control plus additional harmonics suppression function which is useful in high power systems. In [86], multiple resonant controllers and second-order generalized integrator are used for ES to suppress the harmonics and regulate the critical load voltage. Reference [87] uses an improved phase-locked loop (PLL) together with independent  $\delta$  control in each phase to reduce unbalance and harmonic distortion in addition to stabilizing the mains voltage of the microgrid. This is achieved by an improved PLL that separates the fundamental component of the positive sequence of the microgrid voltages from the other sequences and harmonics. An ES based on neutral point clamped H bridge inverter is shown to produce superior high-frequency harmonic suppression and improved total harmonic distortion in [88].

### F. Unbalance Mitigation

In [36], a 3-phase ES is used to reduce unbalance across a building making the building loads adaptive to internal load changes and external mains voltage changes. The experimental and simulation results show how the ES reduces unbalance by redistributing the power across the three phases of the noncritical load while regulating the mains voltages as usual. Mitigation of the negative-sequence and zero-sequence currents with ES-2 control based on radial-chordal decomposition approach is demonstrated in [37] and verified on a 3 kW hardware setup. The ES voltage injected in each phase is set to remove unbalance while minimizing the active power exchanged with the battery storage. In [89], a 3-phase ES is considered for voltage regulation and reducing unbalance based on the theory of instantaneous power which is verified experimentally. Reference [38] uses a modified instantaneous symmetrical component algorithm and hysteresis current control to operate ES in active power filter mode to mitigate harmonics, improve the power factor while regulating the mains voltage. The effectiveness of the proposed approach for ES-1 in achieving multiple functions is established through simulation and experiments. Moreover, the analysis presented in this paper enables the integration of multiple control functions into the ES controller to achieve multiple objectives.

Reference [90] uses DC-ESs to mitigate unbalanced voltage and reduce power losses due to the neutral line current in a bipolar DC distribution network. The coupling between positive and negative pole voltages is analyzed in addition to deriving the small-signal model of the bipolar DC distribution network with DC-ESs. The proposed unbalanced voltage suppression method and decoupling control of DC-ESs are



validated by simulations and experiments for resistive loads only. This is more complicated for constant power loads and is not considered in this paper.

### G. System Resilience

Following extreme natural events, it is important to quickly restore the power supply, especially for the critical loads. Role of ES in enhancing the resilience of a microgrid with intermittent renewable resources is shown in [91]. The voltages across the critical loads are considered as a critical constraint for enhancing resilience during extreme natural events. Case studies presented demonstrate that ESs can enhance the resilience of microgrids with and without a communication system after extreme natural events. The ESs are shown to perform as expected with local information for the strong system while communication is required to retain the same level of performance for weak systems.

### H. System Stability

Impact of several ES on the stability of the power grids is studied in [92]. The concept of relative stability is used to tune the gains of the proportional-integral controllers of the ES to ensure the overall system stability of a weak grid. A case study on IEEE 13-node LV test feeder confirms that the constraints on controller gain become more stringent with an increasing number of ES to achieve system stability. Hence, the maximum number of ES can only be accommodated with the optimally chosen controller gains. Reference [68] presents a small-signal stability analysis of distribution networks with ES-1. The impact of distance of an ES from the substation, proximity between adjacent ESs and the R/X ratio of the network on the small-signal stability of the system is analyzed and compared against the case with equivalent DG inverters. It is shown that ESs installed in distribution networks are not likely to threaten the small-signal stability of the system. In fact, the stability margin with ES installed is more than the case with equivalent penetration of shunt converters such as DG inverters.

In [93], the role of ES in damping low-frequency oscillations in a droop-controlled inverter-based microgrid is demonstrated. This is achieved by modulating the current of the ES based on the oscillations in the inverter reference frequency. The damping capability is shown to depend on the location of the ES. Presence of ES does not adversely affect the small-signal stability if appropriate control parameters are used. However, this is yet to be ascertained for weak grid situations considering different control modes of the ES.

In this section, the system-level impact of ES is summarized in terms of a variety of functionalities/services (e.g. voltage regulation, frequency control, power quality improvement etc.) that it can offer. In practice, an ES might have to provide more than one of these services at different times for which an optimum scheduling mechanism has to be developed [94]. This would then enable a rigorous techno-economic value assessment of the ES technology considering multiple service provision which should further strengthen the business case for ES and expedite the uptake of the technology for mass deployment.

## VI. FUTURE TRENDS OF ELECTRIC SPRING

As reviewed in this paper, electric spring technology has

evolved into various forms as fast and smart demand response technology for smart grids. Currently, several versions of ES (ES-1 and BTB ES) are being practically evaluated by China Southern Power Grid [95]. While the ES circuits are initially associated with the NCLs together as smart loads for demand-side management, it is worthwhile to consider the ES as part of the power supply infrastructure as illustrated in Fig.32. The standard AC mains (with tight voltage tolerance) is regulated by the ES installed in the power supply infrastructure. The outputs of the ES form the adaptive AC mains (with a relatively large voltage tolerance). One business model is to offer discounts to the consumers when their NCLs consume electricity from the adaptive AC mains, because by doing so, they are helping the power companies to stabilize the power grid and install more renewable energy sources.

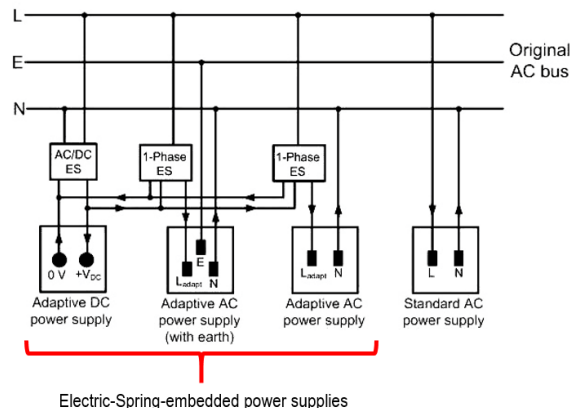


Fig.32 Schematic of an electric-spring-embedded power supply infrastructure

Similar to individual mechanical springs, ESs can work independently without communication. This feature is very important because it ensures a large group of ESs to support the power grid in case the communication network fails. However, it does not mean that using distributed control in a cyber layer or communication network is irrelevant. In fact, more research is needed because distributed control of a large group of ESs distributed in the distribution network will likely offer many new functions that have not been explored. For examples, conduction power loss in a microgrid can be reduced [96] and overvoltage in a distribution network can be avoided [97]. Thus, there is a need for studying distributed control of ESs and also measures against cyberattacks of the distributed ES. While distributed control offers a new dimension of functions, ESs still provide their individual functions by reverting to droop control even if the cyber layer or distributed control fails.

With almost ten years of research and development and industry trial of ES underway, a cost-benefit analysis (CBA) of this technology is necessary to facilitate mass deployment. However, it is not straightforward to do a comprehensive and generalized CBA for an ES taking into account the multiple functionalities (e.g. voltage control, frequency regulation, power quality improvement etc.) it can provide depending on the requirement at a given time. The proper value of an ES can be realised only when it is scheduled to provide multiple services (outlined in Section V) in conjunction with the

competing alternatives (e.g. battery storage, STATCOM etc.). Such a multi-service scheduling framework for ES is yet to be developed due to which the CBA and associated payback calculation for ES are limited to sporadic attempts such as [17] focusing on a single service (e.g. frequency response) only. Also, the requirement and value of these services will change depending on the penetration of renewables which varies a lot between countries/regions and anticipated future scenarios. Our ongoing research is aimed at firming up the CBA of ES for enhanced frequency response in Great Britain for two 2030 scenarios.

## VII. CONCLUSION

This paper reviews recent research and development of the Electric Spring (ES) technology and their applications in the smart grid. Similar to the mechanical springs for mechanical structures, electric springs have been introduced to support and stabilize the power grid with increasing disturbances caused by high penetration of renewable energy sources of intermittent nature. So far, several versions of ES and their associated control strategies have been proposed and practically verified in microgrids. Besides mitigating mains voltage and frequency fluctuations, ES also provides other auxiliary functions such as power quality improvement, reduction of power imbalance and conduction power loss in power systems. The literature review shows that there is an increasing trend of studying a large group of distributed ES in large-scale power systems. With ES reaching the stage of practical evaluation by the power industry, it is envisaged that the ES technology will offer a practical solution to speeding up the adoption of renewable energy sources without causing instability in the power grid in order to combat climate change.

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