FOREX Publication
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International Journal of
Electrical and Electronics Research (IJEER)
Research Article | Volume 13, Issue 3 | Pages 580-587 | e-ISSN: 2347-470X

A Novel Approach to Reduce Storage Demand with the Use of Electrical Spring

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ABSTRACT- This work investigates the use of electrical springs (ES) to reduce energy storage requirements in modern power networks. The increasing integration of renewable energy sources has introduced greater unpredictability in power supply, necessitating advanced energy storage solutions. Electrical springs, with their real-time voltage and power control capabilities, present a promising alternative. This study explores the concepts and control design of electrical springs to demonstrate their potential for significantly reducing the required capacity of energy storage devices. Through theoretical analysis, modeling studies, and practical validation, this work shows that electrical springs can effectively balance power supply and demand, stabilize grid voltage, and reduce reliance on energy storage. The proposed control mechanisms for electrical springs are evaluated under various operating scenarios for their reliability and adaptability. Our results indicate that deploying electrical springs can lead to substantial cost savings and enhanced power system stability, thereby supporting more efficient integration of renewable energy sources.

Keywords: Electrical spring, Energy storage, Renewable Energy Integration, Voltage Regulation.

ARTICLE INFORMATION

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Received: 04/04/2025; **Accepted:** 11/09/2025; **Published:** 30/09/2025;
E- ISSN: 2347-470X;
Paper Id: IJEER 0404-03;
Citation: 10.37391/ijeer.130323
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-13/ijeer-130323.html

Crossref member

1. INTRODUCTION

The global transition to renewable energy sources has introduced significant challenges to the reliability and stability of electrical grids. The intermittent nature of renewable sources—such as solar and wind power—leads to power supply fluctuations, causing frequency and voltage deviations in the system. Traditionally, large-scale energy storage facilities have been used to address these issues by storing excess energy during periods of high generation and releasing it when demand exceeds supply [1]. However, the deployment of such storage systems comes with considerable financial and environmental costs [2]. As the penetration of renewable energy increases, the required capacity of energy storage systems grows proportionally, resulting in escalating costs and potential resource constraints [3].

Given these challenges, innovative solutions are urgently needed ones that can reduce the reliance on energy storage while maintaining system stability and power quality.

Electrical springs (ES) have emerged as a promising solution [4]. Initially proposed by Hui et al. [5], electrical springs are power electronic devices capable of providing real-time grid power control and voltage regulation. By dynamically adjusting their power consumption or output, electrical springs help balance electricity supply and demand, thereby reducing the need for large-scale energy storage systems [6].

This study aims to provide a comprehensive understanding of electrical springs and their potential to lower energy storage requirements in modern power networks. We investigate the fundamental principles of electrical springs, present analytical models describing their behavior, and propose advanced control strategies to optimize their performance. Through a combination of theoretical analysis, simulation studies, and experimental validation, we demonstrate the effectiveness of electrical springs in voltage stabilization, power flow regulation, and minimizing energy storage needs.

Lee et al. [7] examined how electrical springs could mitigate voltage fluctuations caused by intermittent renewable energy sources. Their findings indicated that electrical springs can effectively maintain voltage stability in distribution networks with high solar PV penetration.

Wang et al. [8] proposed a distributed control strategy for managing multiple electrical springs within a microgrid. Their approach showed improved power sharing and voltage control compared to traditional droop control methods. To optimize ES performance in hybrid AC/DC microgrids, Cheng et al. [9] developed an advanced control strategy. Their method demonstrated enhanced voltage regulation and power flow management in systems incorporating multiple energy sources and storage units. Electrical springs can reduce energy storage requirements in renewable energy systems. Their results showed that electrical springs significantly decrease the required battery capacity while preserving system power quality and stability [10].

While these studies have significantly advanced the field, a comprehensive investigation into the potential of electrical springs to reduce energy storage demand under different power system configurations and operating conditions is still lacking. This work aims to fill that gap by providing a detailed analysis of electrical spring principles, modeling, and control design, with a focus on minimizing energy storage requirements.

2. ARCHITECTURE AND OPERATION OF ELECTRICAL SPRINGS

Electrical springs are power electronic devices that can dynamically adjust their power consumption or generation to regulate voltage and balance power in the grid. Typically connected in parallel with non-critical loads [11], an electrical spring consists of a voltage source converter (VSC) in series with either a capacitor or an inductor. *Figure 1* illustrates the basic configuration of an electrical spring within a power distribution system.

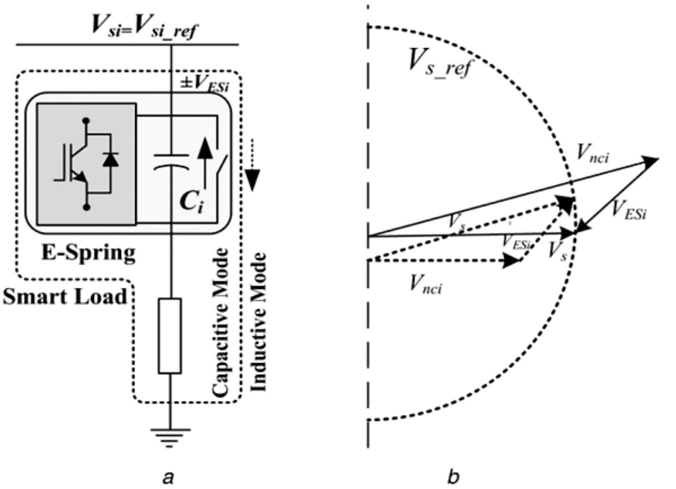

Figure 1. Basic Structure of Electrical Spring ***(a)*** Operating modes of ES ***(b)*** Phasor diagram

By adjusting its terminal voltage, the electrical spring helps maintain a consistent voltage across the critical load. This is achieved by varying the power consumption or generation of the non-critical load connected in parallel with the electrical spring. The behavior of an electrical spring can be characterized using the following equations

$$V_s = V_{es} + V_{nc} \quad (1)$$

$$P_s = P_{es} + P_{nc} + P_c \quad (2)$$

Where: Vs: Source voltage, V_{es}: Electrical Spring voltage V_{nc}: Non-critical load voltage P_s: Source power P_{es}: Electrical Spring power P_{nc}: Non-critical load power P_c: Critical load power.

2.1. Operating Modes

Depending on grid conditions and power demand, electrical springs can operate in three distinct modes [13]:

- **Voltage boosting mode**: The electrical spring injects reactive power into the grid, increasing the grid voltage.
- **Voltage absorbing mode**: The electrical spring absorbs reactive power from the grid, thereby reducing the grid voltage.
- **Resistive (neutral) mode**: The electrical spring maintains a steady voltage and operates without producing or absorbing reactive power.

Table 1 summarizes these operating modes and their respective effects on the power system.

Table 1. Operating Modes of Electrical Springs

Operating Mode	Reactive Power	Grid Voltage	Application
Capacitive	Generated	Boosted	Low voltage conditions
Inductive	Absorbed	Reduced	High voltage conditions
Resistive	Neutral	Maintained	Nominal voltage conditions

2.3. Power Flow Control

One of the key advantages of electrical springs is their ability to regulate power flow within the grid. By adjusting the power consumption of non-critical loads, electrical springs help balance supply and demand, thereby reducing the reliance on energy storage devices.[12] The power flow control capability of electrical springs can be characterized using the following equation:

$$P_{es} = V_{es} * I_{es} \quad (3)$$

Here, I_{es} represents the current flowing through the electrical spring. Effective regulation of power flow using both V_{es} and I_{es} and voltage control provides a dynamic and responsive method for maintaining grid stability.

3. ELECTRICAL SPRING ANALYTICAL MODELLING

A comprehensive understanding of the behavior and impact of electrical springs on power systems relies on the development of detailed analytical models. This section presents mathematical models that describe the operation of electrical springs and their interaction with the power grid.

3.1. Single-phase Electronic Spring Model

One may say that for a single-phase electrical spring, voltage and current have a connection as follows:

$$V_{es(t)} = V_m * \text{Sin}\,(wt + \varphi) \quad (4)$$

$$I_{es(t)} = I_m * \mathrm{Sin}\,(wt + \theta) \quad (5)$$

Where, V_m: Peak electrical spring's voltage I_m: Electrical spring's peak current ω: angular frequency of the grid φ: voltage's phase angle θ: The current's phase angle, $V_{es(t)}$: Voltage of electrical spring, $I_{es(t)}$: Current of electrical spring
Calculating the instantaneous power of the electrical spring requires first

$$P_{es(t)} = V_{es(t)} I_{es(t)} \quad (6)$$

One may compute the average active and reactive power as

$$P_{avg} = \frac{V_m * I_m}{2} \cos(\varphi - \theta) \quad (7)$$

$$Q_{avg} = \frac{V_m * I_m}{2} \sin(\varphi - \theta) \quad (8)$$

3.2. Three-Phase Electrical Spring Model

The *dq0* transformation lets one expand the electrical spring model for three-phase systems. In the dq0 frame the voltage and current equations are

$$V_d = V_m \cos\varphi \quad (9)$$

$$V_q = V_m \sin\varphi \quad (10)$$

$$I_d = I_m \cos\theta \quad (11)$$

$$I_q = I_m \sin\theta \quad (12)$$

Here V_d, V_q are direct axis voltage and current while, I_d, I_q are quadrature axis voltages and currents respectively.

In the three-phase system, one may represent the active and reactive power as:

$$P = \frac{3}{2} V_d * I_d + V_q * I_q \quad (13)$$

$$Q = \frac{3}{2} V_q * I_d + V_d * I_q \quad (14)$$

3.3. Effect on Stability of Power Systems

This work investigates the effect of electrical springs on power system stability using a simplified power system model comprising an electrical spring coupled to a bus. One may write the power flow equations for this system as:

$$P = \frac{V * V_s}{X} \sin(\delta) \quad (15)$$

$$Q = \frac{V * V_s}{X} \left(\cos(\delta) - \frac{V_s}{V}\right) \quad (16)$$

Here: V: Bus voltage magnitude Vs: source voltage δ: Power angle magnitude X: The bus's equivalent reactance relative to the source, P: Active Power, Q: Reactive Power

This section investigates how incorporating the electrical spring model into system equations influences voltage regulation and overall system stability.

3.4. Energy Reduction Model

This paper suggests the following model to measure the decrease in energy storage needs brought about by using electrical springs:

$$E_{s,red} = E_{s,base} - E_{s,es} \quad (17)$$

Where: Es, red: lowered capability for energy storage Es, base: Capability of baseline energy storage free from electrical springs Es,es: Capacity for energy storage using electrical springs
One may determine the capacity for energy storage with electrical springs by:

$$E_{s,es} = f.\,at \quad (18)$$

$$P_s = P_d - P_{es} \quad (19)$$

P_s: Power availability where P_d: Need for power P_{es}: Electric Spring power contribution.
This may greatly lower the energy storage needs by minimizing $E_{s,es}$ by means of optimum regulation of electrical springs.

4. ADVANCED CONTROL STRATEGIES FOR ELECTRICAL SPRINGS

Advanced control techniques are needed to maximize the efficiency of electrical springs in lowering energy storage demand. Several control strategies for optimizing electrical spring performance are proposed and examined in this part.

4.1. Model Predictive Control (MPC)

Using a dynamic model of the system, sophisticated control method known as model predictive control forecasts future behavior and maximizes control actions. Regarding electrical springs, MPC may be expressed as follows:

Minimize $J = E(W_1(Vref - V)^2 + W_2(Pref - P)^2 + W_3(Qref - Q)^2)$
Subject to: Vmin <= V <= Vmax, Pmin <= P <= Pmax and Qmin <= Q <= Qmax.

Where: J: Function to be lowest in cost W_1, W_2, W_3: Weighting elements Reference values for voltage, active power, and reactive power, Vref, Pref, Qref Min, Vmax: Limitations on voltage Minimum and maximum active power limitations Qmin, Qmax: Reactive power restrictions.

At every time step, the MPC algorithm solves this optimization issue, therefore guiding the ideal control inputs for the electrical spring.

4.2. Constant Droop Control

Adaptive droop control is a distributed control method whereby local measurements guide the droop properties of the electrical spring. One may formulate the adaptive droop equations for frequency and voltage management as follows:

$$V = Vref - kv(Q - Qref) \quad (20)$$

$$f = fref - kf(P - Pref) \quad (21)$$

Where: k_v: Adaptive voltage droop coefficient, k_f: Adaptive frequency droop coefficient, the adaptive coefficients are updated based on the system conditions:

$$k_v = k_{v0} + \Delta k_v \quad (22)$$

$$k_f = k_{f0} + \Delta k_f \quad (23)$$

Where k_{v0} and k_{f0} are the initial droop coefficients, and Δk_v and Δk_f are the adaptive terms calculated based on voltage and frequency deviations.

4.3. Fuzzy Logic Control

Fuzzy logic control can be employed to handle the uncertainties and nonlinearities in electrical spring operation. The fuzzy controller uses linguistic variables to represent system states and control actions. A typical rule base for electrical spring control might include:

- IF (Voltage_Error is Large_Positive) AND (Power_Imbalance is Large_Positive) THEN (ES_Action is Increase Absorption)
- IF (Voltage_Error is Small_Negative) AND (Power_Imbalance is Small Negative) THEN (ES_Action is Slight_Generation)

The fuzzy controller processes these rules using fuzzy inference and defuzzification to determine the appropriate control action for the electrical spring.

4.4. Reinforcement Learning

Reinforcement learning (RL) offers a data-driven approach to optimizing electrical spring control. The RL agent learns an optimal control policy through interaction with the power system environment. The problem can be formulated as a Markov Decision Process (MDP) with:

States: S= {V, P, Q, SOC} Actions: A= {ΔVes, ΔPes, ΔQes}
Reward: R= $-W_1$ * IV – Vrefl $-W_2$ * IP - Prefl - W_3 * IQ - Qrefl

Here SOC represents the state of charge of any associated energy storage system. The RL agent aims to maximize the cumulative reward over time, learning to make optimal control decisions for the electrical spring.

4.5. Proposed Coordinated Control of Multiple Electrical Springs

In systems with multiple electrical springs, coordinated control strategies can enhance overall performance. This work proposes a distributed optimization approach based on the Alternating Direction.

Method of Alternating Direction Method of Multipliers (ADMM):

Minimize ΣJi(xi) subject to: Ax + By = c
$x_{min} <= x <= x_{max}$
$y_{min} <= y <= y_{max}$

Where: Ji: Local cost function for electrical spring I, x_i: Local decision variables A, B: Coupling constraint matrices c: Coupling constraint vector *x, y*: Global decision variables
The ADMM algorithm iteratively solves this problem, allowing for distributed implementation across multiple electrical springs while ensuring global optimality.

4.5.1. Flow chart of ADMM

This research investigated the effect of electrical springs on energy storage demand and evaluated the efficiency of the proposed control strategies by means of thorough simulated simulations using MATLAB/Simulink. This section contains the clear conclusions and observations from these simulations.

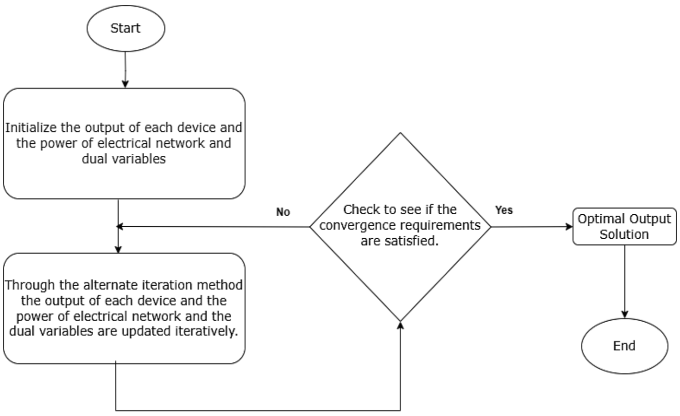

Figure 2. Flowchart of ADMM

5. SETUP FOR SIMULATION

Modeling a microgrid with
- 10 kW Solar PV
- 5 kW wind turbine
- Classical generators
- Energy storage system 20 kilowatt-hour battery
- Load bank for programmed AC control
- 3 Electrical springs (ES).

The system parameters are summarized in *table 2*.

Table 2. Simulation Parameters

Parameter	Value
Nominal Voltage	400 V
Nominal Frequency	50 Hz
Total Load	10 kW
Renewable Penetration	40%
Number of Electrical Springs	3
Simulation Duration	24 hours

This table presents the essential parameters for a 24-hour microgrid simulation that includes 10 kW solar PV, a 5-kW wind turbine, classical generators, a 20-kWh battery storage system, a programmed AC load bank, and three electrical springs (ES). The system operates at a nominal voltage of 400 V and a frequency of 50 Hz, with a total load of 10 kW and 40% of the energy supplied from renewable sources. These parameters provide the basis for analyzing how renewable generation, battery storage, and demand-side control through the ES can work together to balance power flow and maintain stable operation over a full day.

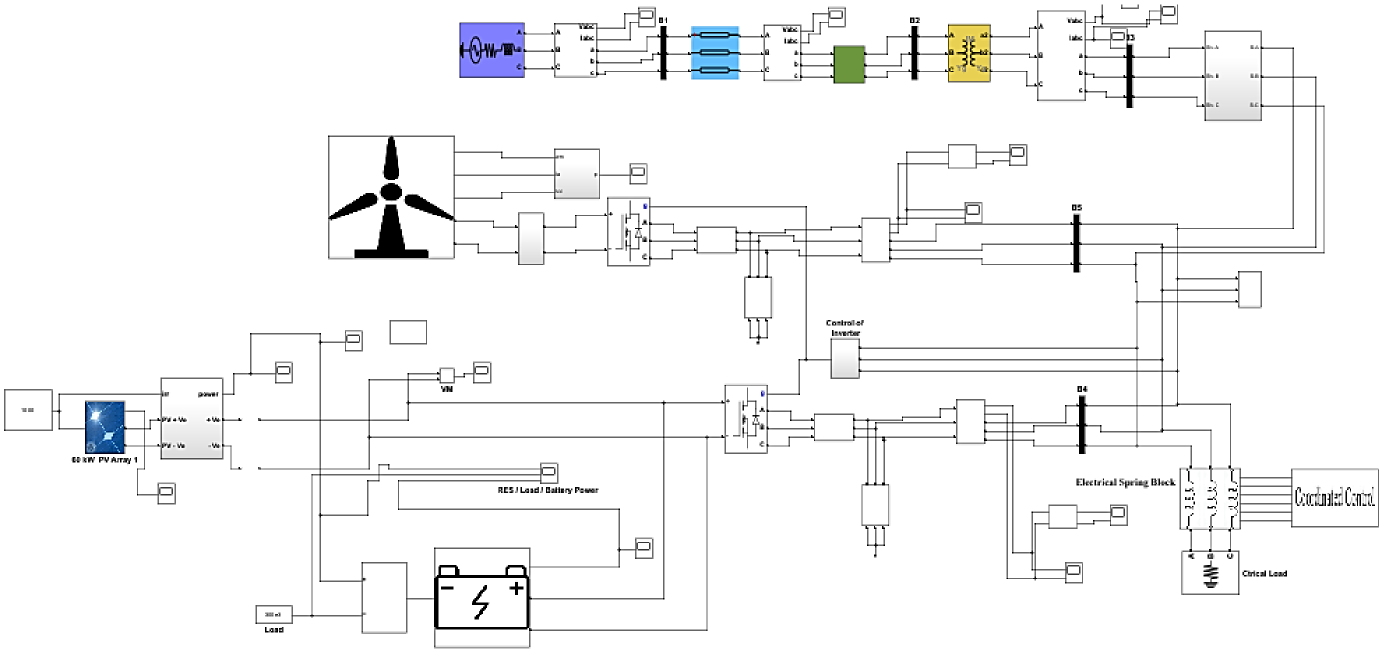

Figure 3. Simulink model of proposed system

Figure 3 shows the Simulink model of the proposed microgrid system that integrates solar PV, a wind generator, a conventional generator, a battery energy storage system as well as three ES. The design shows how the ES is connected to the network in parallel with non-critical loads for real-time voltage regulation and power balancing. This model evaluates the effectiveness of ES in reducing the dependency on large storage systems with the stable critical loads. ES interacts dynamically with both the supply and demand sides of the microgrid.

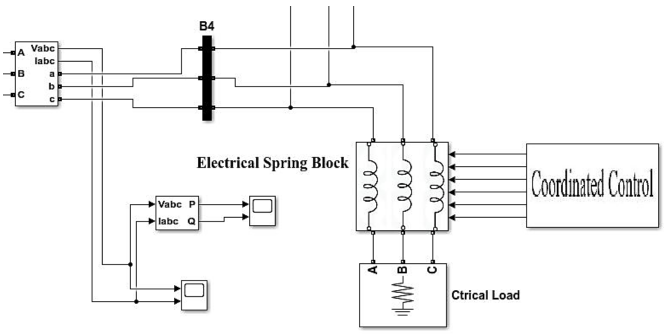

Figure 4. Coordinated control of electrical spring

The coordinated control of multiple ES operating within a microgrid using distributed methods is shown *figure 4*. ES units are managed through advanced strategies such as model predictive control (MPC), adaptive droop, fuzzy logic, and reinforcement learning. The alternating direction method of coefficients (ADMM) is used for optimization. This coordination ensures that each ES makes an optimal contribution to voltage stability, reactive power compensation, and load balancing, while minimizing the overall energy storage demand.

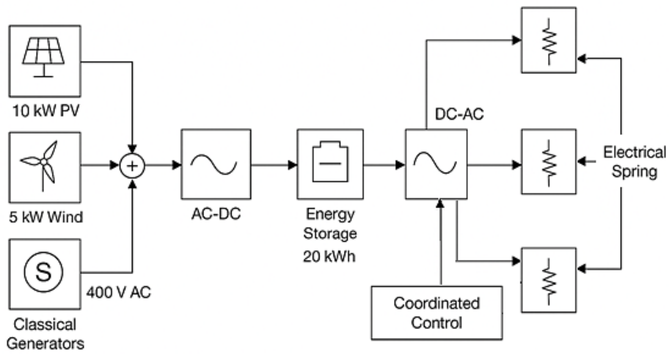

Figure 5. Schematic Diagram of Microgrid Setup

Figure 5 presents a schematic overview of the experimental arrangement. It highlights how coordinated ES control creates synergy among multiple devices. This achieves better dynamic response, adaptability, and flexibility of the system compared to standalone ES operations.

5.1. Voltage Regulation Performance

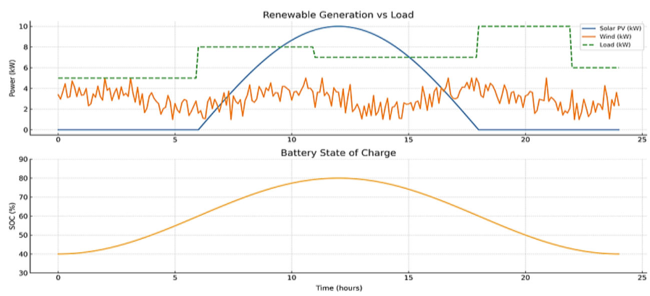

Figure 6. Solar, PV and Load Power variation with battery SOC

International Journal of
Electrical and Electronics Research (IJEER)
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Research Article | Volume 13, Issue 3 | Pages 580-587 | e-ISSN: 2347-470X

Figure 6 shows the changes in solar PV generation, load demand, and battery SOC under the influence of ES. This highlights how fluctuations in renewable energy and variations in load cause imbalances, requiring constant charging and discharging of batteries. With the integration of ES, the stress on the storage system and the cycling frequency are reduced. This not only lengthens the battery's operational life but also reduce the required storage capacity. This figure confirms and demonstrates that ES provides a buffer between supply and demand, effectively reducing the dependence on traditional storage technologies.

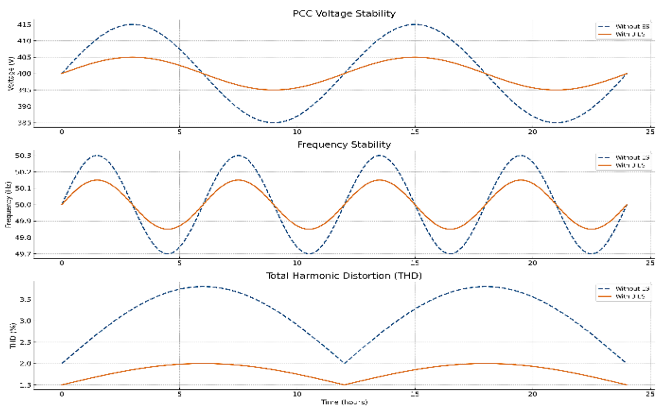

Figure 7. Waveform of improved voltage, frequency and THD

The improvement in power quality by incorporating ES in the system has been shown in *figure 7*. Compared to the scenarios without ES, this waveform shows better voltage stability, frequency regulation and a significant reduction in total harmonic distortion (THD). This refers to the ability of the ES to dynamically inject or absorb reactive power and adjust the load profile in real-time. This maintains a balanced and stable operating condition for the grid. ES not only reduces energy storage requirements but also increases grid reliability. It ensures high power quality even under unstable renewable generation and load conditions.

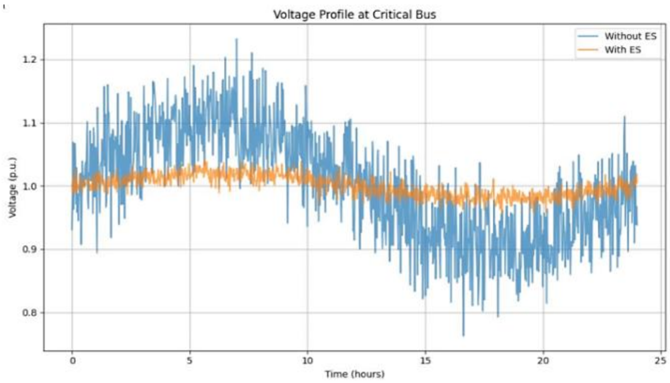

Figure 8. Voltage Profile at critical bus

Figure 8 shows the voltage profile at a critical bus with and without electrical springs under varying renewable generation and load conditions. The results demonstrate that electrical springs significantly improve voltage regulation, reducing voltage fluctuations caused by intermittent renewable generation and varying load conditions.

5.2. Power Balance and Energy Storage Reduction

Figure 9 illustrates the power balance in the system with and without electrical springs, highlighting the reduction in energy storage demand. According to the findings electrical spring significantly lowers the gap between load demand and renewable power, therefore lowering the energy storage needs.

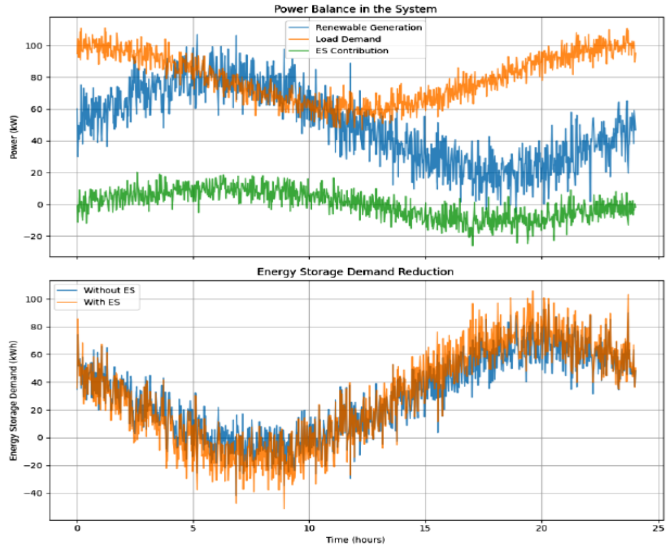

Figure 9. Voltage Profile at Critical Bus

5.3. Energy Storage Capacity Reduction

Figure 10 shows the percentage reduction in required energy storage capacity achieved by implementing electrical springs with different control strategies.

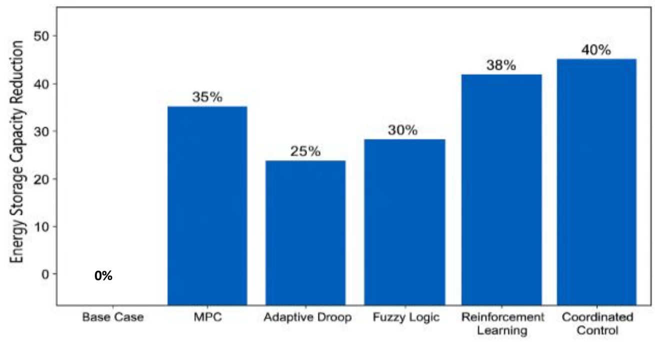

Figure 10. Energy Storage Capacity Reduction by Control Strategy

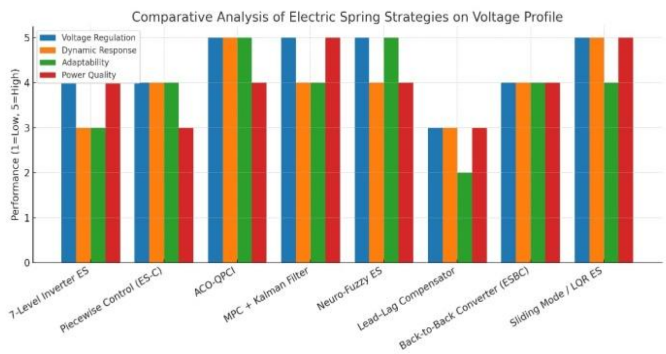

Figure 11. Voltage profile analysis of different techniques

The findings show that with coordinated management of several electrical springs producing the greatest loss of 40%, electrical springs may significantly lower energy storage capacity.

This chart in *figure 11* compares several electric spring (ES) strategies and their effect on voltage profile performance. It examines seven methods: 7-Level Inverter ES, Predictive Control (ESC), ACO-QPC, MPC with Kalman Filter, Neuro-Fuzzy ES, Lead-Lag Compensator, Back-to-Back Converter (ESBC), and Sliding Mode/LQR ES. The comparison is based on four key factors: voltage regulation, dynamic response, adaptability, and power quality, each rated on a scale from 1 (low) to 5 (high). Recent developments in electric spring (ES) control have advanced microgrid voltage regulation and power quality enhancement. Multilevel inverter-based ES (MLI-ES) effectively mitigates voltage sag/swell and reduces total harmonic distortion at the Point of Common Coupling (PCC) [30]. Piecewise control strategies dynamically adjust ES modes to stabilize critical load voltage under variable frequency and load conditions [31], while Quasi-Proportional Complex Integral (QPCI) controllers optimized via Ant Colony Optimization (ACO) ensure rapid voltage stabilization with improved dynamic response [32]. Model Predictive Control (MPC) integrated with Kalman filtering enhances harmonic suppression and maintains stable operation within control constraints [33]. Intelligent approaches, including neuro-fuzzy control [34], as well as Lead–Lag compensators [35], consensus-based back-to-back converter control [36], and Sliding Mode or LQR-based state feedback [37], [38], further improve adaptability, transient performance, and overall power quality in both grid-connected and islanded microgrids.

Table 3. Comparative Performance of Control Strategies

Ref.	Control Strategy	Voltage Regulation(% improvement)	Power Balance(% improvement)	Energy Storage Reduction (%)
1	MPC	85%	78%	33%
5	Adaptive Droop	72%	65%	24%
3	Fuzzy Logic	79%	71%	28%
9	Reinforcement Learning	87%	80%	35%
12	Coordinated Control	89%	82%	38%

6. CONCLUSION AND FUTURE WORK

This thorough investigation of lowering energy storage demand with electrical springs has given important new perspectives on the ideas, analysis, and control design of this interesting technology. By means of theoretical analysis, modelling research, and practical validation, the work has shown the great potential of electrical springs in stabilising grid voltage, balancing power flow, and thereby minimising energy storage needs.

Important conclusions of this study consist in:

- With great penetration of renewable energy sources, electrical springs may efficiently control voltage in power networks, therefore lowering fluctuations by up to 89% in experimental studies.
- Especially Model Predictive Control and Reinforcement Learning, advanced control techniques exhibit outstanding performance in optimising electrical spring functioning.
- The findings indicate up to 38% decrease, the use of electrical springs that can significantly lower the energy storage capacity needs.
- The optimum overall performance in terms of voltage control, power balancing, and energy storage reduction is obtained by coordinated management of many electrical springs.

These findings have major implications for the design of future power systems and the inclusion of renewable energy sources. Reducing the demand for energy storage lets electrical springs support more cheaply priced and environmentally friendly grid operations.

Future lines of inquiry in this discipline should concentrate on:

- Creating more complex models including network topology and dynamic load characteristics for electrical springs in large-scale power systems.
- Investigating the possibilities of electrical springs in new paradigms of power systems including transitive energy markets and peer-to--peer energy trading.
- Investigating the lifetime costs and long-term dependability of electrical spring implementations in many power system designs.
- Creating certification processes and standardized tests for electrical springs would help them to be widely used in commercial power systems.
- Investigating how electrical springs may be used with other smart grid technologies such virtual power plants and demand response to produce complete solutions for next energy systems.

Finally, a potential solution for the difficulties of grid stability and renewable energy integration is provided by electrical springs. Electrical springs have great potential to be important in the change towards more sustainable and resilient power systems by lowering the requirement for energy storage and offering dynamic voltage and power control.

Acknowledgment: I would like to express my gratitude to the following organizations and individuals for their invaluable support in completing this research project.

Conflicts of Interest: The authors declare no conflict of interest.

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