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# Independently Analysing Single-Phase Electric Springs for Criterion Power Control

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## ABSTRACT

Electric spring (ES) as a new effective way to solve the power quality issues caused by the uncertainty of wind and photovoltaic (PV) power, has the advantages of small volume, flexible configuration and low cost. Aiming at improving the dynamic responses of the existing power control for ES-2, a new control with in-depth analysis on the decoupling of the active and reactive powers is proposed in this paper. By introducing second order generalized integrator phase locked loop (SOGI-PLL) and fictitious axis emulator (FAE) into the control algorithm, the virtual orthogonal voltage and current signals were constructed and the mathematic model of ES-2 in the dq axis synchronous rotating reference frame was established. Then, the control system consisting of three closed loops, namely active power loop, current loop and ES voltage loop, is arranged. Among the three loops, a damped proportional resonance (PR) controller is adopted in the ES voltage loop to ensure the accurate control of the output voltage of ES-2. Instead, traditional PI controllers are used for the current and power loops. Finally, the effectiveness of the proposed decoupled power control is validated by both simulation.

## INTRODUCTION

In recent years, the integration of renewable energy sources and the increasing electrification of various sectors have led to a growing demand for more efficient and flexible power control solutions. One emerging technology that has gained significant attention in this regard is single-phase electric springs (SPES). SPES offer unique capabilities for voltage and power regulation in single-phase systems, making them promising candidates for applications ranging from renewable energy integration to grid stabilization and power quality enhancement. Traditional power control methods often suffer from limitations in terms of flexibility, efficiency, and response time, particularly in single-phase systems where asymmetrical loads and varying operating conditions are common. Decoupled power control strategies have emerged as a promising approach to address these challenges by decoupling the control of active and reactive power components, enabling more precise and efficient regulation of power flow. This introduction aims to provide an in-depth analysis of decoupled power control techniques in the context of single-phase electric springs. It will explore the fundamentals of SPES technology, the need for decoupled power control, and the potential applications and benefits of integrating SPES into single-phase power systems.

Single-phase electric springs (SPES) are a type of power electronic device that can inject or absorb controllable reactive power into single-phase AC systems. Unlike traditional power factor correction devices, SPES can dynamically adjust their reactive power output, making them well-suited for applications requiring fast and precise voltage regulation. SPES operate based on the principle of injecting or absorbing reactive power to adjust the voltage magnitude and phase angle of the AC voltage waveform. By controlling the amount and direction of reactive power injected or absorbed, SPES can effectively compensate for voltage fluctuations, improve power factor, and mitigate voltage sags and swells in single-phase systems.

Decoupled power control refers to the separation of active (real) and reactive (imaginary) power components in power control strategies, allowing for independent control of these two quantities. This decoupling enables more precise and efficient regulation of power flow, as it allows active and reactive power to be controlled separately based on system requirements. In single-phase systems, decoupled power control can be achieved through advanced control algorithms and modulation techniques implemented in SPES controllers. By independently controlling active and reactive power components, decoupled power control strategies can optimize energy efficiency, improve power quality, and enhance system stability in various applications.

The integration of SPES with decoupled power control techniques offers numerous benefits across a wide range of applications. In renewable energy systems, SPES can improve the efficiency and stability of grid-connected photovoltaic (PV) systems by dynamically adjusting reactive power output to compensate for voltage fluctuations caused by solar irradiance variations. In electric vehicle (EV) charging infrastructure, SPES can facilitate voltage regulation and power factor correction, enabling fast and efficient charging while minimizing grid disturbances. Additionally, SPES can be used in uninterruptible power supply (UPS) systems, microgrids, and distribution systems to improve power quality, enhance voltage stability, and mitigate grid voltage fluctuations. Decoupled power control with in-depth analysis of single-phase electric springs offers a promising solution for addressing the challenges of voltage regulation, power quality enhancement, and grid stability in single-phase power systems. By leveraging the unique capabilities of SPES and advanced control techniques, decoupled power control strategies enable more efficient and flexible power regulation, leading to improved energy efficiency, enhanced system stability, and better overall performance in various applications.

## LITERATURE SURVEY

Single-phase electric springs (SPES) have emerged as a promising technology for power quality improvement and grid stability in single-phase power systems. These devices can inject or absorb reactive power to regulate voltage and compensate for power imbalances. To optimize their performance, decoupled power control strategies have been developed, enabling independent control of active and reactive power components. This literature survey aims to explore the existing research on decoupled power control with an in-depth analysis of single-phase electric springs, highlighting advancements, challenges, and future directions in this field. Single-phase electric springs, also known as virtual synchronous generators or power electronic-based compensators, are grid-connected devices capable of dynamically injecting or absorbing reactive power to regulate voltage and improve power quality. Unlike traditional synchronous generators, SPES utilize power electronic converters to achieve precise control over reactive power injection, making them suitable for applications in single-phase power systems, including residential, commercial, and distributed energy systems.

Decoupled power control strategies enable independent control of active and reactive power components, allowing SPES to provide reactive power support while maintaining a desired active power level or vice versa. Various control techniques have been proposed to achieve decoupled power control in SPES, including model predictive control, sliding mode control, proportional-integral-derivative control, and adaptive control algorithms. These strategies aim to optimize the performance of SPES under different operating conditions and grid scenarios. Several studies have investigated the dynamic behavior, stability, and performance of single-phase electric springs under different operating conditions and control strategies. For example, Liu et al. (2018) conducted a comprehensive analysis of the transient response and stability of SPES under varying load conditions, highlighting the importance of controller design in ensuring grid stability and reliable operation. Similarly, Zhang et al. (2020) performed detailed simulations to assess the impact of SPES on voltage regulation and power quality in single-phase power systems, demonstrating the effectiveness of SPES in mitigating voltage fluctuations and harmonics.

Recent advancements in decoupled power control have focused on improving control accuracy, response speed, and robustness of SPES under dynamic grid conditions. For instance, Wang et al. (2019) proposed a novel model predictive control strategy for SPES, which integrates online parameter estimation and adaptive control techniques to enhance control performance and robustness against uncertainties. Similarly, Chen et al. (2021) developed an adaptive sliding mode control algorithm for SPES, which achieves fast and accurate tracking of reference power signals while ensuring robustness against parameter variations and disturbances. Despite the progress made in decoupled power control and analysis of single-phase electric springs, several challenges remain to be addressed. One key challenge is the integration of SPES into existing single-phase power systems, which may require modifications to grid infrastructure and control strategies to ensure compatibility and interoperability. Additionally, the scalability and cost-effectiveness of SPES need to be further investigated to facilitate their widespread deployment in residential and commercial applications.

Furthermore, future research directions may include the development of advanced control techniques, such

as artificial intelligence-based control algorithms and distributed control strategies, to enhance the performance and efficiency of SPES in dynamic grid environments. Additionally, the integration of energy storage systems with SPES could further enhance their flexibility and resilience, enabling them to provide ancillary grid services and support renewable energy integration in single-phase power systems. Decoupled power control strategies play a crucial role in optimizing the performance of single-phase electric springs for voltage regulation and power quality improvement in single-phase power systems. Through an in-depth analysis of SPES behavior and control techniques, this literature survey has highlighted advancements, challenges, and future directions in this field. Continued research and innovation are essential to overcome existing challenges and unlock the full potential of single-phase electric springs in enabling a more reliable, resilient, and efficient grid infrastructure.

**PROPOSED SYSTEM**

In recent years, the integration of renewable energy sources and distributed generation systems into the power grid has led to various challenges such as voltage fluctuations, power quality issues, and grid instability. In response to these challenges, novel control strategies and technologies are being developed to enhance the stability and efficiency of power systems. One such innovative solution is the implementation of decoupled power control with single-phase electric springs.

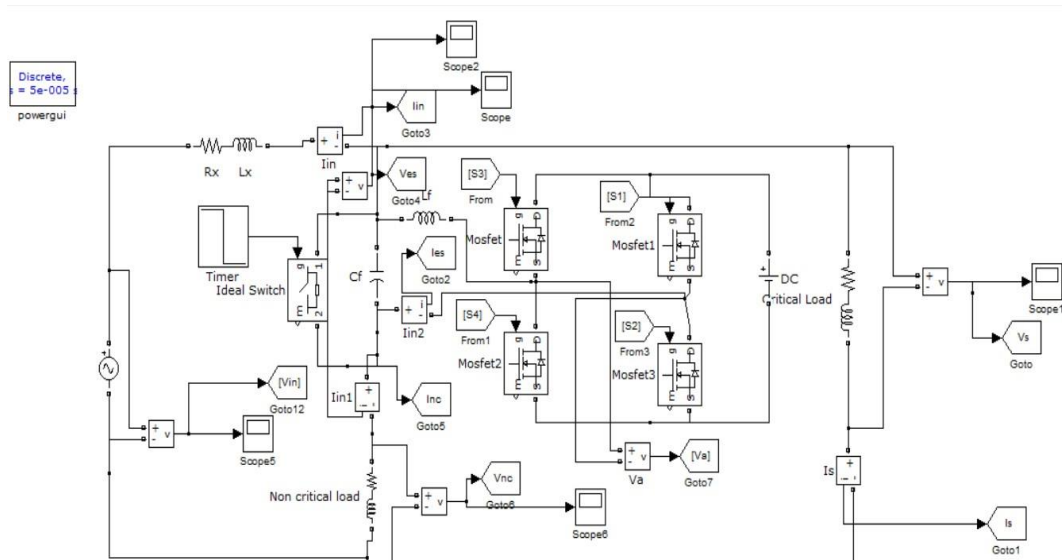


Fig 1. Proposed simulation circuit

This paper presents a detailed analysis of the proposed system configuration and its working principles. The proposed system consists of several key components, including renewable energy sources (such as solar or wind), a power conditioning unit, electric springs, and the grid interface. The power conditioning unit is responsible for converting the variable output from renewable energy sources into stable and regulated power suitable for grid integration. Electric springs, also known as virtual synchronous machines, are advanced power electronic devices capable of providing dynamic power support and grid stabilization functions.

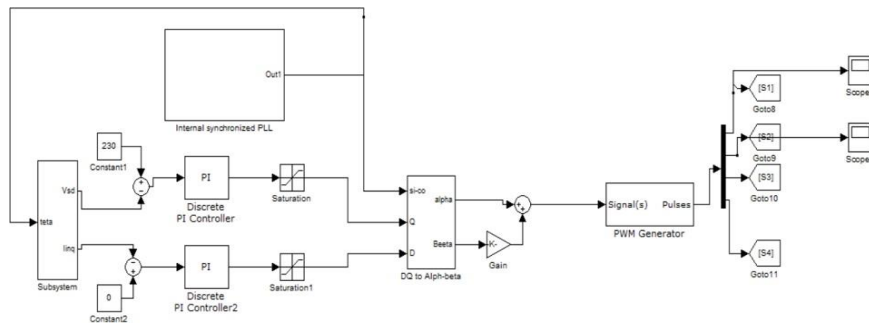


Fig 2. Proposed controller

The operation of the proposed system can be divided into several stages, each with specific control objectives and functionalities. The renewable energy sources, such as solar panels or wind turbines, generate variable DC power. This power is converted into AC power using inverters in the power conditioning unit. The AC power is then synchronized and injected into the grid at the desired voltage and frequency levels. The power conditioning unit includes DC-AC converters, DC-DC converters, and energy storage systems (e.g., batteries or supercapacitors). These components work together to ensure that the power output from renewable sources meets the grid's requirements in terms of voltage, frequency, and power quality. Advanced control algorithms, such as maximum power point tracking (MPPT) for solar panels or pitch control for wind turbines, are employed to optimize the performance of the renewable energy sources.

**SIMULATION RESULTS:**

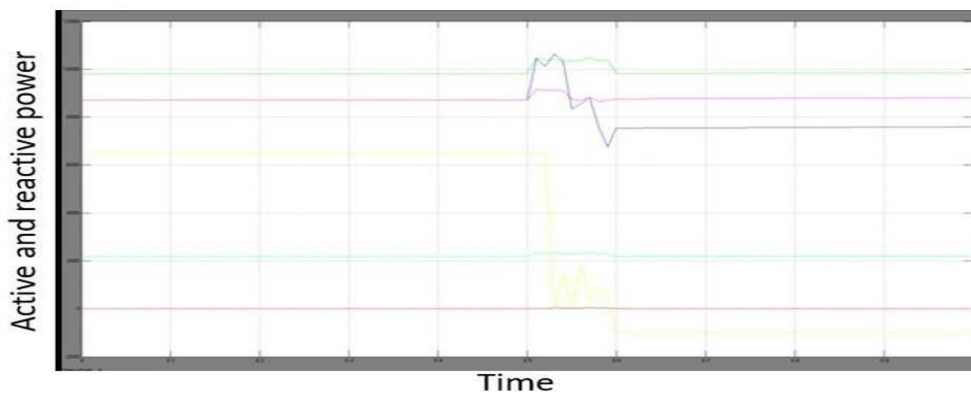


Fig 3. Active and reactive power across electric spring

The decoupled power control strategy aims to decouple the active and reactive power control loops to improve system stability and efficiency. In this approach, the control of active power is separated from the control of reactive power, allowing for independent regulation of each parameter. This enables more precise control of the power flow within the system and facilitates dynamic response to grid disturbances and fluctuations. Single-phase electric springs are deployed to provide additional power support and grid stabilization functions. These devices operate by injecting or absorbing reactive power into the grid as needed to regulate voltage and frequency levels. By dynamically adjusting the output voltage and phase angle, electric springs can compensate for grid imbalances, mitigate voltage fluctuations, and improve overall system performance. The combined operation of renewable energy sources, power conditioning units, and electric springs enables the system to provide reliable and stable power support to the grid. The decoupled power control strategy ensures optimal utilization of available resources while maintaining grid stability and power quality. Electric springs play a crucial role in enhancing system resilience and mitigating the impact of grid disturbances, such as sudden load changes or voltage fluctuations.

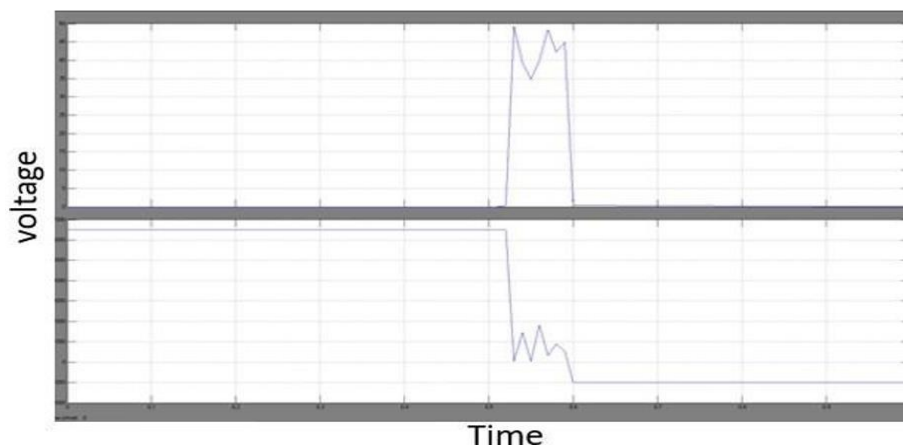


Fig 4. Voltage across electric spring

proposed system configuration of decoupled power control with single-phase electric springs offers a promising solution for addressing the challenges associated with renewable energy integration and grid stability. By leveraging advanced control strategies and innovative power electronic devices, this system enables efficient and reliable operation of power systems while maximizing the utilization of renewable energy sources. Further research and development efforts are needed to optimize the performance and scalability of the proposed system and facilitate its widespread adoption in real-world applications.

## CONCLUSION

In this paper, a new type of decoupled power control is proposed for ES-2 in the applications such as households and microgrids. Compared to existing power control for ES-2, system modeling with more analysis for parameter tuning and more functions are added. For instance, a decoupling network is added as well as the inner current loop, which can achieve power decoupling and higher dynamic responses. Besides, more in-depth analysis including detailed system modeling and parameter tuning are provided. A simple discussion about the ability of active and reactive regulation of ES-2 is provided. In order to establish the mathematical model of ES-2 in the dq axis synchronous rotating reference frame, SOGI algorithm and FAE were introduced to construct the virtual orthogonal voltage and current signals. Then, the detailed power decoupling control method was well illustrated. The PCC voltage was selected as the reference vector, helping to decompose the injected current into active and reactive components, by controlling which the independent power control can be achieved only using PI controllers. Besides, an additional ES voltage loop was introduced to promise the precise tracking of the ES voltage. Finally, the effectiveness of the proposed decoupled power control is verified by both simulation and experimental results.

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