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The Review of ELC and STATCOM Role in Electrical Power Generation from Renewable Energy Sources Based Three-Phase Self-Excited Induction Generator

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Abstract— This paper reviews various control strategies employed in Electronic Load Controllers and Static Synchronous Compensators (STATCOMs) for renewable energy system (RES)-based Self-Excited Induction Generators (SEIGs), with particular emphasis on performance indicators such as voltage and frequency regulation, harmonic distortion mitigation, and dynamic response characteristics. The review was conducted using articles published in reputable scientific journals. A total of 52 articles were selected and analyzed based on predefined inclusion criteria. The findings indicate that the investigated control approaches range from conventional controllers, such as Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers, to intelligent control techniques, including Fuzzy Logic Controllers (FLCs) and Artificial Neural Networks (ANNs). Furthermore, hybrid control schemes, such as Fuzzy-PI controllers and optimization-assisted intelligent controllers (e.g., PI-PSO), have also been widely reported in the literature. The limitations of conventional PI/PID controllers, particularly their fixed gain parameters that are optimized for specific operating conditions, can be effectively addressed through intelligent control techniques. These advanced approaches provide improved adaptability, enhanced dynamic response, and superior harmonic compensation performance. As a result, the reported Total Harmonic Distortion values for both voltage and current are generally maintained within the limits specified by IEEE Standard 519, namely below 5% for both voltage THD and current THD.

Keywords: SEIG, ELC, STATCOM, Conventional Control, Intelligent Control, Hybrid Control

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1. Introduction

The primary challenge in electricity generation from Renewable Energy Sources (RESs) employing a three-phase Self-Excited Induction Generator (SEIG) is the instability of system voltage and frequency caused by fluctuations in turbine speed and load demand. These conditions significantly affect the quality of the supplied power and may reduce the operational lifetime of electrical equipment. Nevertheless, in resource-constrained environments, SEIGs are widely preferred due to their simple mechanical structure, robustness, and low implementation cost [1]–[5].

However, the simplicity of the mechanical structure results in more complex control requirements. To mitigate voltage and frequency instability and ensure acceptable power quality, advanced engineering solutions are required. These solutions commonly involve power electronic-based control devices and power converters, such as Electronic Load Controllers (ELCs) and Static Synchronous Compensators (STATCOMs), which are designed to regulate system operating conditions and enhance overall performance.

An Electronic Load Controller (ELC) is employed to maintain a constant total load on the generator by diverting surplus power to a dummy load. Through this power diversion mechanism, the total output power of the generator can be kept relatively constant, thereby enabling the generator

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voltage and frequency to remain within acceptable operating limits. The typical architecture of an ELC is illustrated in Figure 1. An ELC generally consists of a three-phase diode bridge rectifier, a DC-link ripple capacitor, a controlled power switch, and a dummy load resistor. The rectifier converts the generator output into DC power, while the controlled switch regulates the amount of power dissipated in the dummy load. By continuously adjusting the power absorbed by the dummy load in response to load variations, the ELC contributes to maintaining stable voltage and frequency characteristics and improving the overall power quality of the SEIG-based generation system.

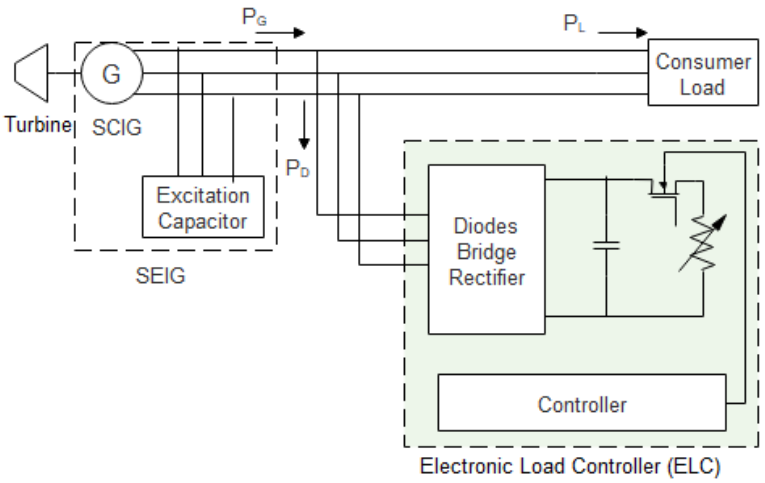


Figure 1. The schematic diagram of SEIG-ELC

One of the most critical components of an Electronic Load Controller (ELC) is its control unit. In the early development of ELC technology, conventional controllers such as Proportional–Integral (PI) [6]–[10] and Proportional–Integral–Derivative (PID) [11], [12] controllers were widely employed. The control action is typically based on the error signal generated from the difference between the reference voltage and the measured terminal voltage. This error signal is processed to regulate the amount of power diverted to the dummy load, thereby maintaining stable generator operation. However, a major limitation of PI/PID controllers lies in their linear structure and fixed gain parameters, which are generally tuned for a specific operating point. In contrast, Self-Excited Induction Generators (SEIGs) exhibit highly dynamic and nonlinear characteristics due to variations in renewable energy input and load demand. Consequently, fixed-parameter PI/PID controllers often struggle to adapt effectively to changing operating conditions. This mismatch may result in degraded control performance, characterized by slow dynamic response, excessive overshoot, prolonged settling time, and oscillations around the reference value.

To achieve faster dynamic response and enhanced reactive power compensation, researchers have developed the Static Synchronous Compensator (STATCOM). A STATCOM is commonly based on a Voltage Source Converter (VSC) that regulates power flow through the switching operation of semiconductor devices, such as Insulated Gate Bipolar Transistors (IGBTs) or Metal–Oxide–Semiconductor Field-Effect Transistors (MOSFETs). The typical architecture of a STATCOM is illustrated in Figure 2.

As shown in Figure 2, the controller injects reactive power into the system to support voltage regulation and improve overall system stability. Although this approach provides significant performance advantages, it also introduces challenges related to harmonic distortion. The high-frequency switching actions of the power electronic devices generate harmonic components in both voltage and current waveforms. If not properly mitigated, these harmonics can degrade system performance, reduce power quality, increase power losses, and adversely affect the operation and lifespan of connected electrical equipment.

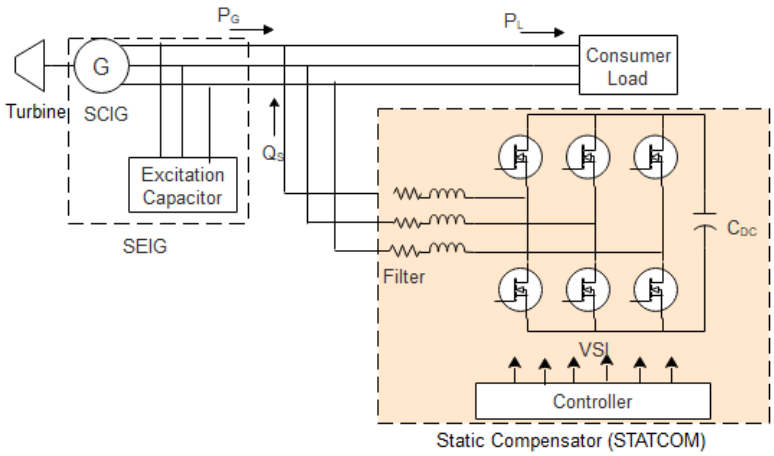


Figure 2. The schematic diagram of SEIG-STATCOM

The application of ELCs employing conventional PI/PID controllers is often constrained by the inherent limitations of linear control structures, including relatively slow dynamic response and reduced effectiveness under varying operating conditions. On the other hand, STATCOM-based solutions offer superior dynamic performance and reactive power compensation capabilities but may introduce harmonic distortion due to the high-frequency switching of power electronic devices. These limitations have motivated extensive research toward the development of control strategies that are nonlinear, adaptive, and capable of providing fast and robust responses under diverse operating conditions. Intelligent control methods have emerged as promising alternatives to address these challenges. Among them, the Fuzzy Logic Controller (FLC) has demonstrated the ability to effectively handle nonlinear systems and uncertainties without requiring an accurate mathematical model of the plant [13]. Furthermore, hybrid control schemes, such as Fuzzy-PI controller [14], have been reported to provide faster dynamic responses, reduced overshoot, and improved disturbance rejection compared with conventional PI controllers. Another widely adopted intelligent control technique is the Artificial Neural Network (ANN), which is capable of learning and modeling complex input–output relationships through a training process based on historical or simulated datasets [15]. In addition, hybrid approaches that combine Fuzzy Logic and ANN, commonly known as Neuro-Fuzzy Control (NFC), offer further performance enhancements by automatically tuning fuzzy membership functions through learning mechanisms. As a result, NFC-based controllers can achieve faster convergence, lower control errors, and more accurate voltage and frequency regulation compared with standalone intelligent or conventional control approaches [16], [17].

This paper presents a comprehensive review of control strategies for Self-Excited Induction Generator (SEIG)-based systems employing either Electronic Load Controllers (ELCs) or Static Synchronous Compensators (STATCOMs). The review encompasses conventional control techniques, such as Proportional–Integral (PI) and Proportional–Integral–Derivative (PID) controllers, intelligent control approaches including Fuzzy Logic Controllers (FLCs) and Artificial Neural Networks (ANNs), as well as hybrid control schemes that integrate conventional and intelligent methods, such as Fuzzy-PI and Neuro Fuzzy Control (NFC). In addition, this review examines advanced intelligent control strategies combined with optimization techniques, including Particle Swarm Optimization (PSO), Modified Perturb and Observe (MP&O) algorithm, Hill Climbing Algorithm (HCA) and Genetic Algorithm (GA). These optimization-assisted controllers have attracted considerable attention due to their potential to enhance controller tuning, improve dynamic performance, and achieve superior voltage and frequency regulation under varying operating conditions. Furthermore, this paper addresses the following research questions:

- What are the prevailing research trends in maintaining voltage and frequency regulation in Renewable Energy Source (RES)-based Self-Excited Induction Generator (SEIG) systems,

particularly regarding the use of Electronic Load Controllers (ELCs) and Static Synchronous Compensators (STATCOMs)?

- Which control strategies are most frequently implemented in RES-based SEIG systems?
- What sensing and feedback variables are commonly employed for controller evaluation and performance assessment?

Furthermore, this review assesses the performance of the reported control strategies based on key performance indicators, including voltage regulation, frequency regulation, dynamic response, and harmonic distortion. Through this comparative analysis, the review aims to determine the most effective control approaches for enhancing the stability and power quality of RES-based SEIG systems.

2. Method

The search for journal and conference articles related to the application of Electronic Load Controllers (ELCs) and Static Synchronous Compensators (STATCOMs) in renewable energy-based electrical power generation systems employing three-phase Self-Excited Induction Generators (SEIGs) was conducted for the period from 2020 to 2026. The literature search covered several major databases, including IEEE Xplore, Google Scholar, Emerald, IOP Conference Series, JSTOR, ScienceDirect, Springer, and Taylor & Francis. Only articles published in reputable journals and conference proceedings indexed by Scopus were considered. Relevant studies were identified using combinations of keywords such as “ELC”, “renewable energy”, “SEIG”, “control”, “STATCOM”, “voltage regulation”, and “frequency regulation”. The initial search yielded a total of 115 articles. The screening process was subsequently carried out according to predefined inclusion criteria. Only articles published in English and focusing on control strategies for RES-based SEIG systems were retained. Furthermore, the selected studies were required to evaluate controller performance based on at least one of the following criteria: voltage regulation, frequency regulation, harmonic distortion mitigation, or dynamic response characteristics. After a detailed screening, selection, and filtering process, 52 articles were identified as relevant and suitable for inclusion in this review. The article selection procedure and the final distribution of the reviewed studies are presented in Table 1.

Table 1. The search articles of SEIG with ELC or STATCOM from RES in 2020-2026.

Journal	Articles number
Emerald	1
Google Scholar	20
IEEE	8
IOP Conference Series	2
JSTOR (SAGE)	1
Nature	1
Science Direct	12
Springer	2
Taylor & Francis	2
WILEY	3

3. Result and Discussion

The control strategies employed in ELC- and STATCOM-based RES-SEIG systems are required to achieve satisfactory performance in terms of voltage and frequency regulation, harmonic distortion mitigation, and dynamic response. The reviewed studies were analyzed based on the control methods implemented, the types of sensors and feedback variables utilized, the renewable energy application areas, and key performance indicators, including voltage regulation, frequency regulation, Total Harmonic Distortion (THD), and dynamic response characteristics. A comparative performance analysis of the selected studies is presented in Tables 2 and 3, which summarize and compare the reported control

strategies, sensing approaches, application domains, and system performance outcomes.

Table 2 presents the control strategies employed in Electronic Load Controller (ELC)-based systems. It can be observed that voltage sensors are the most frequently used feedback elements compared with current and frequency sensors across various control approaches, including conventional controllers such as PI, PID, and PWM-based controllers, as well as intelligent and hybrid intelligent control schemes. This preference is primarily attributed to the direct relationship between terminal voltage regulation and power quality requirements in SEIG-based generation systems. Regarding application areas, the reviewed studies indicate that ELCs are more commonly implemented in hydropower generation systems than in wind energy applications. This trend can be attributed to the widespread deployment of SEIG-based micro-hydropower plants in remote and isolated regions, where ELCs provide a cost-effective and reliable solution for maintaining voltage and frequency stability under varying load conditions.

Table 2. Connection of three phase SEIG and ELC Controller / Optimization Method from RES

References	**ELC Controller / Optimization Method**	**Sensor**	**RES**	**Regulation V,f**	**THD_v and THD_i**	**Dynamic Response**
[18]	PWM / PSO	V	Micro Hydro	accurate	-	accurate
[19]	PI / MP&O algorithm	V, I	Micro Hydro	accurate	-	accurate
[6], [8], [9], [20]	PI	V, I	Micro Hydro	Less accurate	-	Less accurate
[21]	Hybrid Fuzzy-PI	V	Pico Hydro	accurate	2.8% and 2.1 %	accurate
[22]	Hybrid Fuzzy-PI	V, I	Wind	accurate	-	accurate
[23]	PI	V	Wind	Less accurate	-	Less accurate
[24]	PI	V, I	Wind	Less accurate	-	Less accurate
[25]	PWM	I	Pico Hydro	Less accurate	-	Less accurate
[26]	IC PWM / HCA	I	Wind	accurate	-	accurate
[27]	PI, NN / Machine Learning	V	Micro Hydro	accurate	-	accurate
[28]	PWM / SP&O algorithm	V, I	Micro Hydro	accurate	-	accurate
[29]	PID	V	Pico Hydro	Less accurate	-	Less accurate
[30], [31]	NN	f	Hydro	accurate	-	accurate
[32]	ZCD	V, f	Micro Hydro	Less accurate	-	accurate

[Description : ZCD = Zero Crossing Detector, SP&O = Simplified Perturb and Observe]

Table 3 presents the control strategies employed in STATCOM-based systems. In contrast to ELC-based applications, voltage, current, and frequency sensors are utilized with relatively similar frequency as feedback signals across various control approaches, including conventional controllers such as PI, PID, and PWM-based controllers, as well as intelligent and hybrid intelligent control schemes. This observation reflects the multifunctional role of STATCOMs, which require the monitoring of multiple electrical variables to achieve effective voltage regulation, reactive power compensation, and overall system stability. With regard to application areas, the reviewed studies indicate that STATCOMs are more frequently implemented in wind energy systems and hybrid wind–solar generation systems. This trend is largely driven by the intermittent and highly variable nature of these renewable energy sources, which necessitates fast and adaptive control strategies capable of

maintaining voltage stability, enhancing power quality, and supporting dynamic system performance under fluctuating operating conditions.

Table 3. Connection of three phase SEIG and STATCOM Controller / Method from RES

References	STATCOM Controller / Method	Sensor	RES	Regulation V,f	THD	Dynamic Response
[33]	PI / LMA	V, f	Wind	accurate	< 5%	accurate
[34], [35]	Fuzzy / Sliding Mode	V	Wind	accurate	-	accurate
[7]	PI / FCS – MPC	V	Wind/ Hydro	accurate	-	accurate
[12]	PID	V	Wind	Less accurate	-	accurate
[13]	Fuzzy	V	Wind	accurate	-	accurate
[34]	PI, LBC	V, I	Wind	accurate	-	accurate
[37]	PI / dq and CSD	V, I	Wind	accurate	-	accurate
[38]	FPGA / OCC	V	Wind	accurate	-	accurate
[16], [17]	NFC	V	Wind	accurate	-	accurate
[39]	PI, Fuzzy	V	Wind/Hydro	accurate	-	accurate
[40]	PID / LQR, LQI, LQFOI	V, f	Wind	accurate	-	accurate
[41]	PI / FH-PLL	V, I	Wind	accurate	-	accurate
[42]	SMC, RBFNN	I	Wind	accurate	-	accurate
[43]	FOPID	V, I	Wind	accurate	-	accurate
[44], [45]	CSD	V, I	Wind	accurate	-	accurate
[46]	Andronov-HOPF Oscillator	V, I, f	Wind	accurate	< 5%	accurate
[47]	PI	V, I	Wind	Less accurate	-	Less accurate
[48]	PI, GIC	V, f	Micro Hydro	accurate	-	accurate
[49]	PI, Fuzzy	V, I, f	Hybrid Wind-Solar	accurate	-	accurate
[50]	PI, Fuzzy / ESOGI	I	Hybrid Wind-Solar	accurate	-	accurate
[51]	MPPT / P&O Algorithm	V, I	Hybrid Wind-Solar	accurate	-	accurate
[52]	PI, Resonant	V, I, f	Hybrid Hydro-Solar	Less accurate	< 5%	accurate

[Description : LMA = Leaky Momentum-Control Algorithm, FCS = Finite Control Set, MPC = Model Predictive Control, LBC = Lyapunov Based Control, CSD = Current Synchronous Detection, FPGA = Field Programmable Gate Array, OCC = One Cycle Control, NFC = Neuro Fuzzy Control, SMC = Sliding Mode Controller, RBFNN = Radial Basic Function Neural Network, FOPID = Fractional Order PID, GIC = Generalized Impedance Controller, ESOGI = Enhanced Second Order Generalized Integrator.]

Figure 3 illustrates the Total Harmonic Distortion (THD) performance reported for ELC- and STATCOM-based systems in the reviewed studies [5], [18], [21], [33], [52]. The results indicate that hybrid control schemes combining intelligent and conventional control techniques, together with appropriate filtering methods, achieve superior harmonic mitigation performance. As shown in Figure 3, both voltage THD and current THD obtained using these hybrid control approaches remain well within the limits specified by IEEE Standard 519, with THD values consistently maintained below 5%. These findings demonstrate that the integration of intelligent control algorithms with conventional controllers and filtering techniques can effectively suppress harmonics while simultaneously improving voltage and frequency regulation in RES-based SEIG systems.

For future research, advancements in hardware technologies, particularly in microcontrollers and power electronic devices, offer significant opportunities for improving the practical implementation of control systems in RES-based SEIG applications. The increasing computational capability and high-speed signal processing performance of modern embedded platforms enable the realization of advanced control algorithms in real-time environments. Examples of such platforms include ESP32 [14], dSPACE-DS1104 [20] and DSPIC30F401 [23], which have demonstrated promising potential for cost-effective and high-performance control applications. Furthermore, the integration of intelligent control techniques with optimization algorithms is expected to remain an active and rapidly evolving research area. Optimization-assisted controllers can enhance parameter tuning, improve adaptability to changing operating conditions, and achieve superior dynamic performance. Several optimization techniques have been reported in the literature, including Particle Swarm Optimization (PSO) [18], Modified Perturb and Observe (MP&O) [19] and Hill Climbing Algorithm (HCA) [26]. The combination of these optimization methods with intelligent control approaches, such as Fuzzy Logic Controllers and Artificial Neural Networks systems, is anticipated to further improve voltage and frequency regulation, harmonic mitigation, and overall power quality in RES-based SEIG systems.

Despite their promising performance, the practical implementation of intelligent control and optimization-based techniques presents several challenges. One of the primary limitations is the requirement for large volumes of high-quality data that accurately represent the operating conditions and dynamic characteristics of the system. The processes of data acquisition, preprocessing, and model training can be time-consuming and costly, which may limit their applicability in resource-constrained environments. In addition, the deployment of advanced intelligent controllers on low-cost and low-power microcontroller platforms may be constrained by computational complexity and memory requirements. Real-time execution of sophisticated optimization and learning algorithms can impose a significant processing burden, potentially affecting controller performance and system reliability. To address these challenges, MATLAB/Simulink provides an effective preliminary platform for system modeling, controller design, and performance evaluation. Comprehensive simulation studies can be conducted to validate control strategies under a wide range of operating conditions before practical implementation. Such an approach helps reduce development costs, identify potential issues at an early stage, and improve the likelihood of successful deployment in real-world RES-based SEIG systems.

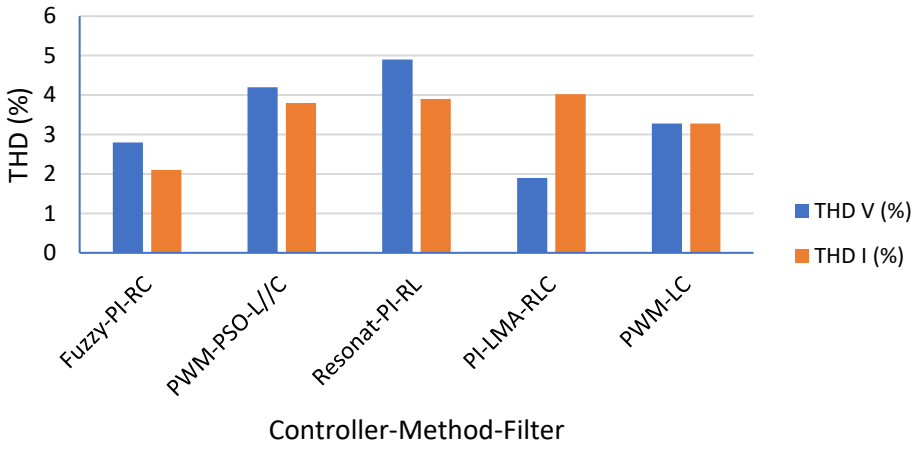


Figure 3. THD of voltage and current using certain controller, method and filter.

4. Conclusion

For Renewable Energy Source (RES)-based applications employing Self-Excited Induction Generators (SEIGs), Electronic Load Controllers (ELCs) are predominantly utilized in hydropower generation systems, whereas Static Synchronous Compensators (STATCOMs) are more commonly applied in wind energy systems. Based on the reviewed literature, both ELCs and STATCOMs achieve superior performance when integrated with intelligent control strategies and optimization techniques. The findings further indicate that intelligent and optimization-assisted control methods provide enhanced voltage and frequency regulation, improved dynamic response, and effective harmonic mitigation. In most reported studies, the Total Harmonic Distortion (THD) of both voltage and current remains below the 5% limit specified by IEEE Standard 519, demonstrating compliance with accepted power quality requirements. Future research should focus on the continued development of intelligent control algorithms and advanced optimization techniques to further enhance system adaptability, robustness, and real-time performance. In addition, efforts should be directed toward reducing computational complexity and facilitating practical implementation on cost-effective embedded platforms for RES-based SEIG applications.

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