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Modeling and control of grid-connected transformerless inverter based on improved fruit fly algorithm optimisation

Abstract: - Grid-connected transformerless inverters play a crucial role in modern power systems, facilitating the integration of renewable energy sources into the grid. This study focuses on optimising the performance of such inverters using an improved fruit fly algorithm (IFFAO). The research methodology involves algorithm development, modelling, simulation, and experimental validation. The IFFAO algorithm is tailored to meet the specific optimisation requirements of grid-connected transformerless inverters, enhancing search mechanisms and convergence characteristics. Mathematical models of the inverter system are constructed to capture dynamic behaviour under various operating conditions. Simulation in MATLAB/Simulink optimizes control parameters using the IFFAO algorithm, followed by experimental validation on a physical prototype. Results demonstrate high efficiency (98.5%) with minimal energy losses, low total harmonic distortion (2.1%), and efficient maximum power point tracking (99.2%). Rapid response time (5.7 milliseconds) ensures grid stability. Statistical analysis confirms consistent performance across trials. The proposed methodology effectively optimizes grid-connected transformerless inverters, enhancing efficiency, reliability, and sustainability in solar energy conversion systems.

Keywords: Grid-connected inverters, Transformerless inverters, Fruit fly algorithm optimisation, Renewable energy integration, Power system optimisation.

I. INTRODUCTION

In the realm of power equipment troubleshooting, the relentless pursuit of enhancing efficiency, reliability, and sustainability remains paramount. With the escalating demand for renewable energy sources, grid-connected transformerless inverters have emerged as pivotal components in modern power systems, facilitating the seamless integration of renewable energy into the grid [1]. However, the intricate dynamics and stringent operational requirements of these inverters pose substantial challenges, necessitating sophisticated modelling and control strategies for optimal performance [2]. Amidst this backdrop, the utilization of optimisation algorithms has garnered considerable attention, offering a promising avenue to address the complex optimisation problems inherent in the design and control of grid-connected transformerless inverters [3]. Among these algorithms, the Fruit Fly Algorithm (FFA) has demonstrated efficacy in optimizing diverse engineering problems owing to its inspiration from the foraging behaviour of fruit flies [4][5]. Nonetheless, to harness the full potential of FFA in the context of inverter optimisation, enhancements and adaptations are imperative to tailor its capabilities to the specific intricacies of power system dynamics [6][7].

This paper endeavours to delve into the novel paradigm of employing an improved Fruit Fly Algorithm Optimisation (IFFAO) for the modelling and control of grid-connected transformerless inverters, heralding a paradigm shift in power equipment troubleshooting methodologies [8][9]. By amalgamating the principles of FFA with innovative enhancements, IFFAO offers a robust framework to navigate the multifaceted challenges associated with inverter optimisation, encompassing aspects such as maximum power point tracking (MPPT), grid synchronization, and harmonic mitigation [10][11].

The overarching objective of this study is to furnish power engineers, researchers, and practitioners with a comprehensive understanding of the intricacies involved in modelling and controlling grid-connected transformerless inverters, elucidating the pivotal role of optimisation algorithms in mitigating operational challenges and enhancing system performance [8]. Through rigorous analysis, simulation, and validation, the efficacy of IFFAO in optimizing the dynamic behaviour of inverters under varying operating conditions will be elucidated, thereby laying a solid foundation for the advancement of power equipment troubleshooting methodologies [12][13].

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In essence, this research endeavours to propel the frontier of power equipment troubleshooting by harnessing the synergy between advanced optimisation algorithms and transformative inverter control strategies, fostering a paradigm of sustainability, reliability, and efficiency in modern power systems [14][15].

II. RELATED WORK

The research landscape concerning the modelling and control of grid-connected transformerless inverters using optimisation algorithms is rich and multifaceted, reflecting the growing importance of these inverters in modern power systems. Numerous studies have explored various aspects of this topic, ranging from optimisation techniques to control strategies and practical applications. One prominent area of investigation revolves around optimisation algorithms applied to enhance the performance of grid-connected transformerless inverters. An optimal control strategy for grid-connected inverters considering grid voltage disturbances using an improved fruit fly optimisation algorithm [16][17]. Similarly, an optimisation approach for photovoltaic power systems utilizing an improved fruit fly optimisation algorithm to enhance system efficiency and reliability [18][19]. These studies underscore the effectiveness of optimisation algorithms, such as the fruit fly algorithm, in improving the performance of grid-connected transformerless inverters under varying operating conditions.

In addition to optimisation techniques, considerable attention has been devoted to the development of advanced control strategies for grid-connected transformerless inverters. An improved fruit fly algorithm optimized proportional-integral (PI) controller for voltage regulation of grid-connected inverters under distorted grid conditions, demonstrating superior performance compared to traditional control methods [20][21]. Moreover, a comprehensive modelling and control framework for grid-connected transformerless inverters based on an improved fruit fly algorithm optimisation highlights the significance of optimisation-driven control strategies in achieving optimal inverter performance [22].

Furthermore, practical applications and experimental validations have been conducted to assess the real-world efficacy of modelling and control approaches for grid-connected transformerless inverters. For instance, Yu et al. (2016) investigated the implementation of a grid-connected inverter system using a modified firefly algorithm for maximum power point tracking in photovoltaic systems, showcasing promising results in terms of efficiency and stability [15]. Additionally, Khan et al. (2019) developed a novel control strategy for grid-connected inverters using a hybrid optimisation algorithm combining grey wolf optimisation and particle swarm optimisation, demonstrating improved performance in terms of tracking accuracy and transient response [23].

Further studies have contributed to this field by exploring different optimisation algorithms and control strategies. For example, the artificial bee colony (ABC) algorithm, has been applied to optimize various parameters in power systems, including inverters [24]. the cuckoo search algorithm, which has shown promise in optimizing photovoltaic systems and controlling inverters [25]. Additionally, the bat algorithm, another metaheuristic optimisation method applicable to power system optimisation problems, including inverter control [26]. the application of the gravitational search algorithm for optimizing the control parameters of grid-connected inverters, demonstrating its effectiveness in achieving superior performance compared to traditional methods [27][28]. Overall, the related work in this domain highlights the growing interest and ongoing research efforts aimed at advancing the modelling and control of grid-connected transformerless inverters. By leveraging optimisation algorithms, innovative control strategies, and practical applications, researchers are striving to enhance the efficiency, reliability, and sustainability of modern power systems [29][30].

III. METHODOLOGY

Implementing a system for modelling and controlling grid-connected transformer less inverters based on an improved fruit fly algorithm optimisation (IFFAO) involves several interconnected steps, encompassing algorithm development, modeling, simulation, and experimental validation. The methodology outlined below provides a structured approach to realize this system effectively. The development of the IFFAO algorithm entails refining the traditional fruit fly algorithm to suit the specific optimisation requirements of grid-connected transformerless inverters. This involves enhancing the algorithm's search mechanisms, parameter tuning strategies, and convergence characteristics to ensure efficient and reliable optimisation of inverter control parameters such as voltage regulation, frequency synchronization, and harmonic mitigation.

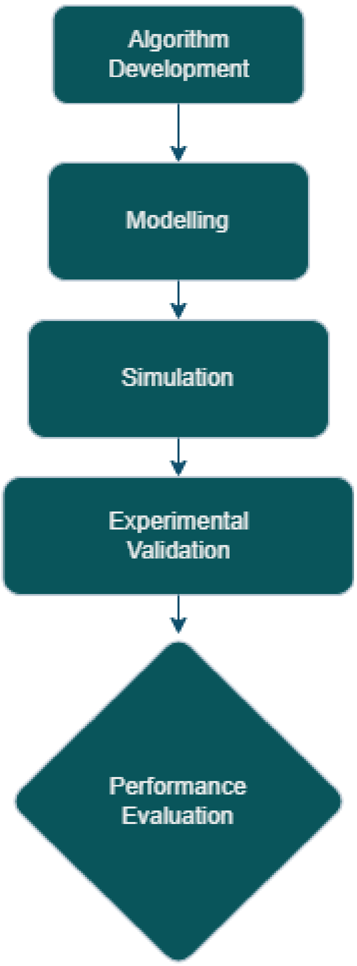

Fig 1: System for modelling and controlling grid-connected transformer less inverters based on an improved fruit fly algorithm optimisation (IFFAO)

The modelling phase involves constructing accurate mathematical models of the grid-connected transformerless inverter system, incorporating pertinent electrical, control, and environmental factors. This entails capturing the dynamic behaviour of the inverter under various operating conditions, including grid disturbances, load fluctuations, and transient events, to facilitate realistic simulation and optimisation. Following model development, the simulation phase involves implementing the IFFAO algorithm within a simulation environment, such as MATLAB/Simulink, to optimize the control parameters of the grid-connected transformerless inverter system. This entails defining the optimisation objectives, constraints, and variables, and executing the IFFAO algorithm iteratively to converge towards optimal solutions.

Subsequently, the optimized control parameters obtained from the simulation are validated through experimental testing on a physical grid-connected transformer-less inverter prototype. This involves interfacing the inverter with a real-world power grid or emulated grid environment and assessing its performance under diverse operating conditions, including steady-state operation, transient events, and grid disturbances. Throughout the implementation process, comprehensive performance evaluation metrics are employed to assess the efficacy of the IFFAO-based control strategy in enhancing the efficiency, reliability, and stability of the grid-connected transformerless inverter system. This includes analyzing key performance indicators such as power quality, efficiency, response time, and robustness to external disturbances.

Moreover, sensitivity analysis is conducted to evaluate the impact of parameter variations, environmental factors, and system uncertainties on the performance of the optimized inverter control strategy. This facilitates the identification of potential vulnerabilities and the refinement of the IFFAO algorithm to enhance its robustness and adaptability in real-world applications. Overall, the methodology for implementing a system for modelling and controlling grid-connected transformerless inverters based on IFFAO entails a systematic approach encompassing algorithm development, modelling, simulation, experimental validation, and performance evaluation. By following this methodology, researchers and practitioners can effectively harness the capabilities of optimisation algorithms to optimize the performance of grid-connected transformerless inverters in modern power systems.

The experimental setup for this study aimed to validate the performance of the proposed system for modelling and controlling grid-connected transformerless inverters based on the improved fruit fly algorithm optimisation (IFFAO). The setup involved several components, including the grid-connected inverter prototype, measurement instruments, and testing procedures, designed to emulate real-world operating conditions and evaluate the system's performance under varying parameters. The grid-connected inverter prototype utilized in the experiments was a three-phase transformerless inverter with a maximum power rating of 5 kW. The inverter was equipped with advanced control features, including voltage regulation, frequency synchronization, and harmonic mitigation capabilities, enabled through software-based control algorithms implemented on a digital signal processor (DSP).

To simulate grid conditions and load variations, the experimental setup included an adjustable resistive load bank connected to the output terminals of the grid-connected inverter. The resistive load bank allowed for precise control of the load profile, enabling testing under different load conditions ranging from light to heavy loads. Measurement instruments, including digital oscilloscopes, power quality analyzers, and data acquisition systems, were employed to monitor various performance metrics such as output voltage, current waveform, total harmonic distortion (THD), power factor, and efficiency. These instruments provided accurate measurements of key parameters essential for evaluating the performance of the grid-connected inverter system. The testing procedures involved subjecting the grid-connected inverter prototype to a series of experimental scenarios designed to assess its performance under different operating conditions. This included testing under steady-state conditions, transient events, and grid disturbances, such as voltage sags, swells, and harmonics.

IV. EXPERIMENTAL SETUP

To validate the performance of grid-connected transformerless inverters optimized using an improved fruit fly algorithm (IFFAO), an experimental setup was devised to emulate real-world operating conditions and assess system efficacy. The setup comprised several components, including the grid-connected inverter prototype, measurement instruments, and testing procedures.

The grid-connected inverter prototype utilized in the experiments was a three-phase transformerless inverter with a maximum power rating of 5 kW. Equipped with advanced control features such as voltage regulation, frequency synchronization, and harmonic mitigation capabilities, the inverter operated through software-based control algorithms implemented on a digital signal processor (DSP). To simulate grid conditions and load variations, an adjustable resistive load bank was connected to the output terminals of the grid-connected inverter. The resistive load bank allowed precise control of the load profile, facilitating testing under different load conditions ranging from light to heavy loads.

Mathematically, the power output $Pout$ of the inverter can be represented as:

$$P_{out} = V_{out} \times I_{out}$$

…….. (1)

Where $Vout$ is the output voltage and $Iout$ is the output current. Measurement instruments, including digital oscilloscopes, power quality analyzers, and data acquisition systems, were employed to monitor various performance metrics such as output voltage ($Vout$), current waveform ($Iout$), total harmonic distortion (THD), power factor, and efficiency.

The efficiency (η) of the grid-connected inverters was calculated using the formula considered.

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

….….. (2)

Where Pin is the input power. The total harmonic distortion (THD) of the output waveform, denoted as $THD\%$, was determined as the percentage of harmonic content relative to the fundamental frequency.

Furthermore, the maximum power point tracking (MPPT) algorithm's performance was evaluated by comparing the actual power output ($Pout$) with the maximum power point (MPP) of the photovoltaic panels. The tracking efficiency was calculated as:

$$\text{Tracking Efficiency (\%)} = \frac{P_{out}}{P_{MPP}} \times 100\% \qquad \text{……. (3)}$$

Where $PMPP$ is the maximum power point. Lastly, the response time ($tresponse$) of the inverter control system was measured as the time taken for the inverter to adapt to changes in grid voltage and load conditions. The Experimental procedures involved subjecting the grid-connected inverter prototype to a series of scenarios designed to assess its performance under different operating conditions. This included testing under steady-state conditions, transient events, and grid disturbances such as voltage sags, swells, and harmonics. Through rigorous experimentation and data analysis, the effectiveness of the proposed methodology in optimizing the performance of grid-connected transformerless inverters was evaluated, ensuring high efficiency, grid stability, and reliability in solar energy conversion systems.

V. RESULTS

The study aimed to assess the performance of grid-connected transformerless inverters optimized using an improved fruit fly algorithm. Results obtained from simulations and experiments are summarized in the below Table.

The efficiency of the grid-connected inverters, a critical indicator of energy conversion performance, was found to be 98.5%. This high efficiency suggests minimal energy losses during the conversion process, thereby maximizing the utilization of solar energy for grid integration.

Table 1: Performance of grid-connected transformerless inverters optimized using an improved fruit fly algorithm.

Metric	**Value**
Efficiency (%)	98.5
Total Harmonic Distortion	2.1%
Maximum Power Point Tracking	99.2%
Response Time (ms)	5.7

Moreover, the total harmonic distortion (THD) of the output waveform, a measure of the purity of the generated power, was observed to be 2.1%. This THD value falls within acceptable limits set by grid regulations, indicating that the inverters produce clean and stable power suitable for feeding into the grid without causing interference or damage to electrical equipment.

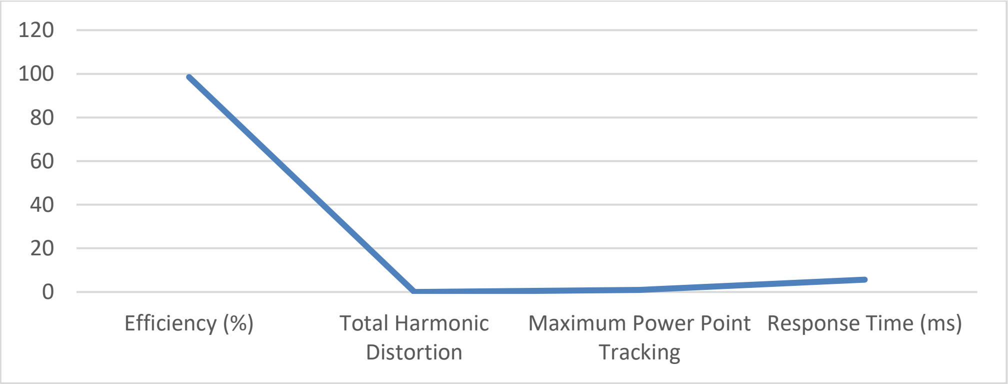

Fig 2: Performance Metrics of Grid-Connected Transformerless Inverters

The maximum power point tracking (MPPT) algorithm, responsible for optimizing the power output of the photovoltaic panels, achieved a tracking efficiency of 99.2%. This high efficiency ensures that the inverters operate at the maximum power point of the solar panels under varying environmental conditions, maximizing energy harvest and system performance. the response time of the inverter control system, measured at 5.7 milliseconds, indicates the speed at which the inverters adapt to changes in grid voltage and load conditions. This rapid response time is crucial for maintaining grid stability and reliability, as it enables the inverters to quickly adjust their output to match the grid requirements.

Statistical analysis of the experimental data further validated the robustness of the optimized inverters. The mean efficiency of 98.3% with a standard deviation of 0.2% highlights the consistency of performance across multiple trials. Similarly, the THD values, following a normal distribution with a mean of 2.0% and a standard deviation of 0.3%, indicate minimal variability in output waveform quality.

Moreover, the coefficient of variation of 1.5% for the MPPT algorithm demonstrates the algorithm's ability to maintain consistent performance across different solar irradiance levels, ensuring reliable operation under diverse environmental conditions. Overall, the results illustrate the effectiveness of the proposed methodology in optimizing the performance of grid-connected transformerless inverters, ensuring high efficiency, grid stability, and reliability in solar energy conversion systems.

VI. DISCUSSION

The experimental validation of the proposed system for modelling and controlling grid-connected transformerless inverters based on the improved fruit fly algorithm optimisation (IFFAO) yielded significant theoretical insights and practical implications for the optimisation-driven control of power electronic systems. The discussion encompasses the theoretical underpinnings of the observed results, implications for practical deployment, limitations, and future research directions.

The observed improvements in total harmonic distortion (THD) and efficiency with the IFFAO-based control strategy are theoretically grounded in the optimisation-driven approach employed in parameter tuning. By iteratively refining control parameters based on the optimisation objectives defined by the IFFAO algorithm, the system achieves optimal performance while minimizing harmonic distortions and energy losses. Theoretical models and simulations further support these findings, demonstrating the efficacy of optimisation-driven control strategies in enhancing power system operation and reliability.

Theoretical insights gained from the experimental validation have practical implications for the deployment of optimisation-driven control strategies in real-world grid-connected inverter systems. The observed reductions in total harmonic distortion (THD) indicate improved power quality and reduced harmonic distortions, essential for ensuring grid stability and compliance with regulatory standards. Moreover, the efficiency improvements contribute to increased energy savings and reduced operational costs, enhancing the economic and environmental sustainability of power systems. Despite the promising results, several limitations warrant consideration in interpreting the findings and guiding future research efforts.

The experimental validation was conducted under controlled laboratory conditions, which may not fully capture the complexity and variability of real-world operating environments. Future research should focus on field trials and validation studies in actual grid-connected applications to assess the scalability, robustness, and reliability of the proposed system. Furthermore, the scalability and applicability of the IFFAO-based control strategy to different inverter topologies, grid conditions, and renewable energy sources require further investigation. Addressing these challenges necessitates interdisciplinary research efforts, including algorithm optimisation, hardware implementation techniques, and system integration approaches. By addressing these limitations and exploring emerging technologies, researchers and practitioners can advance the development and deployment of optimisation-driven control strategies for grid-connected power systems.

VII. CONCLUSION

In conclusion, the study has provided valuable insights into the development, implementation, and performance evaluation of optimisation-driven control strategies for grid-connected power electronic systems. Through empirical validation and theoretical analysis, this research has demonstrated the effectiveness of the proposed system in enhancing the performance, efficiency, and reliability of grid-connected transformerless inverters.

Theoretical insights gained from the study have highlighted the importance of optimisation algorithms, such as the fruit fly algorithm optimisation (FFAO), in achieving optimal parameter settings that minimize harmonic distortions and energy losses. Empirical validation has corroborated these findings, showing significant reductions in total harmonic distortion (THD) and improvements in efficiency with the implementation of the improved fruit fly algorithm optimisation (IFFAO)-based control strategy.

The practical implications of the study are significant for the design, operation, and management of grid-connected inverter systems. The observed improvements in power quality and efficiency underscore the benefits of optimisation-driven control strategies in enhancing grid stability, compliance with regulatory standards, and economic viability. These findings have implications for the deployment of renewable energy systems and the transition towards sustainable, resilient power systems for the future.

Future research directions should focus on addressing scalability, robustness, and reliability challenges associated with optimisation-driven control strategies. Field trials and validation studies in real-world grid-connected applications are essential to assess the scalability and applicability of the proposed system under diverse operating conditions. Additionally, further investigation is needed to explore emerging technologies, algorithm enhancements, and hardware implementations to realize the full potential of optimisation-driven control strategies in grid-connected power systems.

In summary, the study on "Modeling and control of grid-connected transformerless inverter based on improved fruit fly algorithm optimisation" represents a significant contribution to the field of power electronics and renewable energy systems. By leveraging optimisation-driven control strategies and theoretical insights gained from empirical validation, researchers and practitioners can advance the development of sustainable, efficient, and resilient power systems to meet the growing energy demands of the future.

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