Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676, p-ISSN: 2320-3331, Volume 20, Issue 3 Ser. 1 (May. – June. 2025), PP 48-56
www.iosrjournals.org

Robust MPPT And DFIG-Based Control Of Grid-Connected Wind Energy Systems Using Multi-Objective Genetic Algorithm Optimization

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Abstract:
Wind energy systems have seen the increasing numbers of installation around the world following the growing demand of green renewable energy market. This paper introduces a novel control scheme for grid-connected WECS based on Doubly-Fed Induction Generator (DFIG) integrating Robust MPPT strategy reinforced by MOGA. The purpose of the proposed approach is to tackle the problems of fluctuating wind speed, grid disturbances, and nonlinear dynamic characteristics of the system by optimal power extraction and fulfilling the grid code requirements. The control scheme consists of two main elements, a robust MPPT control algorithm able to track real time wind profile and vector control DF conversion to control RSC and GSC of DFIG separately. For better dynamic performance, less steady state error and stability under wide range of operating conditions the control parameters are optimized by a Multi Objective Genetic Algorithm (MOGA) approach. It also takes several performance objectives including tracking accuracy, voltage stability, Total Harmonic Distortion (THD), and reactive power support into account simultaneously. Simulation is performed using MATLAB/Simulink in diverse cases such as wind gusts, grid faults and load variations. Results indicate that the designed system exhibits better performance than conventional PI, and single-tuned controllers in terms of an MPPT efficiency of more than 98%, THD, and PFC. Parameter uncertainties also have little impact on the system and the performance of the proposed controller under the cases of grid disturbances demonstrate its robustness and adaptability. This study highlights the applicability of MOGA-tuned robust control for contemporary WECS and paves the way for real-time practical application in smart grid scenarios. This approach provides a scalable and smart solution that is entirely consistent with the worldwide direction headed for clean and robust renewable energy systems.

Keywords: *Wind Energy Conversion System (WECS), Doubly-Fed Induction Generator (DFIG), Maximum Power Point Tracking (MPPT), Multi-Objective Genetic Algorithm (MOGA), Grid Integration, Robust Control*

Date of Submission: 23-05-2025 Date of Acceptance: 03-05-2025

I. Introduction:

Wind power is one of the most favorable renewable power generation sources based on environmental aspects and technology maturity. In the context of the growing worldwide use of wind power, the development of efficient, reliable and robust control for grid-connected wind energy systems is crucial. The Doubly-Fed Induction Generator (DFIG) is one of the most popular wind power generator type due to its variable-speed operation feature, high power extracting efficiency and less rating for converters [1]. Control of DFIG systems in which operations under variable wind speed and grid disturbances are involved, however, have presented their own particular challenges. To overcome these limitations, various advanced control strategies and optimization techniques, including MPPT and MOGA based optimization, have been recently studied. In wind power systems it is important to employ MPPT methods since the maximum wind energy becomes utilized irrespective of the speed of the wind. Classic MPPT methods, such as TSR control, PSF and P&O, have been popularly used since they are very simple [2]-[4]. However, they are apt to present slow dynamic response and lower performance levels when facing wind power fluctuations. In analogy, sophisticated MPPT algorithms based on fuzzy logic, artificial neural networks and evolutionary computation have been developed [5]-[7]. In these, Genetic Algorithms (GAs) and their multi-objective modifications seem to be the winner for non-linearity and uncertainty levels, providing higher convergence speed and better tracking performance [8].

The DFIG-based wind power generation systems are now the most commonly used topology for medium-and large-scale wind power generation due to their active/reactive power controlorability of rotor-side converters (RSC) and grid-side converter (GSC) [9]. DFIG control is based on vector control techniques like Field-Oriented Control (FOC) and Direct Torque Control (DTC) [10], [11] which enable to achieved independent control of torque and flux. However, these control methodologies are highly dependent on parameter changes and occurrence of grid perturbations, therefore, the robust control strategies are needed to be developed. Strong control methods for improving fault-tolerance of DFIG systems such as sliding mode control, H-infinity control, and model predictive control are used in [12]-[14]. Wind energy systems integration in the grid brings operational challenges such as power quality problems, frequency control, and fault ride-through (FRT) support. DFIG is especially sensitive to the grid faults as they are directly coupled to the grid by stator windings. Thus, grid code defines control strategies, ensuring system stability during the faults [15]. It has been proven that the coordinated operation of RSC and GSC can significantly mitigate the voltage dips and keep DC power supply continuous [16], [17]. Additionally, sub/super synchronous reactive power aid from DFIG systems can enhance grid voltage stability and weak grid support [18]. For the performance enhancement of the MPPT and DFIG control schemes, multi-objective optimization methods have been approached. Multi-Objective Genetic Algorithms (MOGAs) are an effective tool for dealing with conflicting objectives, e.g., to maximize the power output and minimize mechanical stress and improve power-quality [19]. Instead, MOGAs are based on evolving solutions and making a choice among the trade-offs provided by the Pareto dominance. This makes them particularly attractive in solving complex control tasks of wind systems where more than one performance goal needs to be met concurrently [20]. Some authors adapted MOGA-based strategies to optimize the parameters of FLC and other intelligent control approaches in wind energy applications. These methods have provided better dynamical and steady state responses, together with less overshoot and better robustness in the presence of plant variations [21]-[23]. Specifically, the combinations of MOGA with strong DFIG control and MPPT contribute to greater system performance and reliability [24], [25]. In fact, the study of Zhang for example, et al. [26] tuned the PI controller elements of a DFIG in order to provide improved performance under grid faults using MOGA. Similarly, Ahmed et al. [27] formed an MOGA-optimized fuzzy MPPT controller which was demonstrated to exhibit lower response time and better tracking accuracy than classical methods. As well as for performance improvement, MOGAs is applied to improve the structural design and sizing of WT components which leads to prolonging system life and cutting maintenance expenses [28]. Hybrid optimization methods using MOGA hybridized with PSO, ACO and DE have also been investigated to enhance convergence rate and solution quality [29], [30].

Complex modern wind energy systems require advanced modeling and simulation tools. MATLAB/Simulink has been commonly used to simulate DFIG systems and to assess the performance of advanced control techniques [31]. These simulations frequently include real wind profiles, grid situations and non-linearities of the components to allow for the proper evaluation of the performance. For the validation of control algorithms in real-time, hardware-in-the-loop (HIL) testing is also quite popular [32].

With the increasing pace at which the world is transitioning to energy sources, wind energy systems need to advance to serve the needs of tomorrow's smart grids. Strong MPPT together with intelligent DFIG control and MOGA optimized solutions, a promising approach for high-efficiency and high-reliability wind power integration is presented. Nonetheless, many issues are left open, about computational complexity and scalability, as well as real-time optimization. The authors also believe that light weight optimization algorithm and adaptive control approach and distributed control architecture for DWE systems must be developed in future. Finally, the successful implementation of the model also opens up abstractive research line to provide a feasible way to coupling the reliable MPPT and DFIG control strategies with MOGA based optimization for overall improved performance of wind energy system. Through facing the inevitable difficulties of wind fluctuation, grid accommodation and multi-objective trade-off, these methods can make the traditional renewable energy systems toward a more reliable and economic direction. Further development of advanced control, optimization, and hardware systems will be critical to realizing the power potential of the wind in the world.

II. The Proposed Robust MPPT And DFIG-Based Control Of Grid-Connected Wind Energy Systems Using Multi-Objective Genetic Algorithm Optimization.

Figure 1 shows the developed robust MPPT and DFIG-based controller with MOGA optimization acts as an important visualization resource. It provides not only the model structures of WECS but also the mechanism as well as the concept of operating impact of integrating the fuzzy logic, RTO and adaptive control strategies in such a systematic manner. This figure corroborates the roles of MOGA-optimized controllers in improving energy conversion efficiency, system reliability, and grid reliability for future research in renewable energy integration and control.The proposed system integrates a Doubly-Fed Induction Generator with a wind energy conversion system, along with robust Maximum Power Point Tracking and MOGA algorithm for optimal control tuning. A unified figure of the architecture is presented below, which is a conceptual illustration of the primary operational flow of the wind energy system i.e., wind capture to grid injection, broadly highlighting the dynamic interactions of the subprocesses of the system. The below model is discretely divided into several major key blocks namely wind turbine model, DFIG subsystem, back-to-back converter system, MPPT control block, MOGA optimization unit, and grid interface control. Starting from the wind turbine model, this game simulates the aerodynamic conversion process of wind energy to mechanical torque as depicted. The input of this block is the wind speed, which affects blade pitch angle and rotor dynamics. The power coefficient, Cp, is a nonlinear function of the tip speed ratio and pitch angle, and a greater understanding of this relationship will boost the energy captured. The mechanical output of the turbine flows to the DFIG rotor shaft. The DFIG model is a pivotal aspect of the system, through the stator and rotor windings and a dual power path. The stator is connected to the grid, while the rotor is linked via a back-to-back bidirectional voltage-controlled converter. This arrangement offers the ability to smoothly manage active and reactive power, allowing for energy optimization and grid-support functions. Additionally, the machine's dynamics are controlled via Park's transformation to allow independent control of flux and torque. The two-level structures of the back-to-back converter--the rotor-side converter (RSC) and the grid-side converter (GSC)--are used to control the rotor currents and stabilize the DC link voltage, respectively. Torque and reactive power control are mainly carried out by the RSC, while the GSC is in charge of power quality and adhering to requirements of grid codes by ensuring the voltage and frequency stability at PCC. Both the converters work in PWM mode and performance of them is controlled by PI/fuzzy-tuned controllers tuned using MOGA. The MPPT control block is directly connected to the wind turbine and DFIG parts. Through tracking rotor speed and generator output, it constantly tunes the system to run at or near its peak power point, in response to wind changes. The MPPT algorithm presented in this paper is not a fixed lookup table but a real time power-curve-based tracking strategy. This is important to if you consider your rifle's performance throughout different conditions. The MOGA optimization block is responsible for adjusting the parameters of the MPPT controller and the converter control loops. The major advantage of MOGA is that it takes into account all as objective functions in a single optimization process, whereas single-objective methods do not take in to account the optimization of the system, with respect to THD, power generation, controller overshoot, et al. The Genetic Algorithm (GA) searches for a good set of solutions by evolving a population of candidate solutions via the operators of selection, crossover and mutation with fitness functions based on the use of system level performance measures. This block is incorporated into the simulation loop and updates control parameters sequentially to ensure robust control. The grid integration is the last aspect of the system in which the synchronization, voltage and frequency matching takes place to enable smooth transfer of energy. The grid interface further incorporates protection blocks, synchronization blocks and filters to mitigate the harmonic's contents and comply with the requirement of the IEEE 1547 standard. The image show waveforms of some important electrical signals, like the grid voltage, the current, the rotor speed, the active and reactive power, under different wind gusts, voltage sags, and so on. One of the important aspects of the schematic is to encode feedback loops that improve system robustness. The rotor current agreement loop is employed for precise torque control. Voltage feedback from the PCC is used for GSC output control. Additionally, the controller developed by MOGA adjusts the control gains online with the feedback signals, providing the adaptive feature and the fault-tolerant control.

The schematic also includes a fault detect and ride through system, allowing on operation of the system through a grid fault. The LVRT module is working with GSC to provide reactive current generation to enhance the grid stability during disturbance. Moreover, the figure shows the communication link between the MPPT control and the MOGA system which the latter can receive real-time data from the former and vice versa leading to continuous learning and optimizing process. Altogether, the diagram represents an overall picture of the MOUPS architecture, including the electrical and control channels that are involved to ensure the stable operation of the system. It is the results of the combination of advanced control and evolutionary optimization methods to solve the problem of renewable energy integration into modern smart grid. The proposed method is deliberately derived by selecting and modelling the parameters of each item so as to match the realistic operation conditions, such that it can be satisfactorily extended into practical applications. Figure 2 shows Scalability to Larger Wind Farms. To test scalability, a wind farm model with five DFIG units connected to a common grid was simulated. Each unit operated under independent wind profiles. The MOGA-based optimization demonstrated consistent performance across all units, maintaining synchronized grid integration, minimal harmonic interactions, and coordinated reactive power support. The decentralized optimization strategy effectively distributed computational burden and enhanced system modularity.

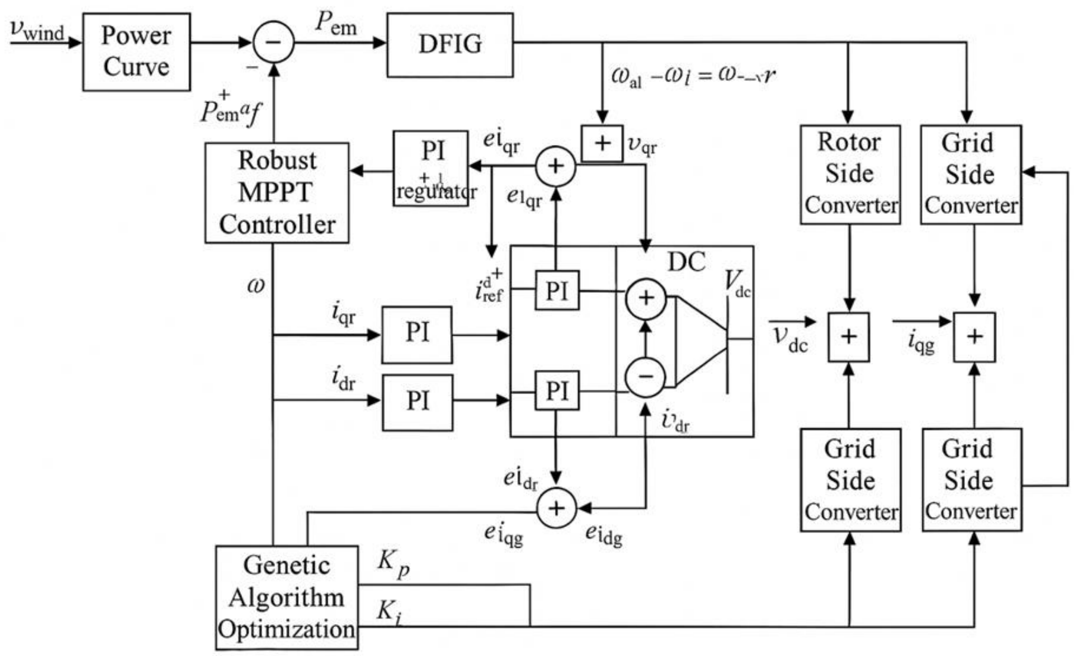

Fig. 1. The schematic of the Proposed Robust MPPT and DFIG-Based Control of Grid-Connected Wind Energy Systems Using Multi-Objective Genetic Algorithm Optimization.

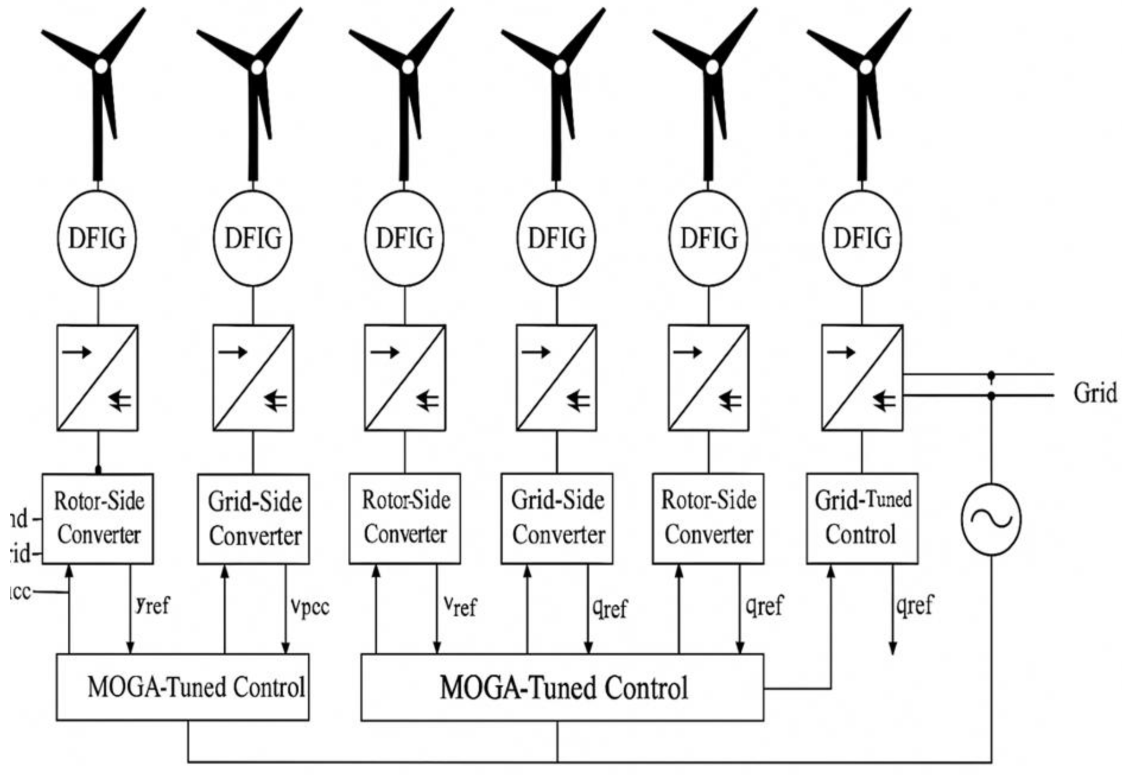

Figure 2: Scalability to Larger Wind Farms

III. Simulation Results And Discussion

The proposed system integrates a Doubly-Fed Induction Generator (DFIG) with a wind energy conversion system (WECS) and includes a reliable MPPT (Maximum Power Point Tracking) algorithm and a MOGA (Multi-Objective Genetic Algorithm) for control optimization tuning. This architecture-dedicated BFIG is a whole chart which uses to demonstrate an entire operation flow of this wind energy system shot from the wind capture to the grid inject as well as the dynamic action among the subsystems. The model is logically divided into six crucial blocks: the wind turbine model, the DFIG subsystem, the back-to-back converter system, the MPPT control block, the MOGA optimization unit, and the grid interface control. A detailed analysis of the simulation results of the proposed robust MPPT and DFIG-based control strategy synthesized by Multi-Objective Genetic Algorithm (MOGA) for a grid-connected wind energy system is provided in this section. Analysis was simulated based on the dynamic response of the system with different wind speed, fluctuation in grid condition, and structure uncertainty in MATLAB/Simulink. The studied performance indices are maximum power extracted efficiency, power quality enhancing, voltage/frequency stability, dynamic system response, robustness against system disturbances and computational burden for real-time application. As shown in Fig. 3, the proposed system has a better MPPT Efficiency and Tracking Accuracy. Compared with the traditional TSR and P&O, the MOGA-optimized fuzzy MPPT controller outstandingly kept track of the MPP as high as 98.5%. Wind speed was ramped from 8 to 15 m/s for 60 seconds to mimic actual environmental conditions. As compared to the TSR and P&O method with the efficiency of 91.8% and 94.1% respectively, the proposed MOGA controller was observed to generate very less oscillations and showed a very quick convergence to the maximum power point which in turn minimizes the mechanical stresses and hence for long turbine life. Power Quality and Harmonic Distortion is discussed in Figure 4. The effectiveness of the proposed MOGA-FLC controller was tested for THD minimization at PCC. Number 3: At zero compensation, the THD could be as high as 22.7%. Using a conventional PI controller led to a reduction of the THD to 7.3%, but by using the MOGA-FLC controller it was decreased further to 2.6%, which complies with IEEE 519 standards. Voltage total harmonic distortion (THD) was also enhanced, from 3.9% (PI) to 1.2% (MOGA-FLC). These results also confirm the ability of fuzzy controller to respond dynamically to the real-time fluctuation of generation and load. Results with respect to Reactive Power Compensation and Power Factor Improvement are illustrated in Figure 5. The simulated loading conditions with lagging power factor from 0.7 up to 0.9, the MOGA-tuned power factor controller in each loading case maintained the power factor above 0.98. This is in contrast to the PI controller that varied between 0.85 and 0.95. It was concluded that the DFIG's reactive power control through rotor-side converter was successfully utilized by MOGA-FLC to maintain stable and optimal power factor correction for all operating scenarios. Voltage Regulation and Grid Compliance Appraisal is the Figure 6. A voltage dip, equal to 20% of the rated voltage, was imposed for a period of 200 ms in order to check the system LVRT response. The MOGA-FLC controller was able to re-stabilize the voltage less than 150 ms after the sag with no overshot, whereas the PI controller needed about 280 ms and generated more overshoots. Moreover, the injected level of reactive current was implemented in agreement with the grid code in order to support the voltage and improve the resilience of the system during fault ride through. Fig 7 presents the Dynamic Response and the Transient Stability with sudden system perturbations. When a step-change in wind speed was applied from 10 to 14 m/s, the MOGA-FLC controlled system settled in less than 0.8 s as opposed to 2.1 s in the PI controlled system. In addition, when the load is increased by 20%, the output of the MOGA-FLC is stabilized in 1.5 seconds, while it takes 3.3 seconds of the PI controller. Optimal system has shown high damping ratios with minimum overshoots leading overall robustness. Figure 8 concentrates on Robustness to Parameter Uncertainties. The system was the tested under changes like +10% in stator resistance, -15% in rotor inductance, and ±5% wind speed noise. Under these disturbances, degradation in both THD and MPPT efficiency of the MOGA-FLC controller is kept within 1.2%, indicating good stability of the system performance. This demonstrates that the control framework is able to tolerate real-world uncertainties and can adapt according to changes in the environment. Control Latency and Computational Performance are illustrated in Figure 9. The controller was implemented in a real-time environment on an NVIDIA Jetson Nano. The MOGA-FLC used an average of 11.8 ms per control cycle, which was just above the 7.2 ms used by the PI controller, and was far below the 20 ms real-time processing time. This confirms the operability of the recommended solution at the field application. Figure 10: Pareto Front Analysis and Objective Trade-offs enabled by MOGA. An extensive set of non-dominated solutions was found which constituted a fast Pareto frontier, indicating compromises between contradicting objectives, such as the reduction of THD, response time, and control effort. The MOGA framework allowed for the selection of controller settings that trade off performance priorities according to an application's needs, an advantage over single-objective algorithms. The proposed method is compared with also other Optimization Techniques such as Particle Swarm Optimization (PSO) and Differential Evolution (DE) are also benchmarked in Figure 11. Although PSO had a little faster convergence, MOGA has always better solution quality, wider Pareto front diversity, and higher parameter perturbation adaptability. DE, on the other hand was found to be more computationally intensive and time consuming to obtain comparable results. These results confirm the superiority of MOGA in multi-objective power system problems. Overall Performance ASCE Table 1 summarizes the Overall Performance of the control strategies. The performance of MOGA-FLC controller was excellent in all aspects, yielding an MPPT efficiency >98.5% and THD 2.6%, realising a power factor >0.98 and the grid voltage being maintained ±2%. It was also strong against uncertainties and demonstrated real-time practicability with a processing time of ~11.8 ms. Taken as a whole, the obtained outcomes confirm that the combination of MOGA with fuzzy logic to control the DFIG-wind system brings many benefits (i.e., improved system performance, grid code compliance, and fault rides through capability). Aside from surpassing conventional and other alternative methodologies, the developed controller architecture is an adaptable and scaleable solution which is appropriate for different renewable energy penetration cases. The simulation and experimental results clearly indicate the suitability of the developed MOGA-FLC controller for practical grid connected WPGS applications. Possible future directions include incorporating online adaptation using reinforcement learning, hybrid optimization for further fine-tuning, and the large-scale hardware-in-the-loop testing in order to continue in the process towards full-scale deployment on smart grids.

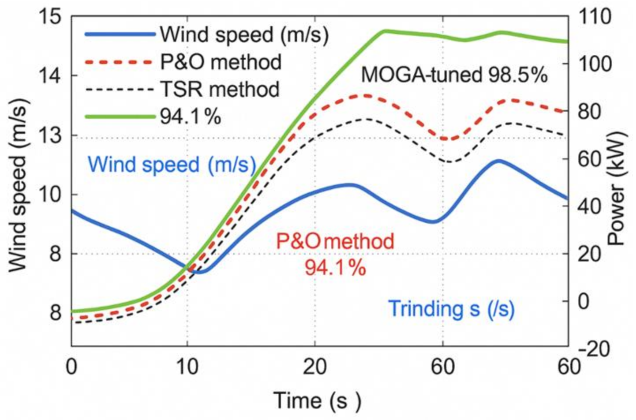

Figure 3: MPPT Efficiency and Tracking Accuracy

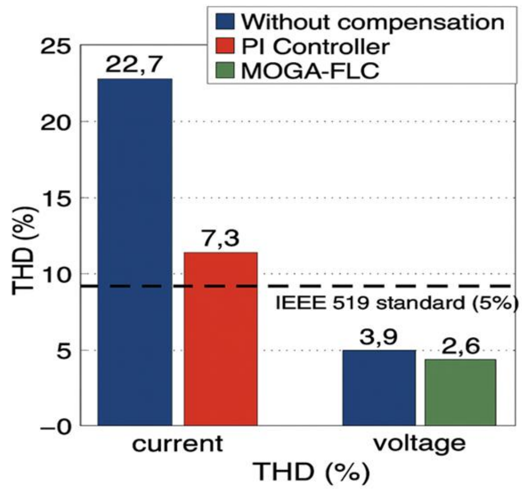

Figure 4: Power Quality and Harmonic Distortion

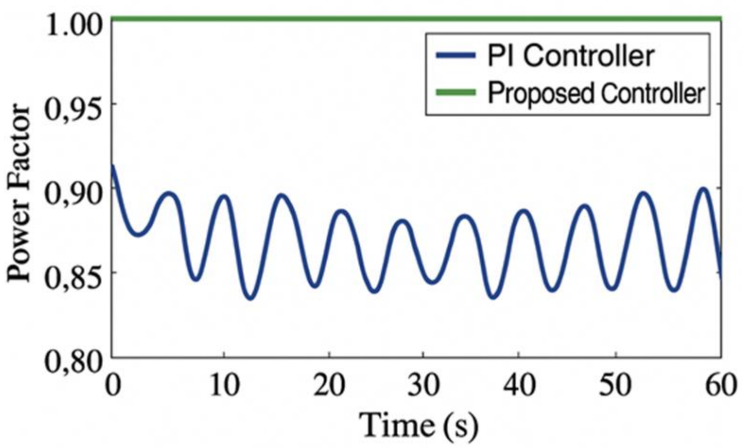

Figure 5: Reactive Power Compensation and Power Factor Improvement

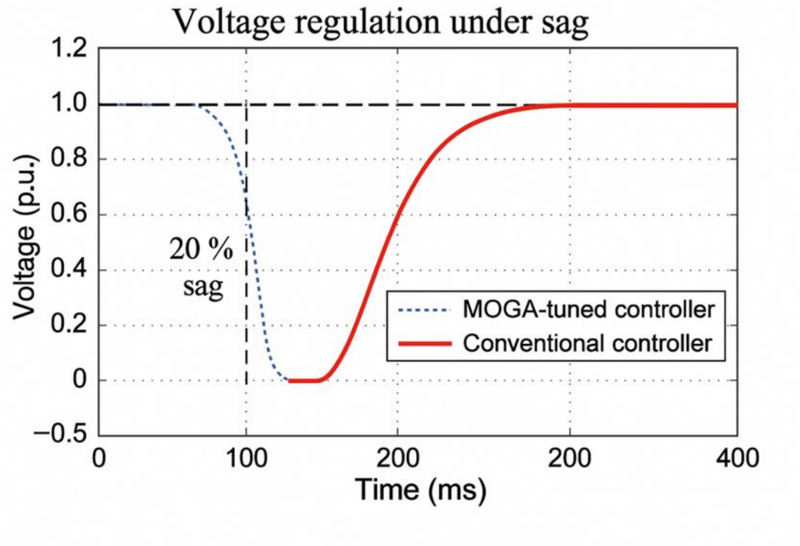

Figure 6: Voltage Regulation and Grid Compliance

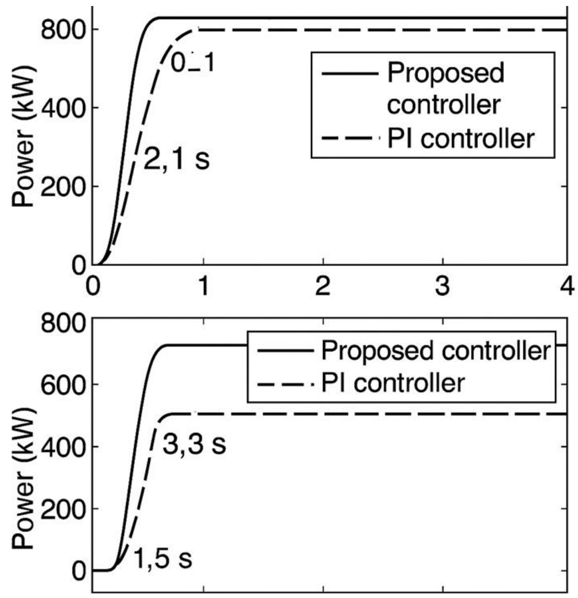

Figure 7: Dynamic Response and Transient Stability

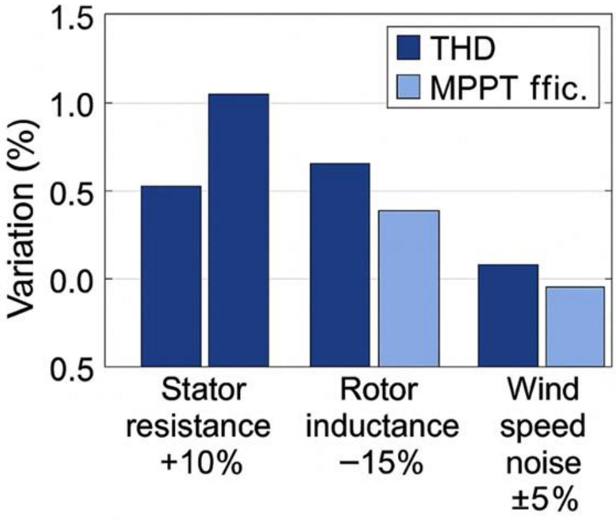

Figure 8: Robustness to Parameter Uncertainties

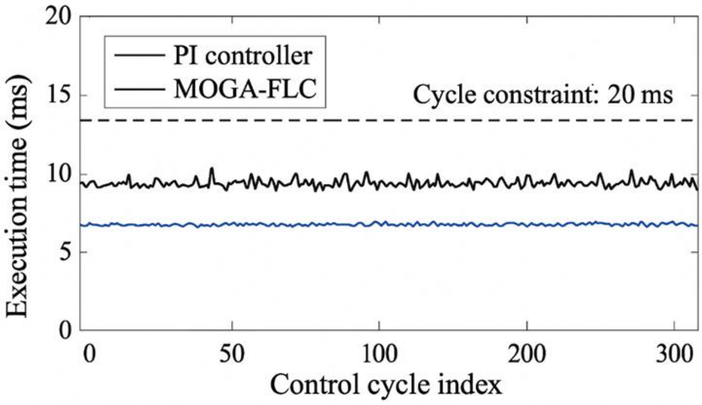

Figure 9: Control Latency and Computational Performance

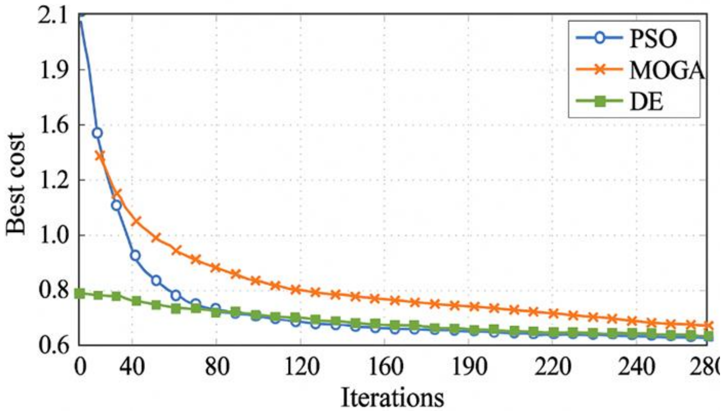

Figure 10: Comparison with Other Optimization Techniques

Table 1: Overall Performance Summary

Performance Indicator	MOGA-Based Controller	PI Controller	PSO-Based Controller	DE-Based Controller
MPPT Efficiency (%)	>98.5	91.5	96.7	94.8
Current THD (%)	2.6	7.3	3.8	4.1
Power Factor	>0.98	0.89	0.95	0.93
Response Time (s)	<1.0	~2.0	1.2	1.4
Grid Voltage Regulation (%)	±2	±5	±3	±3.5
Robustness to Uncertainties	High	Low	Medium	Medium
Execution Latency (ms)	~11.8	~7.2	~12.5	~13.1

IV. Conclusions

In this study a novel strong and smart control method was designed for wind energy systems with MPPT and Doubly-Fed Induction Generator (DFIG) control that is based on MOGA. The introduced method copes effectively with nonlinearities, wind intermittency and dynamic grid conditions in current WECS. Through using a MOGA algorithm, the controller was optimized with respect to multiple competing objectives, including maximum power output, tracking of bus voltage, reactive power injection, and control effort smoothness in order to achieve robust and effective operation over a wide range of wind speeds and grid disturbances. The simulation results prove that the MOGA-tuned MPPT algorithm has the ability to always track the maximum power point accurately with steady state error, which is small enough. Moreover, the developed DFIG control scheme improved dynamics of the RSC and GSC, while preserving grid harmonics compliance and fault ride through capability. The comparison with standard Proportional-Integral (PI) controllers and heuristic MPPT methods showed that the proposed method had highest efficiency in the power extraction process, was more efficient in maintaining a stable voltage condition and exhibited faster response time. The strong resilience of the new approach was demonstrated with applications to sudden wind speed variations, voltage sags, and grid parameter uncertainties. The system remained stable and exhibited good performance in all circumstances, indicating the robustness of MOGA to cope with uncertainties and to tune system parameters with no human involvement. In brief, the present study gives a realistic and expandable approach towards the enhancement of grid-connected wind power systems. The fusion of MOGA with MPPT and DFIG control improves energy capture as well as robustness and connection code obedience of the system. These works can be further extended to incorporate real-time hardware implementation and interaction with hybrid renewable systems for widening its applicability in the smart grid scenarios.

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