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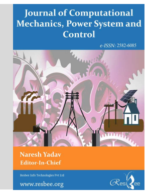

Adaptive Speed Controller for Micro Gas Turbine Systems Using Evolutionary Search Based on Genetic Algorithms

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Abstract: Micro Gas Turbines (MGTs) are compact power generation systems that offer several advantages such as highpower density, low emissions, and fuel flexibility. They are commonly used in remote areas where grid connectivity is limited or unreliable. However, MGTs suffer from inherent instability issues due to their small size and high rotational speeds. These instabilities can lead to irregular speed responses, affecting the overall performance and reliability of the system. To address these concerns, the researchers utilized a genetic algorithm (GA)-based approach and conducted sensitivity studies to analyze the iteration parameter of the GA and its impact on the speed response of the MGTs. To evaluate the performance of the developed solution, they employed the Mean Step of Absolute Speed Error (MSASE) evaluation metric and compared the outcomes of the proposed strategy with a baseline Proportional Integral (PI)-only solution. The results demonstrated that the proposed solution surpassed the baseline approach by delivering a superior error response. Similarly, the findings suggested that the optimal iteration parameter setting for the GA was a maximum of 30 compared to 20 and 10 consequently lessening the settling time from 140s to 60s. Accordingly, the researchers concluded that optimizing the GA's iteration parameter could lead to enhanced stability in the speed response of the MGT units. Subsequently, this can bolster the power generation capacities of the units, highlighting the potential for enhanced efficiency and stability in MGT operations. As a final recommendation, the study advised practitioners working with MGTs to adopt the proposed GA-based speed control strategy to optimize the overall performance and reliability of these units.

Keywords: Micro Gas Turbines;Genetic Algorithms;Power;Engineering;Mean Step of Absolute Speed Error;Iteration.

Nomenclature

Abbreviations	Descriptions
GA	Genetic Algorithms
MGTs	Micro Gas Turbines
MSASE	Mean Step of Absolute Speed Error
PI	Proportional Integral
AI	Artificial Intelligence
PSO	Particle Swarm Optimization
EIC	Evolutionary Intelligent Computing
GA-mGT	Genetic Algorithm Micro Gas Turbine
LFC	Load Frequency Control
SOA	Seeker Optimization Algorithm
PEM	Proton Exchange Membrane
ANFIS	Adaptive Neuro-Fuzzy Inference System
PID	Proportional-Integral-Derivative
MATLAB	Matrix Laboratory
MATLAB-SIMULINK	Matrix Laboratory-Simulating Dynamic Systems
DGs	Distributed Generators
MILP	Mixed Integer Linear Programming
NSGA-II	Non-Dominant Sorting Genetic Algorithm

1. Background to the Study

MGTs have gained popularity in power generation due to their high efficiency, compact size, and low emission levels[7]. However, ensuring the efficient operation of these systems requires precise control of the turbine's rotational speed. A promising solution to this challenge is the use of an adaptive speed controller for MGT systems through an evolutionary search based on GA[19].

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GA isinspired by natural selection, where individuals with favorable traits are more likely to survive and reproduce [24]. In the context of adaptive speed control for MGT, the GA creates a population of potential solutions (Individuals) represented as sets of control parameters that undergo selection, crossover (Recombination), and mutation operations to produce new generations with improved fitness (Performance). Through successive generations, the algorithm converges towards an optimal set of control parameters that maximize the performance of the MGTs[19]. This intelligent control technique provides a faster and more precise feedback mechanism that can adapt to various operational conditions[16]. It uses GA to optimize the turbine's speed of rotation, allowing for continuous optimization and adaptation to changing operating conditions, resulting in improved performance and efficiency.

Notably, MGTs are widely used in various applications[4], including distributed power generation, cogeneration, and hybrid electric vehicles. They require precise speed control to ensure optimal performance and efficiency[8]. Traditional control methods often struggle to achieve the desired level of performance due to the complex and nonlinear nature of micro gas turbine systems. Research is currently ongoing on various stabilizing techniques such as the conventional PI controller[13], and the enhancement of PI parameters using AI-based solvers such as PSO[26][23] and GA[27]. The GA as an EIC technique has shown some promising results in several research studies[6][15]. However, to ensure their level of precision in problem-solving, it is important to consider some specific parameters with their search strategy or solutions.

1.1Statement of the Problem

In recent years, the development of MGT systems has received significant attention due to their potential for providing efficient and reliable power generation in a variety of industrial applications. However, their inability to maintain a steady-state operational speed during dynamic changes in load demand or fuel input continues to be a significant issue, severely damaging the turbine and generator, and limiting their performance and reliability. To address this problem, this study has been developed to propose the mechanism of adaptive speed controller for MGTs using evolutionary search based on GA.

1.2Aim and Objectives of the Study

This study was aimed at exploring the viability ofadaptive speed controllers for MGTs using evolutionary search based on GASpecifically, the objectives were to:

1. Analyze the iteration parameter of the GAfor the MGTs.
2. Evaluate the performance of the developed solution.

1.3 Research Questions

1. What is the iteration parameter of the GAfor the MGTs?
2. What is the performance of the developed solution?

In this research study, the GA-mGT optimizer is applied in the solution of the PI parameters considering the influence of the GA iteration parameter. A new fitness objective is introduced based on anMSASE as a metric of evaluation for the proposed GA-mGT. The MGT presents a viable power machine for use in small-scale distributed power systems co-generation applications due to their higher total efficiency and flexibility. With continuous research, the application of GA in MGTs will undoubtedly lead to significant breakthroughs in power engineering.

The paper is organized as follows: Section 2 covers the literature review. Section 3 details the Materials and Methodology, and 4 emphasizes the results and discussion. Section 5 mentions the advantages and disadvantages of the proposed method. The conclusion is recapitulated in Section 5.

2. Literature Review

The field of dynamic speed control, stability, and power generation for gas turbines and MGTs has been the focus of numerous research studies that aim to optimize turbine output states. While some studies utilize industry-standard procedures, others employ advanced optimization strategies.

[29]discussed the dynamic performance of automatic LFC using a PID controller to enhance the response time of a three-area power system by reducing settling time and oscillations.

[1] presented an advanced strategy for managing renewable energy systems, using the White Shark optimizer, which includes photovoltaic and fuel cells with battery and supercapacitor storage.

[3] introduced a multi-stage fuzzy-based flexible controller for stabilizing voltage in power systems, which enhances voltage stability and improves system performance in the face of disturbances.

Similarly, [20] developed an optimal LFC for a multi-area power system using the PID controller parameter regulation based on the SOA. The proposed controller enhanced the electric power quality, power system reliability, and eliminated power system oscillations.

[21] provided an introduction to a special issue focused on advanced optimization and forecasting methods in power engineering. They explored the latest developments in these areas and their potential benefits in power engineering.

[2] proposed a new maximum power point tracking method for PEM fuel cell power systems using an ANFIS combined with the modified manta ray foraging algorithm. The method maximizes the power output of the fuel cell by tracking its maximum power point.

[5] studied the reliable control of a turbine-generator set used in oscillating-water-column wave energy converters. They presented a numerical model of the turbine-generator set and compared the model to field data, highlighting the importance of reliable control strategies in this type of energy conversion system.

2.1 Review Table

Authors	Methodology	Advantage	Disadvantages
Takerhi and Dąbrowski [22]	GA approach	• Allows optimization of natural gas networks and compressor stations, specifically focusing on fuel consumption minimization. • A systematic and efficient way to find the optimal flow rates, node pressures, and compressor speeds. • Reduced CO2 emissions in natural gas network operations. • considered the variation of compressor speeds to control pressure ratios and discharge pressure.	• There is still room for improvement in the GA's ability to optimize compressor station fuel consumption. • The effectiveness of the GA approach may depend on the specific characteristics and complexity of the gas network and compressor station being optimized.
Fasihizadeh *et al.*, [11]	Simulation algorithms	• Decreased energy consumption in compressor stations, leading to cost savings and extended overhaul time. • Improved efficiency in gas transportation flows through the use of appropriate connections, resulting in decreased compressor load.	• As the process is simulated, the simulation algorithmscan further improves the gas transmission network operation.
Xie *et al.*, [25]	SAGA	• Enhanced the speed and efficiency of the algorithm, leading to improved real-time control of the microgrid. • The self-adaptive GA shows that most solutions have relatively small objective values, indicating the effectiveness of the proposed method	• Does not provide a comprehensive analysis of the performance of the algorithm in different scenarios or under varying conditions. • Does not address the scalability of the algorithm for larger microgrid systems or its adaptability to different types of distributed generation sources.
Nemati *et al.*, [18]	GAand MILP	• Efficient utilization of renewable energy resources. • Accurately predict battery degradation and optimize their usage. • Efficient distribution and utilization of power. • The SPMprocess selectively limits and regulates the mutation process based on critical constraints of microgrids, such as power balance and voltage violations. • Reduced the power injection of renewable energy sources in case of voltage limitations, ensuring grid stability.	• Limitations in theGA and MILP approach used in the optimization process. • The accuracy of the predictions or the impact of different battery chemistries is not discussed.
Alhumade*et al.*, [1]	EMS, WSO, and PEMFC	• Reduces the consumed hydrogen by 34.17% compared to the SMCS. • Increased the efficiency by 6.05% compared to SMCS.	• No information is provided regarding any potential challenges. • Does not provide any insights into the potential impact of external factors, such as variations in weather conditions or load demand, on the performance of the proposed EMS-based WSO
Carrelhas*et al.*, [5]	Oscillating-water-column (OWC)	• Identify the physical interactions between the PTO system and the OWC system, and use this information to develop the control algorithm. • Experimental data from real operation at sea is compared with the results obtained using the control algorithm • Maximize power generation while protecting the PTO in energetic sea states and minimizing overspeeding and the use of a safety valve.	• The performance under different sea state conditions or its scalability to larger turbine-generator sets are not discussed in the paper. • Does not provide a comprehensive analysis of the economic feasibility or cost-effectiveness of implementing control algorithms in real-world applications.

2.2 Identified Research Gap

This study was geared towards optimizing performance in real-time by delving into a significant research gap. What sets this study apart is its utilization of evolutionary search based on GA. These algorithms offer a potent optimization technique that emulates the workings of natural selection and evolution. By employing this approach, the study endeavors to develop an efficient, robust, and adaptable speed controller. Unlike existing studies that predominantly focus on developed countries with vastly different infrastructure and operational conditions.This study acknowledges the distinctive challenges faced by developing nations, specifically tailored for micro gas turbine systems. The study recognizes the absence of effective adaptive speed control mechanisms in these countries, where limited resources, unreliable power grids, and harsh environmental conditions pose major obstacles to ensuring optimal functionality.

In addition, [7][9][28][4] studied the use of MGTs in cogeneration applications for heat production. Here, this research paper seeks to contribute to the field of evolutionary-inspired adaptive speed control for MGT-based systems using genetically optimized solutions. This includes the newly proposed fitness evaluation metric known as the MSASE.

2.3 Theoretical Framework

John Holland proposed GA in 1975 as a metheuristic that belongs to the family of evolutionary algorithms and is inspired by the process of natural selection. The GA aims to find an optimal solution to a problem by simulating natural selection and evolution[14]. It follows Darwin's theory of natural selection, where the fittest individuals are chosen for reproduction, resulting in better offspring in the next generation. The theory of GA is applied in this study to find an optimal solution to a control problem in MGT systems. This study uses GA to simulate natural selection and evolution to find the best control parameters for the speed controller of anMGT. The GA generates a population of candidate solutions, evaluates their fitness, and selects the best individuals for reproduction and mutation. Through this iterative process, the GA converges towards an optimal set of control parameters that maximize the turbine's performance. This study demonstrates how GA can be applied to solve optimization problems in Engineering systems by mimicking natural selection and evolution. By using GA, this study offers a promising method for finding optimal solutions to complex Engineering problems.

3. Materials and Methodology

3.1 Micro Gas Turbine System Modelling

The current dynamic model of the system is utilized in the creation of anMGT model [23]. This model employs the s-parameter space model technique from MATLAB's system identification toolbox, which significantly aids in dynamic system-level programming and analysis. However, it also increases the memory footprint during numerical optimizations due to the computational intensity of bridging symbolic and numeric worlds. The model comprises four main components: a PID controller, an actuator, the turbine, and a speed sensor, all represented as s-functions for easier analysis. The PID controller is the primary module of interest as it regulates the speed control operation from an appropriate drive, ensuring the turbine compression system's reliable operation. The controller's parameters, the proportional (kp) and integral (ki) constants, must be optimized for the turbine system's dependable operation. The influence of the controller process input can be defined as:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)\Delta t \tag{1}$$

Where,

e = the MSASE of the mGT speed response profile

Δt = the time interval change.

Considering the model in Eq.1, the PI controller will generically adjust the input *u(t)*, to minimize the error e. This is fundamentally achieved after a certain number of iterations. However, the proper choice of the PI parameters, k_p, and k_i is always not known in advance and requires an informed initial guess in addition to several value permutations.

3.2Genetic Algorithm Solution

The GA presents a highly sophisticated bio-evolutionary inspired computing approach to solving non-linear computable problems. The idea of GA is to simulate the processes that occur in bio-organisms for general problem-solving in computing software. In the GA solution, the core principles of evolution based on Darwinian representative modeling arereplicated in software such that it may be used to optimally evolve better model structures and/or evolve to discover more optimal solutions to computational problems.The GA itself is not represented by a single equation, but rather a set of equations and operations that work together to solve an optimization or search problem. This set of equations and operations are given as follows:

i. **Fitness Function**: The fitness function evaluates the quality or performance of a candidate solution. It maps a solution to a numerical value that represents its fitness. The fitness function can be defined as:

$$F(x) \tag{2}$$

Wherex is a candidate solution.

ii. **Selection Probability**: The selection probability of an individual in the population is often calculated based on its fitness value relative to the total fitness of the population. It can be represented as:

$$P(x) = F(x) / \Sigma F(x) \tag{3}$$

Where,
P(x) is the selection probability of solution x.
F(x) is its fitness value.
ΣF(x) is the sum of fitness values for all solutions in the population.

iii. **Crossover Operator**: This combines genetic data from two parent chromosomes to create offspring. The method differs depending on the encoding scheme. A popular technique is a one-point crossover, which swaps genes beyond a randomly selected point between parents.

iv. **Mutation Operator**: This introduces random gene alterations in individual chromosomes to preserve population diversity. The mutation probability, PM, dictates mutation frequency. A basic mutation operation flips a binary chromosome bit or alters a gene in other encoding schemes.

4. Results and Discussions

4.1 Answers to Research Questions

Research Question 1: What is the iteration parameter of the genetic algorithm for the micro gas turbine systems?

This study's simulations were conducted using MATLAB and its System Identification Toolbox's s-functions. Given the GA optimizer's sensitivity to memory footprints, we meticulously selected parameters for optimal results. We employed the default GA parameters, as shown in Table 2, to find the best PI control values. These parameters were used in the search routine to estimate the gain parameters, kp, and ki. Furthermore, a standard PI controller with baseline gain values of kp = 0.5 and ki = 0.0001 was examined for comparison.

Table2: *Default GA Parameter Settings*

id	Parameter	Symbol	Value
1	Maximum iterations	max_iters	10
2	Population size	pop	2
3	Extra Range Factor	γ	0.4
4	Mutation Rate	M	0.1

The procedure for adjustment of boundary conditions for a given GT MSASE simulation is as follows:

i. Start with a reasonably high enough value of k_p and k_i say $k_p = 1$, $k_i = 1$
ii. Run the GA program search routine to estimate optimal k_p and k_i
iii. Test the estimated values in (2) in the speed-error response program and verify that the generated plots follow the standard reducing twirling pattern; this should finally settle to a value of around 0 at its tail.
iv. If the test condition in (3) is not met reduce the k_p, and k_i values and repeat step 2.

Once a satisfactory boundary condition and its corresponding MSASE fitness objective aremet, the GA-optimized PI-based mGT system can then serve the gas turbine without further system optimizations.

Research Question 2: What is the performance of the developed solution?

To assess the performance of the developed solution, an evaluation metric known as MSASE was used. The evaluation was conducted through error time response simulation. The resulting MSASE fitness objective response curve, using default GA parameter values (as listed in Table 2), is depicted in Fig. 1. The corresponding optimized parameter values and test MSASE response curve are presented in Table 3 and Fig. 2 respectively. Furthermore, Fig. 3 displays the baseline MSASE step response curve before optimization.

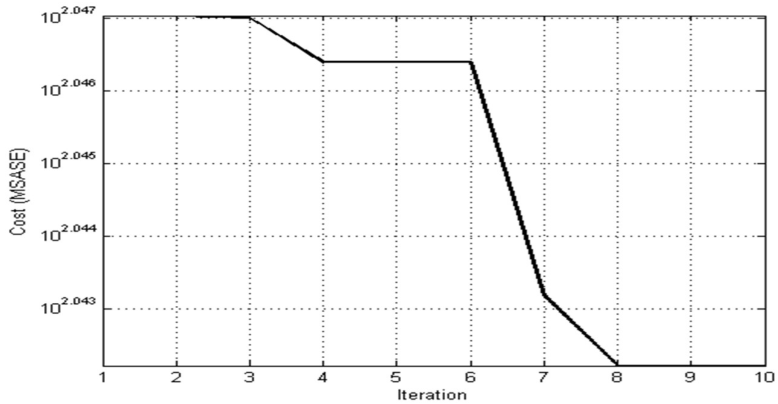

Fig.1. *GA Fitness Objective error response for default setting (pop = 10; max_iters = 10)*

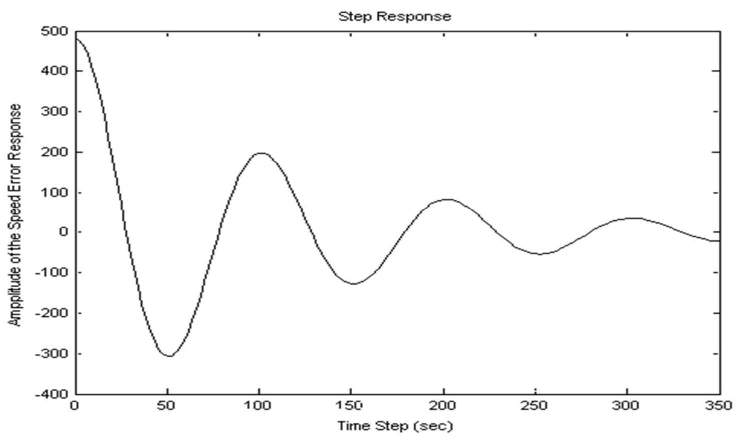

Fig.2. *GA MSASE test error response for default setting (pop = 10; max_iters = 10)*

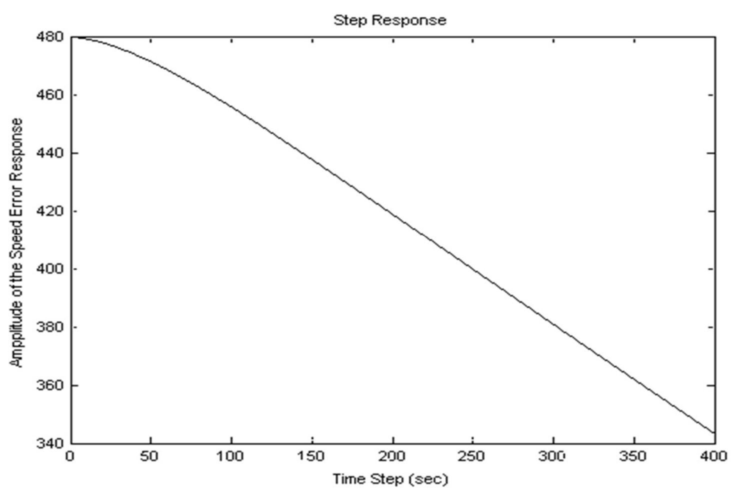

Fig.3. *Baseline MSASE error response ($k_p = 0.5$; $k_i = 0.0001$)*

Table 3: *GA Optimized Boundary Constraints for Default Case*

id	Symbol	Optimal Value
1	k_p	$3.1211*10^{-6}$
2	k_i	$9.2755*10^{-8}$

As can be seen from Fig.2, there is an initial high fitness objective error during the beginning of the GA search but this gradually reduces as the iteration steps increase till a value around the 8th iteration when pre-mature convergence begins. The corresponding test error response as shown in Fig. 3 shows a settling time at around 350s towards the expected zero error level. For this simulation, the optimal value of k_p was found to be slightly lower than that of the k_i. When compared to the baseline PI value settings, thereis a great disparity in the error response as the baseline is unable to solve the system hence validating the use of optimizations in this research.

In the sensitivity settings of error time response simulations, The MSASE fitness objective response considering a variation of the max_iters parameter at values of 20 and 30 iterations and for a fixed pop = 10 are presented in Fig.4. The optimal PI gain values found are as shown in Table 4.

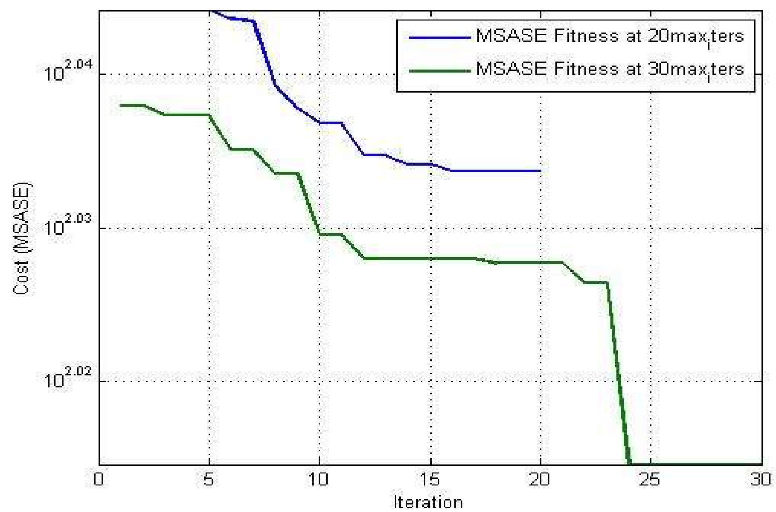

Fig.4. MSASE fitness objective response for variable settings (pop = 10; max_iters = 20; 30).

Table 4: *GA Optimized Boundary Constraints for Variable Case*

id	max_iters	Optimal Value	
		k_p	k_i
1	20	0	$7.1916*10^{-8}$
2	30	$2.9967*10^{-8}$	0

As can be seen from Fig. 4, increasing the max_iters from beyond the default value of 10 gives a much better fitness objective response. The optimal gain values found (see Table 4) show a reversal in the magnitude of k_p and k_i as the k_p is greater than k_i for the 20max_iters but lower at 30max_iters. The implication of the reversal is also clearly shown in Fig. 5 indicating a much-improved step error response for higher max_iters.

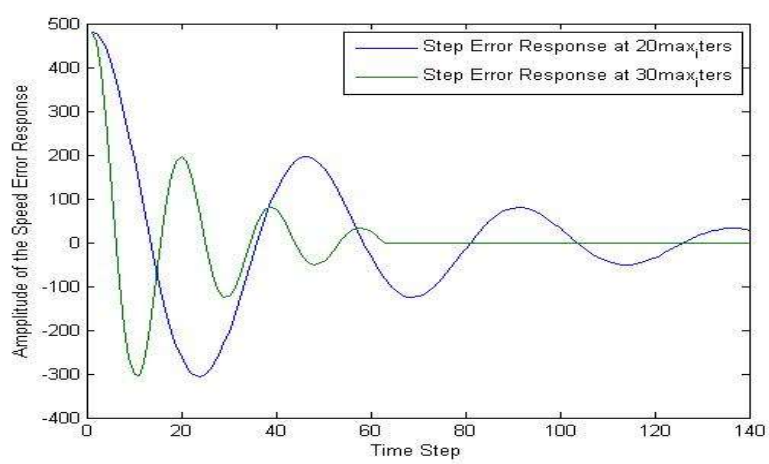

Fig.5. *MSASE Step error response for variable setting (pop = 10; max_iters = 20; 30)*

As shown in Fig. 5, when the GA iteration parameter max_iters setting is at 30iters, it results in a shorter settling time of around 60s when compared to a setting of 20 iters which gave a higher settling time of around 140s.

4.2 Discussion

The optimization of the compression system suitable for MGTs using the GA involves an analysis of the iteration parameter. The GA technique involves the evaluation and adaptation of the system architecture in the MATLAB-SIMULINK dynamic programming environment. The system comprises four key blocks including a controller PID, an actuator, the turbine, and a speed sensor. The proportional (kp) and integral (ki) constants are key parameters for this block, which were optimized through the GA algorithm to ensure reliable operation of the turbine system.

The MATLAB programming environment, in combination with the MATLAB system identification toolbox's s-functions, was used to run simulations and evaluate the system. Error time response simulation was conducted to evaluate the simulation results. The optimal value of kp was found to be 3.121110^-6, and the optimal value of ki was 9.275510^-8. The use of scientific notation is a shorthand way of expressing very large or small numbers. These optimal kp and ki values indicate that the system can operate efficiently and can be used as reference points for further optimization or for developing control systems for different applications. For the default case, the Baseline MSASE error response (kp = 0.5 and ki = 0.0001) showed an initial high fitness objective error at the beginning of the GA search, which gradually reduced with increasing iteration steps. Premature convergence began around the 8^{th} iteration.

Comparing the optimal values to the baseline PI value settings, it is evident that the baseline cannot solve the system, validating the use of optimizations in this research. In the sensitivity settings of error time response simulations, the MSASE fitness objective response considering a variation of the max_iters parameter showed that increasing the max_iters from beyond the default value of 10 gives a much better fitness objective response. The optimal gain values found show a reversal in the magnitude of kp and ki. The kp value is greater than ki for the 20max_iters but lower at 30max_iters. The reversal implies that when the GA iteration parameter max_iters setting is at 30iters, it results in a shorter settling time of around 60s when compared to a setting of 20 iters, which gave a higher settling time of around 140s. Through this study, the use of the GA technique in optimizing the compression system for MGTs proves effective in ensuring system efficiency.

5.Advantages and Disadvantages of Adaptive Speed Controller for Micro Gas Turbine Systems Using Evolutionary Search Based on GA

Advantages:

i. **Improved Efficiency**: Adaptive speed control using GA can optimize the operation of MGT systems, leading to improved efficiency. The algorithm can adjust the speed of the turbine based on real-time conditions, ensuring that it operates at its most efficient point.

ii. **Enhanced Performance**: By continuously adapting the speed control strategy, the system can achieve better performance in terms of power output and response time. GA can optimize the control parameters to maximize power generation while minimizing response time and transient behavior.

iii. **Robustness**: GAcan find optimal solutions even in complex and uncertain environments. This robustness allows adaptive speed control systems to handle variations in operating conditions, such as changes in load demand or fuel characteristics.

iv. **Reduced Fuel Consumption**: Optimizing the speed control strategy using GA can lead to reduced fuel consumption in MGT systems. By finding the most efficient operating point, the system can minimize fuel usage while still meeting the required power output.

v. **Flexibility**: Adaptive speed control based on GA provides flexibility in adapting to different operating conditions and requirements. The algorithm can be easily adjusted or reconfigured to accommodate changes in load demand or other system constraints.

Disadvantages:

i. **Computational Complexity**: GA involves complex calculations and requires significant computational resources. The optimization process may take a considerable amount of time, especially for large-scale MGT systems with numerous control parameters.

ii. **Parameter Tuning Difficulty**: GA relies on a set of control parameters that need to be properly tuned for optimal performance. Determining the appropriate parameter values can be challenging and may require extensive experimentation or expert knowledge.

iii. **Limited Real-Time Adaptation**: While GA can adapt the speed control strategy based on historical data, it may not be able to respond quickly to sudden changes in operating conditions. Real-time adaptation may be limited due to the time required for optimization and the need for system stability.

6. Conclusion and Recommendation

The study determined that through optimization of the iteration parameter in GA, it is possible to achieve better stability in the speed response of MGT units. The enhanced stability can significantly boost the power generation capacities of the units, thereby improving the efficiency and stability of MGT operations. This optimization process has enormous potential to offer a more reliable and efficient energy system, which could benefit various industries. Therefore, practitioners need to consider implementing GA-based speed control strategies to enhance the performance of MGT units. The study offers practical insights that could be useful in optimizing MGT operations, ultimately leading to increased efficiency, stability, and productivity. Such a development will have a positive impact, not only on the environment by reducing carbon emissions but also on business costs, making it a viable option for companies looking to optimize their operations and make a lasting impact on the industry. Therefore, the study recommended that MGT practitioners adopt the GA-based speed control strategy to optimize the overall performance and reliability of the units.

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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