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Energy-Efficient Control of a Gas Turbine Power Generation System

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Abstract: Gas turbines are used in the energy sectors as propulsion and power generation technologies. Despite technological advances in power generation and the emergence of numerous energy resources, gas turbine technology remains important due to its flexibility in load demand following, dynamical behavior, and the ability to work on different fuels with minor design changes. However, there would be no ambitious progress for gas turbines without reliable modeling and simulation. This paper describes a novel approach for modeling, identifying, and controlling a running gas turbine power plant. A simplified nonlinear model structure composed of s-domain transfer functions and nonlinear blocks represented by rate limiters, saturations, and look-up tables has been proposed. The model parameters have been optimized to fit real-world data. The verified model was then used to design a multiple PI/PD control to regulate the gas turbine via the inlet guide vane and fuel vales. The aim is to raise and stabilize the compressor's differential pressure or pressure ratio, as well as raise the set-point of the temperature exhausted from the combustion turbine; as a result, energy efficiency has been improved by an average of 237.16 MWh saving in energy (or 8.96% reduction in fuel consumption) for a load range of 120 MW to 240 MW.

Keywords: gas turbine; whale optimizer; modeling; identification; control

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1. Introduction

1.1. Background and Motivation

Natural gas, hydrogen, fuel oil, and biogas are all fuels that can be used to power a gas turbine (GT), if the GT is properly configured or manufactured [1,2]. Apart from this input flexibility, the GT is classified as a flexible energy resource due to its output flexibility to follow the dynamics of electricity demand in a stable and efficient manner [3,4]. Therefore, investing more research effort into development of more efficient gas turbines can be very useful in terms of fuel, energy, and the environment. The issue of improvement in such devices is an endless research problem that requires continuous work by recent and future engineers with multidisciplinary objectives or various collaborative disciplines, such as Electrical Engineering, Artificial Intelligence, Mechanical Engineering, Chemical Engineering, and so on. The recent energy crisis caused by instabilities in the Middle East and Arabian region has made research even more difficult. Flexibility is thus an inherent feature of GTs due to its thermodynamic operational characteristic. The thermodynamics of a very basic GT is demonstrated below, where Figure 1 represents the basic components of a gas turbine and the corresponding temperature–entropy diagram is shown in Figure 2. The air compression is demonstrated by the isentropic process (1–2), in the isobaric process (2–3), the air/fuel mixture is combusted, then expanded in the isentropic gas turbine process (3–4) to create useful work for power production. In process (4–1), the output heat at constant pressure is then either rejected into the atmosphere or injected to a heat recovery steam generator (HRSG) to produce more power from the exhausted gas.

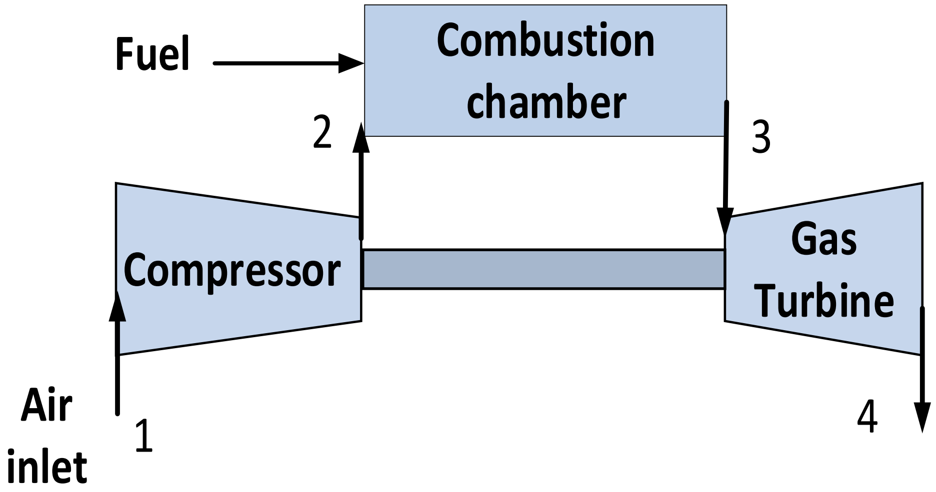

Figure 1. Main components of gas turbine unit [3].

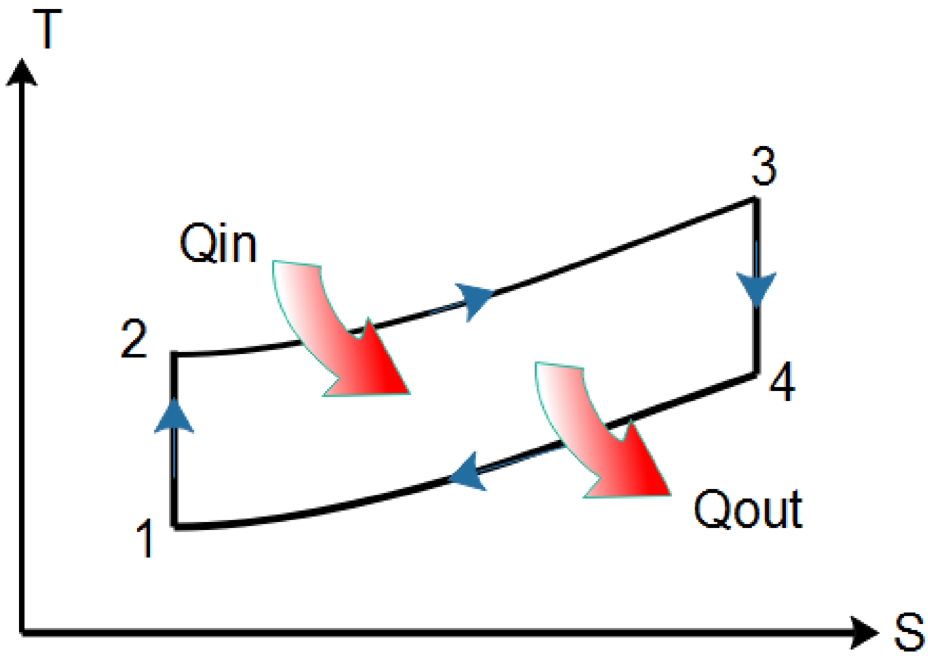

Figure 2. Temperature–Entropy (or T–S) diagram [3].

Despite technological advances in intensive research of control system technology, the directed research methodology continues to hold analogous steps towards successful control system implementation. The case under study may be far more complex for dual fuel GTs, which has been adopted in this paper, in which there are two main operating modes: the premix mode where the pilot valve and natural gas valve supply gas to the combustion chamber, and the diffusion mode where the fuel oil is permitted through the pilot valve from the fuel boosting system. In the case of low loads, the diffusion mode is better for stable combustion before, whereas the premix mode is preferable for high, peak, or near peak loads for more efficient operation. However, the situation could be further improved in the premix mode, which is the most likely situation, by proper control system design. The steps for control system design for energy-efficient improvement are depicted in Figure 3 with emphasis on our own research, which has the major steps to be explained throughout the paper context.

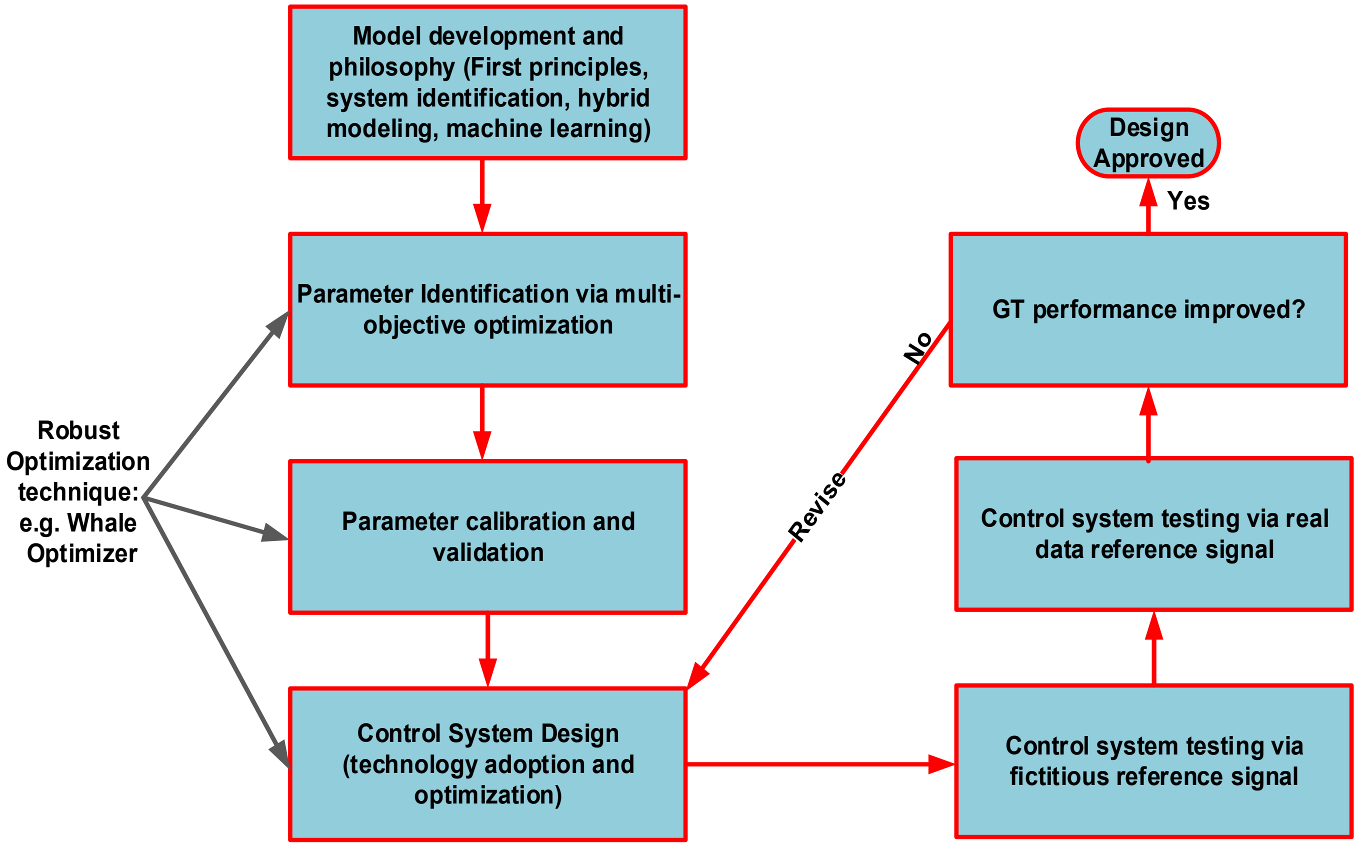

Figure 3. Directed research steps for GT control system development.

The importance of modeling GTs can be further clarified by the literature review and the explained paper contribution to theory, knowledge, and practice. This is detailed in the next subsection.

1.2. Literature Review and Paper Contributions

The control system design of Gas Turbines (GTs) has become a challenge across the world due to its intricate requirements, as its multi-timescale dynamics are naturally nonlinear and its process requirements are critical. Having multiple constraints add a huge computational load on classical control algorithms, therefore, its control requirements have raised the bar and require careful attention and intensive research.

Renewable energy sources are becoming increasingly popular; however, their intermittent nature poses a problem when integrated into the grid because it causes fluctuations in the levels of electricity generated; thus, controlling such fluctuations necessitates radical control techniques. Having the load change instantly necessitates the use of a controller that allows the power plant to respond to load changes without violating or exceeding the predefined limits or set-points, while keeping the power plant's efficiency as high as possible and meeting all of these requirements in a timely manner.

Fast load following operations, which are becoming more popular, have recently reduced plant efficiencies and shortened equipment life as load following capabilities have become more critical. This can have disastrous consequences because it increases mechanical and thermal stresses when the plant is not operating at full capacity. As a result, more intricate design requirements have been added in order to satisfy both load following capabilities and power efficiency.

The most recent control schemes are focused on increasing efficiency, lowering capital costs and running costs, reducing emissions, and enhancing operational flexibility. Being able to design and implement an optimizer that solves metaheuristic algorithms such as implementing the whale optimizer algorithm can be a potential solution.

The use of whale optimizer for of enhancing load following capabilities will ultimately minimize operating costs while explicitly fulfilling and satisfying the physical constraints associated with these power plants without causing huge burdens on the computational load. However, such a controller could require generous investment into the initial investment to fulfill these requirements.

The control of gas turbines has proven to be challenging due to their nonlinear multi-timescale dynamics, along with intrinsic constraints that need to be satisfied. Nowadays, classical control methods are adopted such as PID controllers [5], since PID controllers have the ability to offset the proportional controller which is considered a major advantage of such controllers along with their quicker response time. However, their limitations are highlighted by their high steady-state error and precincts in feedback loop stability.

The main components of a GT that need to be included in the design and analyzed are the compressor, combustion chamber, turbine, and generator. The models that have been used recently for these nonlinear systems are obtained from identification techniques only around a certain operating region. Thus, requiring improved control strategies that minimize operating costs and consider the physical constraints that exist within such a system is needed. One option which was analyzed in one of previous studies was the model predictive controller (MPC) [5–7].

The natural plant's operation begins with the compressor. The compressor is in charge of drawing filtered air from its surroundings and pressurizing it to the appropriate levels. Pressurized gas is important because having a higher-pressure gas increases the kinetic energy stored in the gas particles, thus the potential to produce more energy, but the levels to which the pressure can be leveled up must be carefully maintained. The compressed air then enters the heart of the operation, the combustion chamber, where it is mixed with natural gas, allowing it to ignite and reach high temperatures and pressures. In some cases, fuel oil must be fed into the system. It is then expanded through the turbine, causing the turbine's blades to rotate and the generator to begin producing electricity. With its nonlinear dynamics, all of these processes require careful thought and design because they are interrelated and affect one another.

The firing temperature and gas flow control the turbine's output. The inlet guide vane, which is connected to the compressor and controls the amount of gas entering the combustion chamber, is another important mechanism. The desired load is determined by the firing temperature, the inlet guide vane (IGV), and the exhaust temperature. Furthermore, the amount of fuel fed into the system and ignited has a direct impact on the load.

The gas turbine has six main controllers, each are interconnected and interdependent on one another, which are [5]:

1. Starting controller, which sets the right amount of fuel for ignition.
2. Run up controller takes over; this controller will begin during start-up and until the right speed is reached where the next controller takes over.
3. Frequency and load controller, which takes control of the turbine speed before reaching the synchronous speed, also known as full load.
4. Maximum load controller, as the name suggests, limits the maximum active power generated.
5. Temperature controllers, controls the inlet and outlet turbine temperature by controlling the variable guide vane (VGV).
6. Maximum Turbine Inlet Temperature Limiter: its main function is to limit the inlet temperature of the turbine in times of malfunction and in times of rapid load changes.

One of the most important components and working parts of the system is the variable guide vanes, which are manually handled by controlling the firing angle to acquire the desired mass flow rate; they are, in other words, responsible for regulating the amount of mass flow into the combustion chamber, and thus will ultimately control the temperature and this is crucial for the thermodynamics of the power plant. The other major components are the combustion chamber and the turbine, the fuel mass flow rate is controlled by a separate controller [7,8].

Overall, the mechanical output power of the gas turbine is the difference between the generated power of the turbine and the power consumed by the compressor. The energy is converted from chemical energy which is stored in the fuel that will be ignited, to mechanical energy, which is yielded for the turbine which will in turn rotate the shaft connected to the generator, which will in turn converts the energy to electrical energy.

It is important that a control system be designed in order to maintain constant power when the demand is so, execute the demand changes that are required, and keep a stable output voltage. A controller design was inspired from Montazer Ghaem gas power plant. They developed a controller to control the rotor speed during the start-up and changes in power demand.

Furthermore, Shete and Jape [9] have stated that during operations, gas turbines are typically operating in high-temperature and high-speed environments. The paper then has introduced Fuzzy Modified Model Reference Adaptive Controller for the speed by controlling the input fuel flowing into the combustion chamber.

Previously, PID controllers were the solution for this system because they can respond to such robust responses and can be easily tuned, but the system's efficiency becomes a concern. An alternative solution, however, has been proposed that uses a fuzzy modified model reference adaptive controller (FMMRAC) to adapt to these responses. This model is based on Rowen's model [9], a thermodynamics-based model that represents an improved and well-established GT model.

Another study simulates the behavior of a high-efficiency gas turbine with advanced cycles obtained through the use of a regenerator, an intercoder, an economizer, and steam or water injection. These components necessitate research into efficiency optimization in design, off-design, and especially transient conditions [10]. Although the addition of these components improves the overall efficiency of the system, they change the system dynamics and present some challenges to existing control schemes because these additions affect system dynamics and increase the computational load.

Gas turbines exist as single shafted or multi-shafted, where multi-shafted are assumed to be superior because they are able to adapt better, have better cost effectiveness with load variations, the mechanical inertia is much lower, and even the electromechanical time constants are at least half or a quarter of that of a single shafted gas turbine [11]. Therefore, even though multi-shafted turbines need a more generous investment and the constraints may be amplified, the benefits of implementing multi-shafted turbines enhance flexibility and working conditions.

The rotational speed is usually controlled mostly by the change in the amount of fuel supply or fuel mass flow rate to the combustion chamber which will ignite. When using gas turbine plants in isolated power system stations, frequency and voltage deviations may be neglected which will greatly affect the power quality.

Another valid solution suggested is the use of a prognostic algorithm that introduces a forecast parameter which has the ability to perfect classical control methods with minimal costs. The use of Automatic Speed Regulator (ASR) or Automatic Voltage Regulator (AVR) will limit the overshooting and transient time of voltage which provides some supremacy to PID controllers, and will maintain the rotor rotational speeds without the need for costly complicated adjustments to be implemented to control the rotational speed in the system [12], which is vital for safe performance of the GT.

The AVR and ASR results, as well as the conclusions that can be drawn from them, allows additional loads to be connected to the system in the event of load shredding abruptly.

Nowadays, industrial heavy-duty gas turbines have proven to be more reliable and more widely spread [13], especially using a hybrid system along with a pilot valve that provides fuel oil when needed, makes the gas turbines more efficient to use.

Gas turbines are composed of many interrelated systems: thermal, mechanical, and electrical to be exact. Their interaction and their dependence require deep understanding of modelling since this interaction complicates the requirements to reach an acceptable modelling accuracy.

Two main control loops are needed in the system, one is the speed governor loop for load frequency control, and the exhaust temperature control loop for energy efficiency preservation, these control the output torque and the exhaust temperature, in which these directly control the turbine behavior. The maximum allowable harvested power depends on many factors including the frequency of the system and the exhaust temperature. The temperature control limits the exhaust temperature through the cooling air system.

The complications of gas turbines basically stem from the concept of having working fluids inside them, as they are operating under high temperature and pressure, and are working under thermodynamic processes such as combustion and expansion, which have been already described as the Brayton cycle. The high temperature and pressure add to the thermal stresses that the components of the GT will be exposed to, and will affect the lifespan of the GT.

The cycle begins with the compression of air in the compressor to increase its pressure, then the compressed air is mixed with the fuel generating a high-temperature flue, which is finally expanded in the turbine in order to produce mechanical energy, which is responsible for producing the electrical power.

Other considerations that fuel control systems require in aerospace engineering are as follows [14]:

- Provides the necessary fuel for the combustion chamber;
- Controls the fuel requirements for the start-up process;
- Limits the maximum speed of the gas turbine; and
- Limits the maximum fuel flow.

Other studies that focus on power generation application of gas turbines, including this study in the present paper, usually express a combined cycle that also incorporates a gas turbine along with a heat recovery steam generator and speed, temperature, and IGV control. These combined cycles provide higher efficiency, lower unit cost, quicker construction, and have less emissions. These combined cycles differ from conventional plants in terms of their dynamic performance [15].

The existing temperature control is reflected in the open-loop system as a proportional and integral controller (PI) which limits the fuel request. It compares the exhaust temperature with the reference temperature, where the difference represents the error variable which will instigate the proper action on the controller.

Other research analyzes the transient cases where simulation and modelling of a gas power plant is important, which are start-up, variable loads, and unexpected shutdowns. As a result, the control schemes that are implemented must be chosen with great care and caution [16]. The effect of fast load following operation is basically negative to plant efficiency and reduces the equipment lifespan. As renewable sources of energy become more widespread, along with the knowledge of renewable sources of energy having an intermittent property, conventional plants must cycle their loads more often and follow the fluctuations in energy demand [17].

Natural gas combined cycles have been recognized to be more efficient, have fewer capital costs, produce less emissions, and have higher operational flexibility than coal. However, the impacts of load following capabilities disturbed by renewables may negatively affect plant efficiency, and increase the thermal and mechanical stresses on the equipment compared to operating on the base conditions, because load following focuses on decreasing the deviation between the reference and the actual without prioritizing the capabilities of the actual GT. The outage probability increases during load following, and thus increases the maintenance costs.

To promote plant efficiency, dynamic optimization must be maximized under load following. However, there are a few points to keep in mind:

1. Stresses should be kept within certain limits.
2. Temperatures should also be kept within a narrow range.
3. Maximum overall cycle efficiency should be maintained.

These constraints, which are also imposed on the multi-objective function, make it more difficult to generate a feasible solution, particularly with a high ramp rate; thus, relaxing the ramp rate is more necessary and required to solve this dilemma. It is assumed that, first, the average ramp rate is satisfied rather than the instantaneous ramp rate, and that, second, the average ramp rate can be relaxed if necessary. However, these assumptions or considerations are dependent on the system's state and operation, whether ramping up or down. When ramping up, the deviation of the average ramp rate from the desired rate is minimized to maximize efficiency. When the optimizer sees a whole ramping down, a larger relaxation, it will relax as much as possible because lowering the ramp rate improves efficiency. The desired ramp rate is the most important parameter to satisfy when using the lexicographic approach during load following operations, because all other operational objectives are naturally ordered in terms of priority. As load increases during ramp-up operations, the efficiency of the optimizer will be also improved, so simply solving a single objective optimization problem by maximizing efficiency leads to the minimization of ramp rate relaxation. The multi-objective problem becomes apparent during ramp-down operations and must be resolved.

The tradeoff that can be concluded from this reference is between the relaxation in the ramp rate and the thermal efficiency of the power plant, which means that it is difficult to satisfy both at the same time at maximum levels, but there could be some operating point where they can be both satisfied at acceptable levels. The optimal MIMO controllers may emphasize different aspects in control theory and practical characteristics, such as load following capability [18], H_2 and H_∞ for GT control as a subsystem of a combined cycle unit [19], or decentralized active disturbance rejection [20]. The latter is applicable to other power plants, fueled even by coal [21].

From a deep investigation of the literature, Whale Optimizer (WO) is still not applied and evaluated in the field of gas turbines' modeling and control. Although WO has been applied for a coal unit [22], it is worth investigating specifically on GT control system because of the high number of differences in the design, characteristics, and practical viability between the two types of power plants, which offers an opportunity for more novel achievements in this research area. The contributions of this paper are then stated as follows:

- A simplified nonlinear model of a practically operating GT has been developed and the parameters are identified by WO. The model accurately captures the turbine dynamics from 120 MW to 220 MW. The issue of petameters' calibration has been supported by the results over a wide range of settings. Moreover, the effect of relaxation of parameters on the model robustness has been investigated for the first time, which leads to high accuracy for a broader range of power changes.
- A MIMO PI/PD controller has been optimized and incorporated into the model of the existing GT as additional loops and the controller parameters have been tuned and calibrated by WO to improve the existing controller performance in terms of fuel consumption, and hence the energy efficiency. The likely operation of the adopted GT is the premix mode. Therefore, in light of this practically feasible assumption, the overall efficiency is found to be improved with significant reduction in gas consumption. This aspect has been validated through simulations of the lower natural gas consumption for the same power trends from data of existing GTs.

The rest of the paper is organized as follows: Section 1.3 presents an overview on WO, Section 2 explains the modeling approach and depicts the model simulation results, Section 3 shows the control strategy and verifies the practical feasibility, and Section 4 concludes the paper with some research findings and future recommendations.

1.3. An Overview on Whale Optimization Algorithm

There are various levels of algorithm problems, one of which is metaheuristic problems. Such problems necessitate the use of sophisticated optimization techniques. Whale optimization, which has been used in this study, is a metaheuristic algorithm that implements the hunting and feeding techniques used by whales. It can thus be implemented into power plant control schemes because it requires simple concepts, does not require gradient information, has the ability to bypass local optima, which is necessary in many scenarios, and is more important [23]. Whale optimization technique involves two main processes:

1. Exploration; which is basically a general search, where the optimizer includes all information in the search area.
2. Exploitation; which is basically an explicit search, where it investigates details in promising areas in the region of the local search.

The challenge lies in finding a balance between both processes and finding the optima in the least amount of time. "Why study whales?" one may ask. Whales are actually one of the smartest creatures scientifically as they possess twice the amount of spindle cells as humans do, and the methods they use to acquire or hunt for food are extraordinary. They use a method called bubble-net feeding either in an upward spiral or double loops. Basically, they begin by creating a bubble shape, in one of the two directions mentioned previously, around the prey and then swim up to the surface. A mathematical model has been done in one of the papers for the three main stages of their "feeding" method.

1. Encircling the prey. It is basically suggested as the first or closest value to the optima or "first guess", where then the best search agent is defined, and other search agents will update their position towards the best search agent. One of the variables is a random vector which allows the search to go beyond and search all possible regions.
2. Bubble-net attacking method, also known as exploitation. This stage consists of two approaches: either shrinking encircling mechanism or spiral updating position, each having equal probability of occurring at any interval.
3. Search for the prey (exploration), this stage basically begins the search in other promising regions.

The basic difference between exploitation and exploration is the concept of searching either locally or globally, as the exploration stage does, which is essentially determined by the value of the vector A being higher or less than 1. The basic flow chart of WO is shown in Figure 4, where X_i and X^* are the initial population and the best search agent, respectively.

According to the results of this paper, the WO tends to exploit extensively in the early stages because the first guess should be close to the optimal value, but it does lean into the early stages to switch abruptly between exploration and exploitation. Another critical parameter is the death penalty function, which considers the main objective function that must be resolved and optimized while ignoring infeasible solutions. Because of the aforementioned literature and brief background on WO, the method of modeling, identification, and control proposed in this research is expected to be superior to other techniques discussed above; the only way to determine this is to apply previous techniques of tuning the models on our developed model and observe the differences. This will involve using GA and GWO and comparing them to WO in terms of model accuracies and control system performance, which will eventually lead to valuable contributions in the field of gas turbine modeling and control.

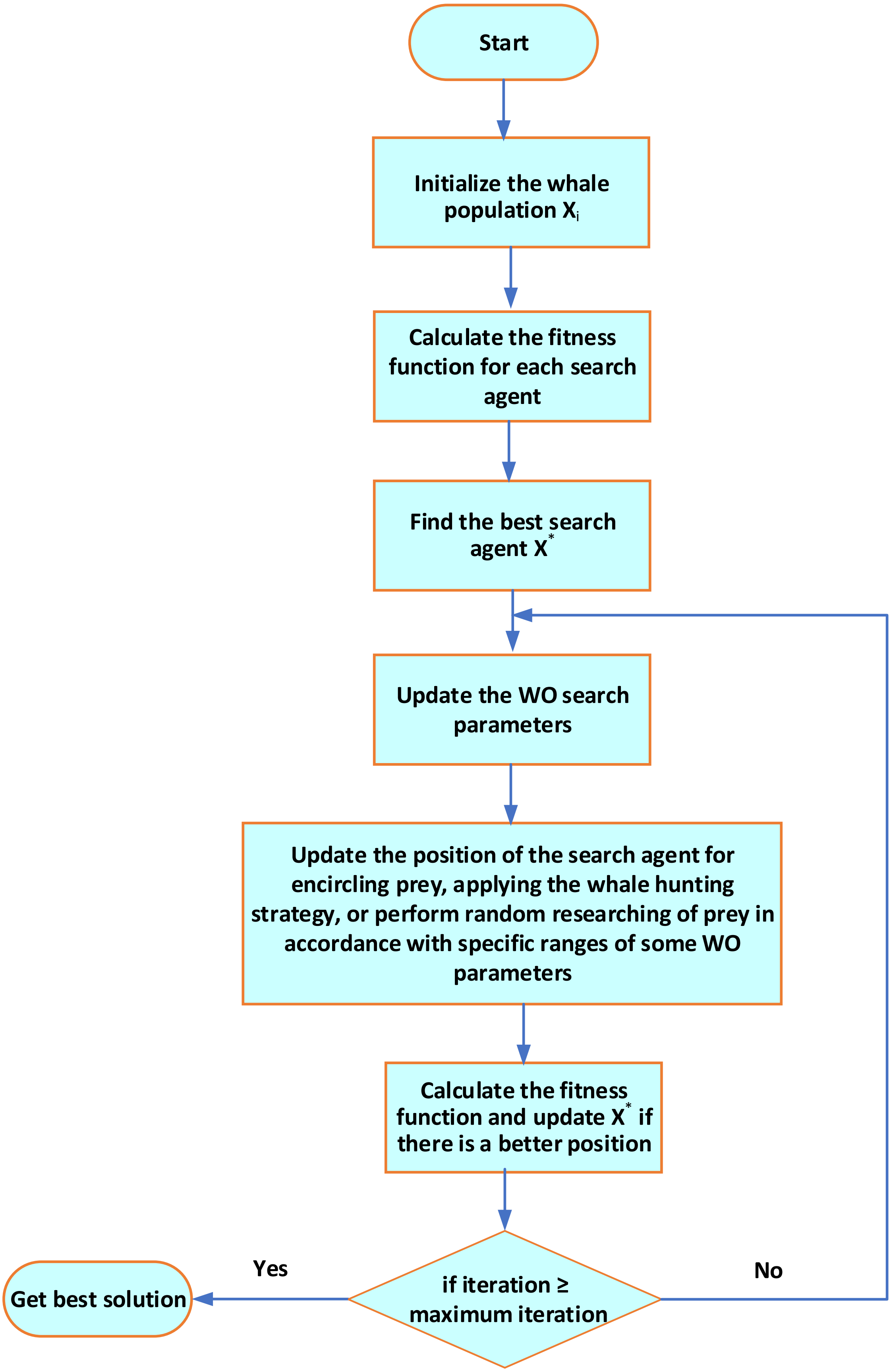

Figure 4. The flow chart of the basic working mechanism of a whale optimizer.

2. Modeling and Optimum Parameter Identification via WO

This section focuses on modeling the GT and MATLAB simulations for the approach of the GT modeling and identifying its unknown parameters. The power plant is fueled by natural gas and fuel oil which may be regulated via inlet guide vanes, and the data covers the operation from 120 MW to about 240 MW, which have been reproduced from Open Access previous publications of the corresponding author [6].

The inputs of the power plant are as follows: Natural gas valve, pilot valve, and compressor output pressure ratio. They are all represented by their normalized percentages of opening. The outputs of the power plant are active power measured in megawatts (MW) and exhaust temperature measured in degree Celsius. The final model structure is shown in Figure 5

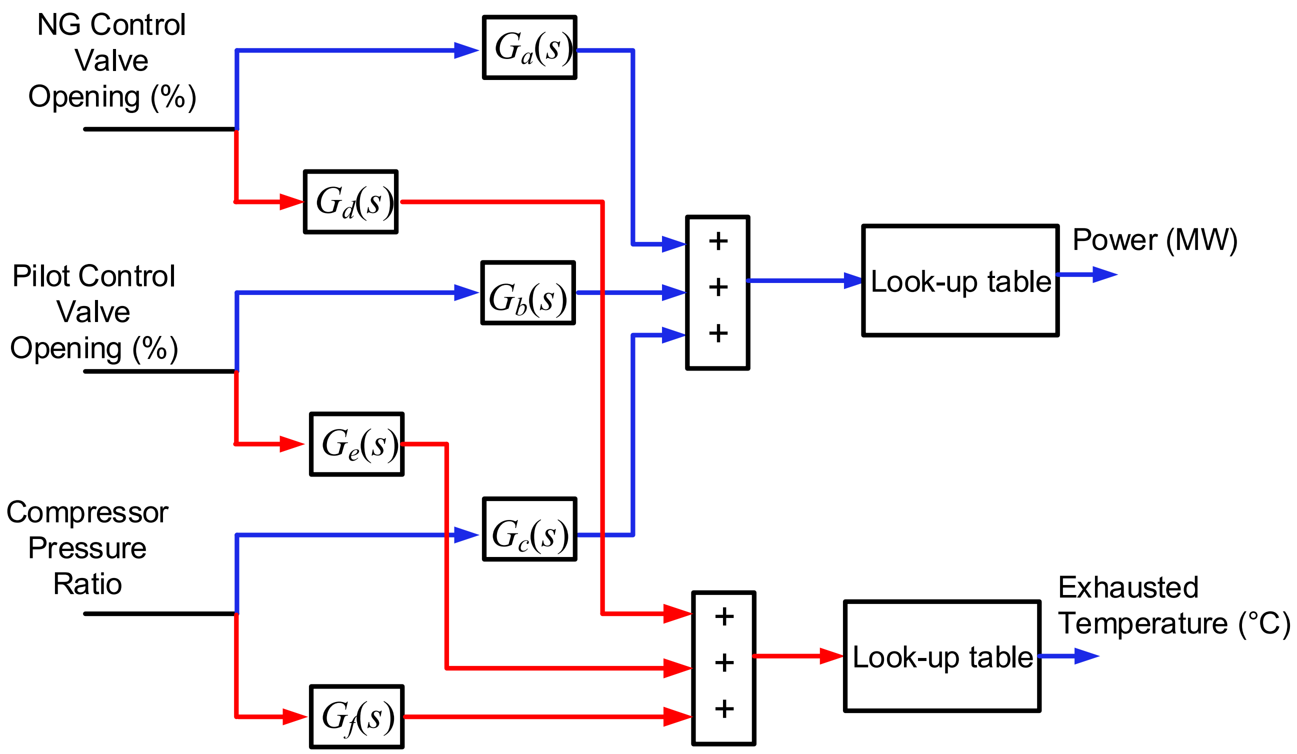

Figure 5. The Mathematical Model of the Gas Turbine, Red: the input signal flows through the system to the exhausted temperature, Blue: the input signal flows through the system to the output power.

The transfer functions of the system in Figure 5 are adopted to be as follows:

$$G_a(s) = \frac{a_1 s + a_2}{a_3 s^2 + a_4 s + a_5} \tag{1}$$

$$G_b(s) = \frac{b_1 s^2 + b_2 s + b_3}{b_4 s^2 + b_5 s + b_6} \tag{2}$$

$$G_c(s) = \frac{c_1 s^2 + c_2 s + c_3}{c_4 s^2 + c_5 s + c_6} \tag{3}$$

$$G_d(s) = \frac{d_1 s + d_2}{d_3 s^2 + d_4 s + d_5} \tag{4}$$

$$G_e(s) = \frac{e_1 s + e_2}{e_3 s^2 + e_4 s + e_5} \tag{5}$$

$$G_f(s) = \frac{f_1}{f_2 s^2 + f_3 s + f_4} \quad (6)$$

The chosen order of the numerator and denominator for each function is selected through several trails and comparison before inclusion of the WO optimizer in order to ensure realistic dynamical influences of the three inputs to the two outputs. Furthermore, the nonlinear region of operation has been emulated through look-up tables, which represents the nonlinear components in the model. Then, the parameters of every transfer function have been tuned by WO by tightening and relaxation of the bounds of the parameters.

First, data for an actual dual fuel gas turbine power plant has been taken, where it was resampled into intervals of 30 s, having a total of 2040 samples, which represents operating time of exactly 17 h. The model parameters were initially guessed by trial and error, then the implemented model was embedded into the code that represents the cost function. The cost function is the squared error between measured and simulated results. WO, with carefully chosen settings, was used to compute the optimum set of parameters. In order to ensure that the parameters are able to yield close enough results to the actual values of the model, the error has been calculated several times with changing WO setting parameters and the lower and upper bounds of every model parameter. It has been done for 10 iterations through 30 iterations of the whale optimizer. The constraints on the parameters were set as 0.05. To analyze the difference in the results when the whale optimizer constraints are relaxed and tightened, the simulation was done when the constraints were tightened to 0.005 and then relaxed to 0.1. The effect of parameters' relaxation is shown in Table 1 and the optimum set of parameters, based on the best case, are given in Table 1, and the optimum set of parameters is shown in Table 2. Simulation results for the selected set of data have been depicted in Figures 6–10. The next stage is dedicated for controller development. The simulated trajectory has the ability to follow the actual trajectory of the power plant, however, there is some clear deviation at some points, which proves the need for a modified version of the power plant. A controller should be embedded in the design to improve the input and output. The parameters were identified offline, and it took several hours to obtain the final optimal set of parameters.

Table 1. The effect of WO iterations and relaxation of the bounds of model parameters.

Iterations	Root Mean Square Error	
	Tightened to 0.005	**Relaxed to 0.1**
Ten	0.0878	0.0880
Twenty	0.0886	0.0947
Thirty	0.0891	0.0880

Table 2. Optimum set of parameters.

Function	Parameters						
$G_a(s)$	a_1–a_5	2.8957	9.9945	0.1080	1.8984	2.6918	-
$G_b(s)$	b_1–b_6	0.4933	3.0072	0.4927	0.1004	0.2988	0.2991
$G_c(s)$	c_1–c_6	0.8924	0.7027	0.9986	0.1070	0.3047	0.4919
$G_d(s)$	d_1–d_5	0.5063	0.6916	0.9079	0.5970	0.2011	-
$G_e(s)$	e_1–e_5	0.9963	1.1993	0.3048	0.9044	0.1900	-
$G_f(s)$	f_1–f_4	0.8568	0.8017	0.6997	0.0962	-	-

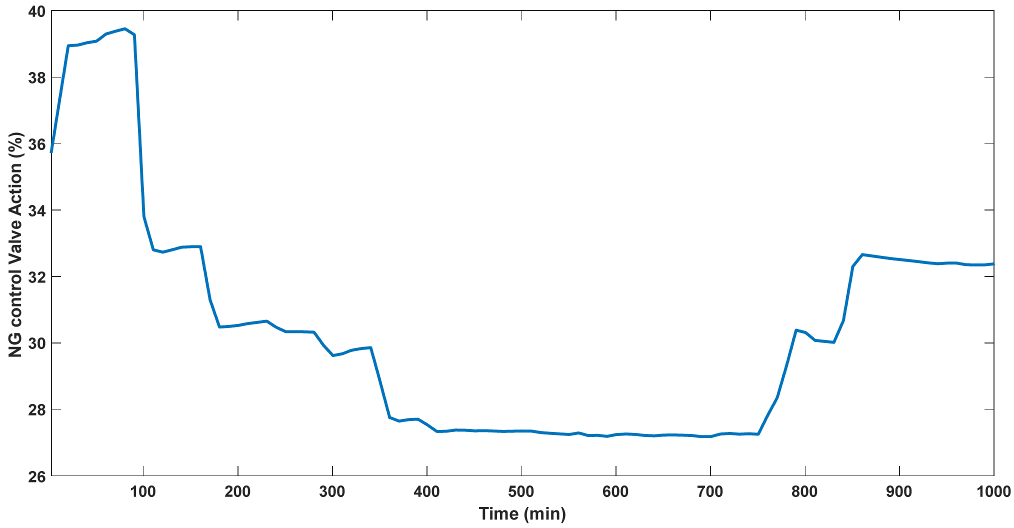

Figure 6. Input NG control valve opening.

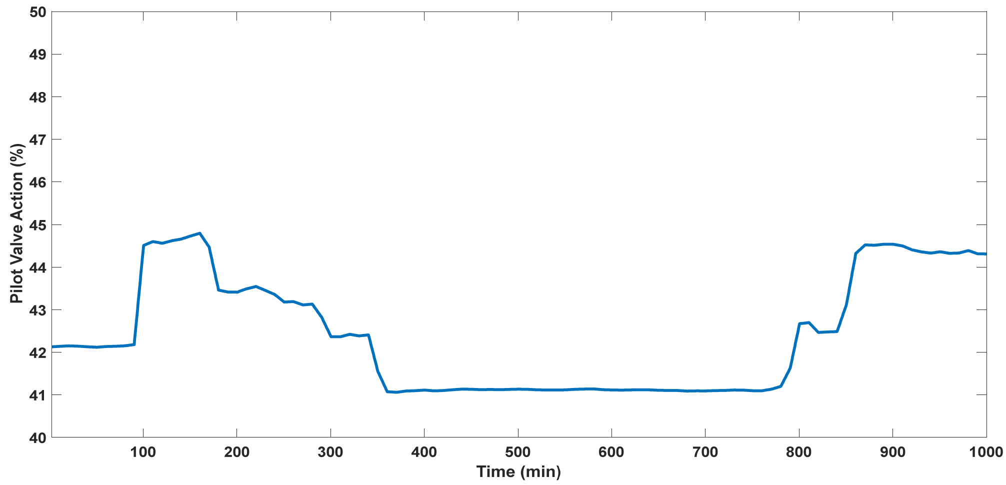

Figure 7. Input Pilot control valve opening.

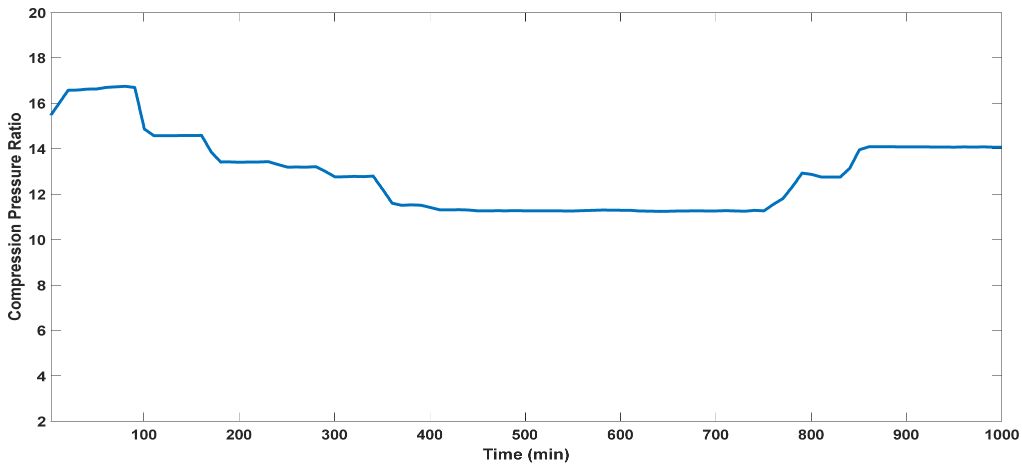

Figure 8. Compression pressure ratio.

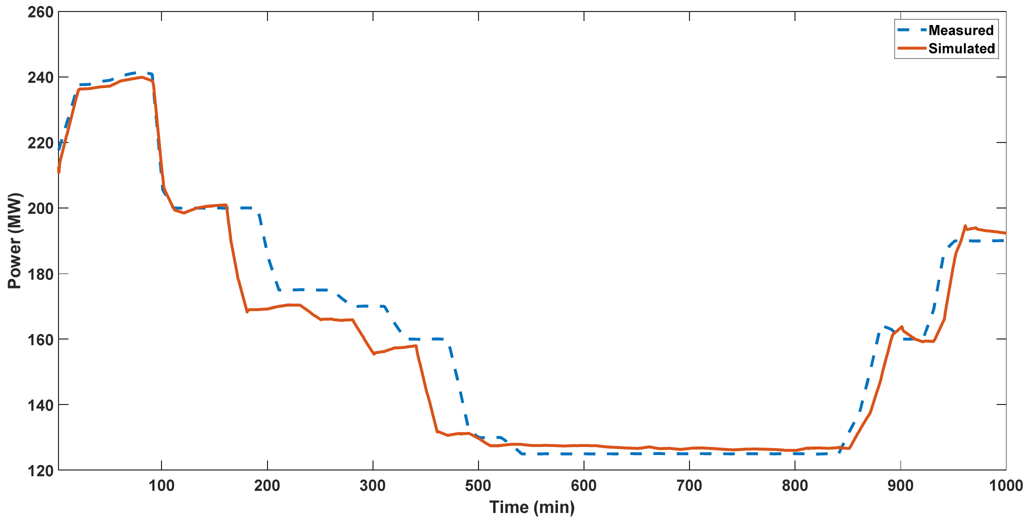

Figure 9. Measured and simulated output power responses.

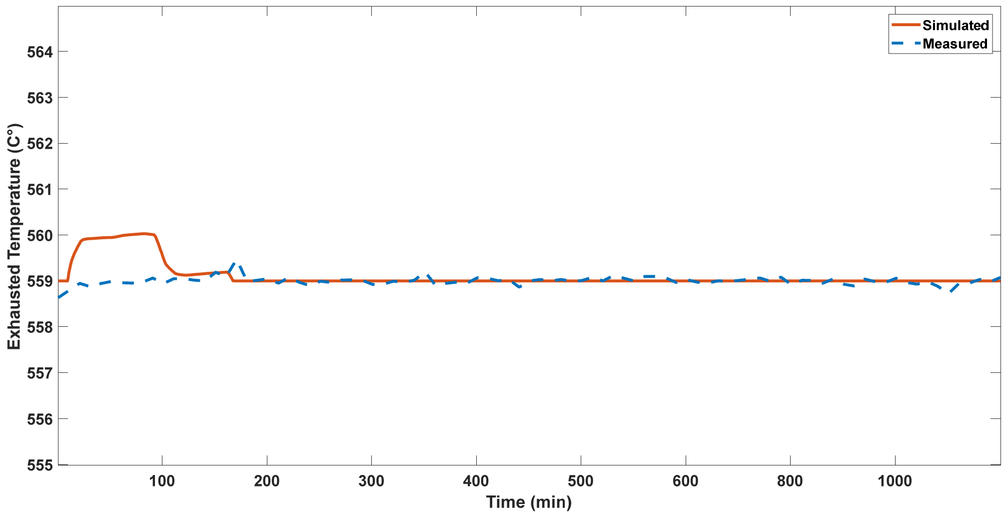

Figure 10. Measured and simulated exhausted temperature responses.

3. Control System Design and Testing via WO

The control system configuration has been assumed to correct the action over the existing control system [3]. It is well known that the identification that has been applied in Section 2 is a closed-loop identification, therefore, one must ensure the proposed controller will not interfere with existing control. From control theory point of view, nothing ensures that except authentic simulations of the proposed controller and comparison–that is rooted from experience–with existing performance. The MIMO controller has been assumed to have two PI controllers, one to regulate the NG and Pilot control valves together and the other to control the compression ratio through the IGV. The coupling control element between the two PI controllers has been chosen to be the PD controller. This structure has been widely accepted for thermal power plant control in general with different control philosophies and parameter tuning [3,6,19–21]. The proposed control system is shown in Figure 11. The rate limiters and saturations help avoid undesirable stresses that may result from extensive changes in the control signals.

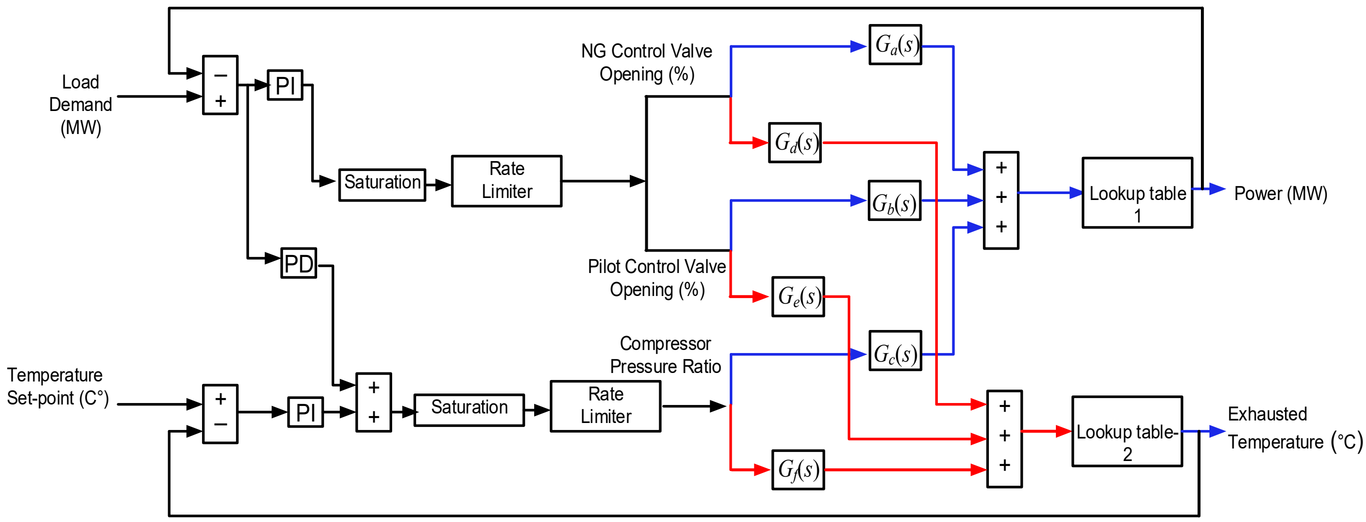

Figure 11. Simulink model with the suggested controller.

The controller has been tuned by WO to minimize the error between set-point and output from the model. It has been tested first with a fictitious pulse load signal that varies from 120 MW to 240 MW, whereas the temperature signal has been constant at 560 °C. The two signals have been implemented into the model, with the addition of loop controllers, along with rate limiters and saturation blocks. The PI/PD controllers have been optimized to follow the signals introduced to the model, with their appropriate parameters. Two proportional-integral (PI) controllers were needed along with one proportional-derivative (PD) controller. Table 3 shows the optimal set of the controller parameters.

Table 3. Controller Parameters.

	PI Controller Parameters for the Fuel Preparation System	PI Controller Parameters for the Compressor	Coupling PD Parameters
K_P	3	0.35	2.65
K_I	10.1	2	-
K_D	-	-	0.2526

The reason why the signals were designed as such: signal one demonstrates the change in active power, and this will prove whether the controller can satisfy the load following capabilities, and whether the exhaust temperature can be controlled in such a manner that would keep it at a constant value. As can be seen in Figures 12 and 13, after introducing the controller with their appropriate parameters, the power plant is capable of following the load demand signal rapidly, even though the signal increased by 120 MW as it would during sudden load application and rejection, the power plant is able to satisfy this change in a timely manner.

The power plant is also capable of stabilizing the exhaust temperature. Keep in mind that it has been able to do so with no considerable changes to the exhaust temperature and was kept at 560 degrees Celsius. This proves the success and validity of the controller in a mathematical sense; however, another practical test is required to ensure the energy-efficient aspect of the controller. One way to ensure this is to apply the data signal of the load demand as a reference set-point to the controller with a little bit higher temperature reference signal. As a consequence, the control system decisions for the fuel preparation system have shown uneven changes in the control actions. Figures 14 and 15 shows higher pilot valve action requirement while the NG valve action is lower. The improvement could be decided with full confidence through the total consumed fuel during premix mode, which is depicted in Figure 16. The average fuel reduction has been 8.96% fuel consumption, which is equivalent to about 237.16 MWh average energy savings for the entire time window of operation.

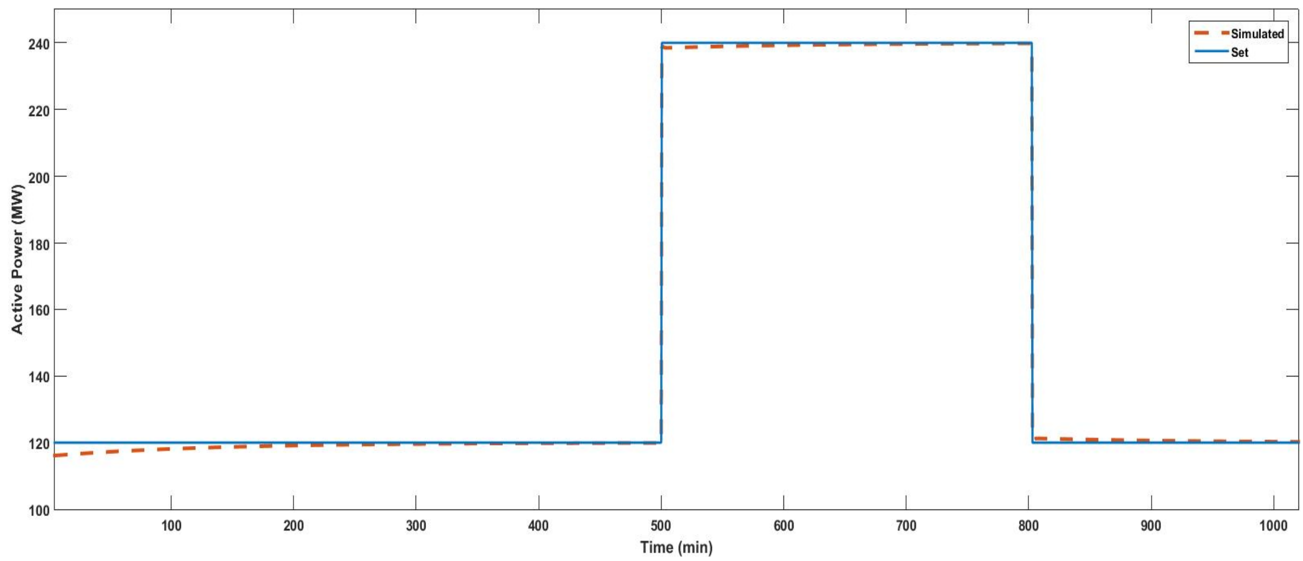

Figure 12. Active power simulated after implementing the controller (dashed orange) along with the actual active power signal that should be followed (blue).

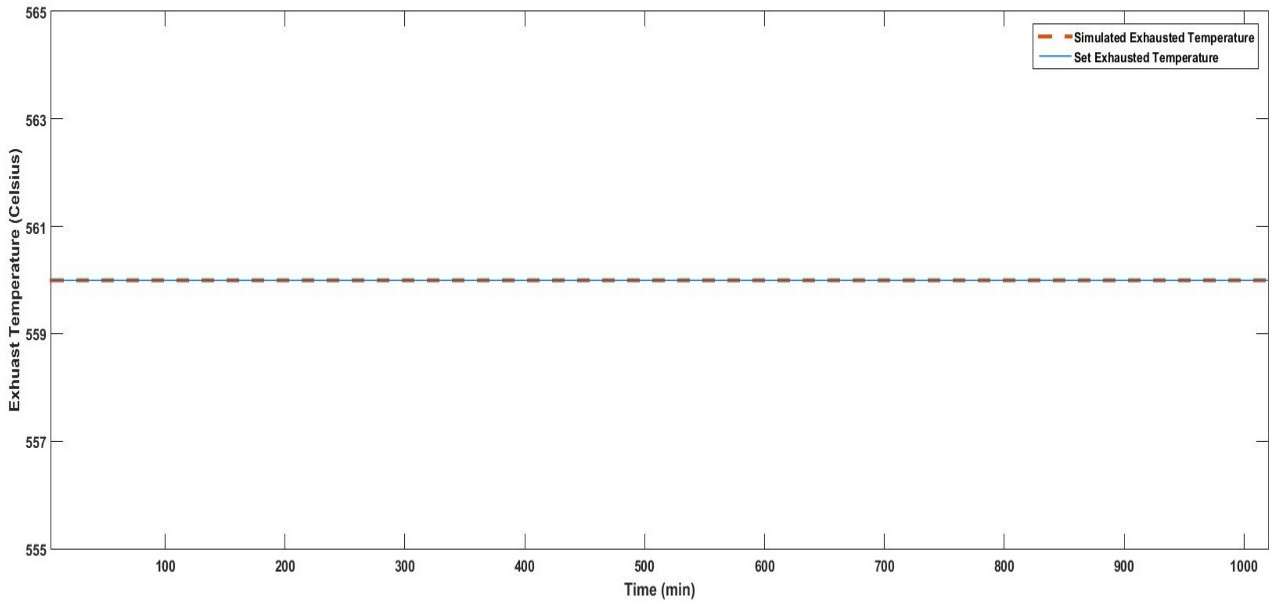

Figure 13. Exhaust temperature simulated after implementing the controller (dashed orange) along with the actual exhaust temperature signal that should be followed (blue).

Overall, there are fewer running costs and less use of raw materials which is necessary and a non-ending goal for the design of most power plants. Figure 17 shows that high and constant compression is required for compressor pressure output ratio response with the controller, where the value was constant during the simulation period which fundamentally proves that the efficiency of the plant has been improved, but higher input should be invested through the compressor. Figure 17 shows that more kinetic energy should be invested to the compressor through higher and constant compression ratio over the existing or measured case, in which the energy conservation principle can be proved. As can be seen in Figures 18 and 19, the active power was followed during the whole 17 h, almost perfectly taking into consideration that the total input has dropped from the actual value yet the yield of active power stayed the same. The exhaust temperature shows almost a 4 degrees Celsius increase over the actual value with no fluctuations, which is also significant to prove the controller has improved overall.

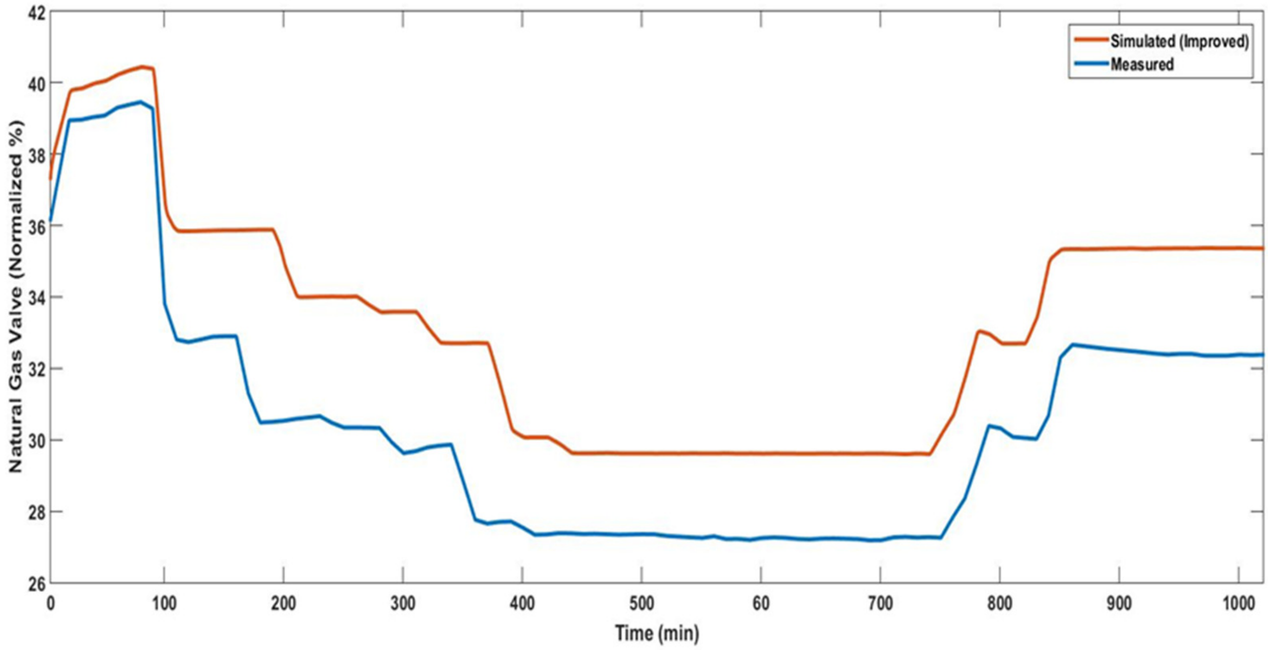

Figure 14. The Pilot valve dynamics, showing the existing and actual fuel oil (diffusion mode)/natural gas (premix mode) consumption (blue) and the simulated (improved dynamics (orange)). Notice: higher fuel consumption from the Pilot valve.

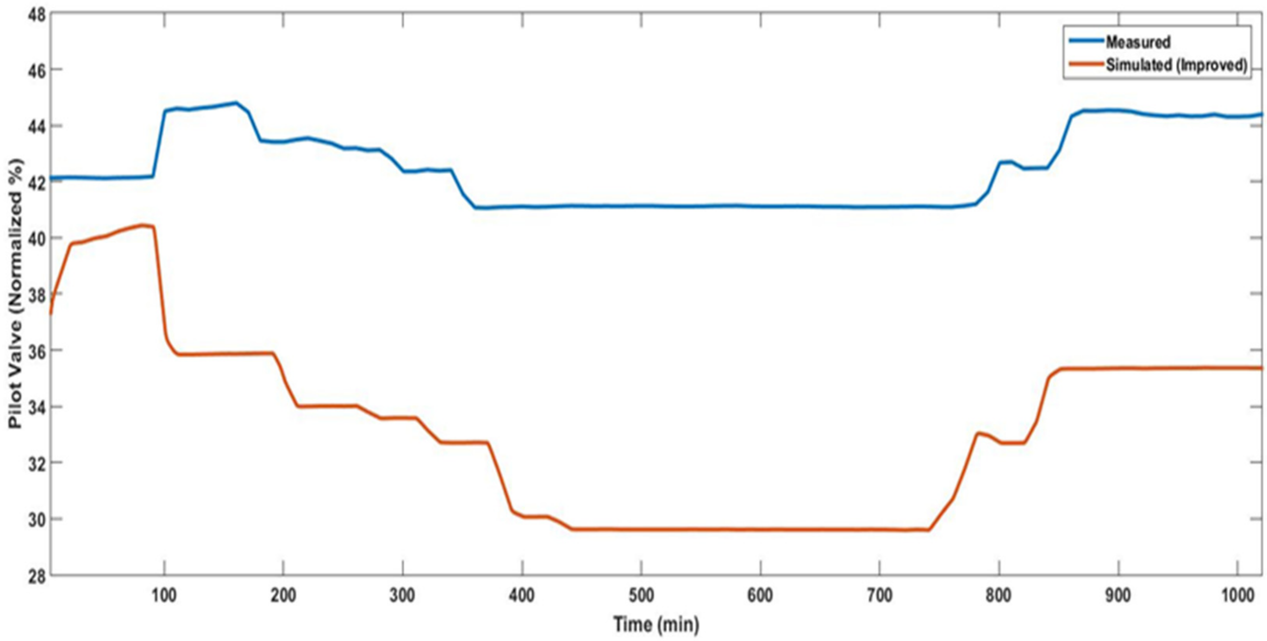

Figure 15. The NG valve dynamics, showing much lower fuel consumption with the simulated (improved with the controller) (orange) and the existing case (blue).

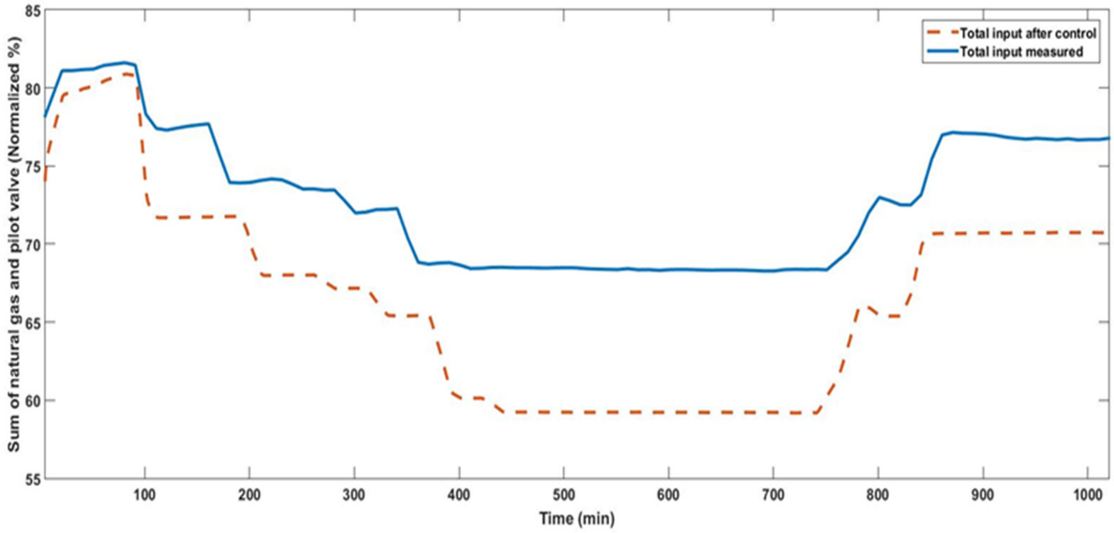

Figure 16. Total fuel input to the plant (pilot valve flow + NG flow) showing significant reduction in fuel or natural gas consumption (dashed orange) if operated totally on NG (i.e., premix mode) over the existing operation fuel consumption (blue).

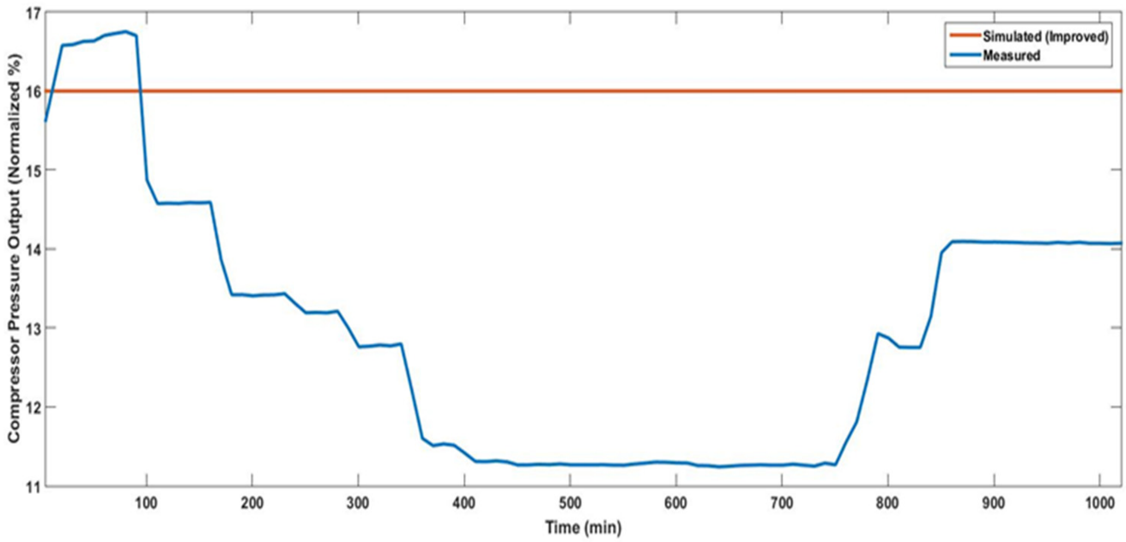

Figure 17. Compressor ratios in the improved (ornage) and existing case (blue).

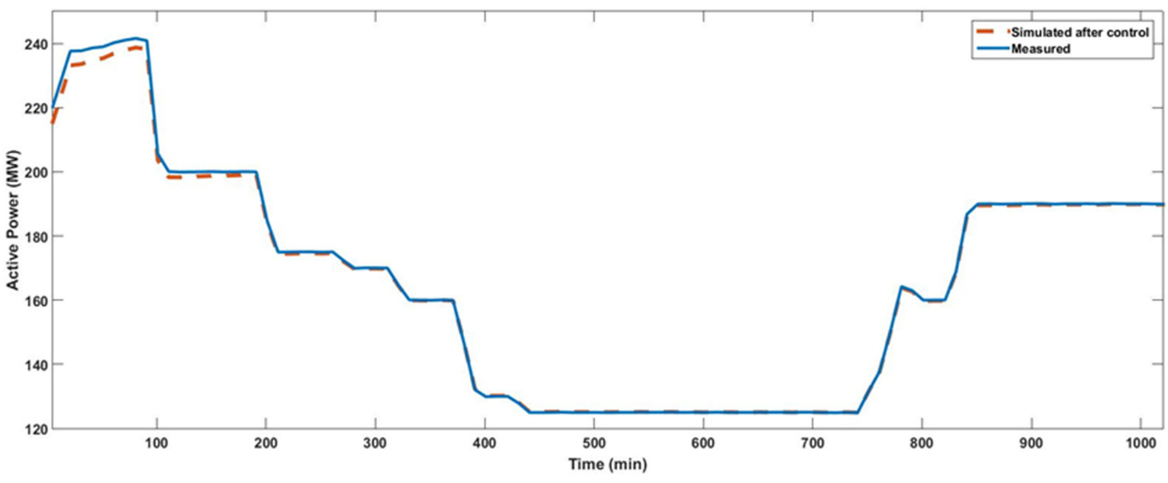

Figure 18. GT output (dashed orange) following the load demand (blue solid).

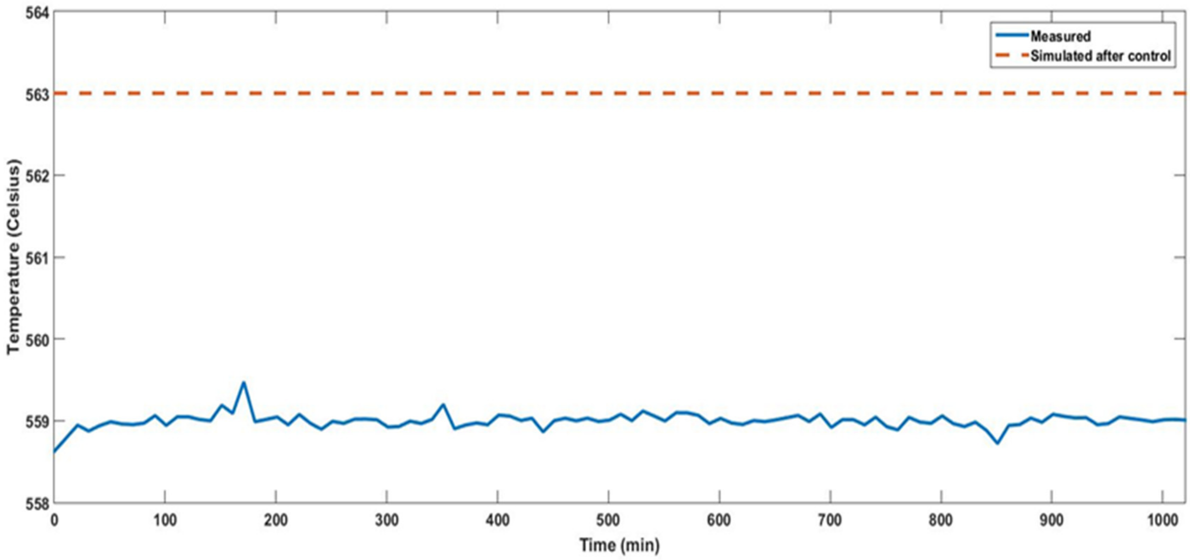

Figure 19. Exhaust temperature, the actual exhausted temperature (blue) along with the improved exhausted temperature response (dashed orange).

The next section concludes the research findings and recommends future points.

4. Conclusions

In this paper, a new simplified model for capturing the essential dynamical performance for a heavy-duty GT has been presented. The model embeds linear and nonlinear components, and the unknown parameters have been optimized using WO with sufficient relaxation of the bounds of the parameter. The model outputs have been verified from a load range of 120 MW up to 240 MW with reasonable accuracy. In addition, a MIMO PI/PD controller has been designed with optimal adjustments of the control parameters by WO. It has been shown that the controller regulates the essential outputs of the plant with more efficient operation. Thereby, it has been proven that WO is a robust optimizer for GT modeling, identification, and control.

There are some future opportunities to investigate, for example, using different metaheuristic optimizers for quantified comparison with WO in terms of accuracy and computation requirements. Different and modern GTs could also be tested with this control strategy, which are fueled by hydrogen or biogas. An economic feasibility study of the control practical implementation in real time is also a scientific merit that could be achieved.

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