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Improvement in efficiency of thermal power plant using optimization and robust controller

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ABSTRACT

This paper briefs on some of the most effective control configurations that can be used to improve the efficiency of coal fueled thermal power plant, thus practically saving coal and increasing energy produce at a significant level. Our control theory is based on the real time data we collected at the 500 MW capacity unit of NPTL Thermal Power Plant Tuticorin. The collected data helped us to design an accurate model of coal, air and feed water flow rate. With the use of evolution and optimization technique the controllers for all the three loops were adjusted to perfection. The best features of the controllers are highlighted as to give the readers an educated opinion to choose between the discussed controller types.

Abbreviations and nomenclature

BFO	Bacterial Foraging Optimization
BFPSO	Bacterial Foraging Particle Swarm Optimization
CCGT	Combined Cycle Gas Turbine
FPE	Final Prediction Error
GA	Genetic Algorithm
ISE	Integral Square Error
kWh	kilowatt hour
MW	Mega Watt
NTPL	NLC Tamilnadu Power Limited
OTEC	Ocean Thermal Energy Conversion
PD	Proportional Derivative
PID	Proportional-Integral-Derivative
PSO	Particle Swarm Optimization
TFEE	Total-Factor Energy Efficiency
TPH	Tonnes Per Hour

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TPP	Thermal Power Plant
QFT	Quantitative Feedback Technique

1. Introduction

Our comprehension of the physical and material world around us has vastly advanced as a result of rigorous observation and experimentation. As new technologies emerge to take control, the energy demand deepens. Looking at the abundant fossil fuel resources, the question is certainly not if we could produce energy but it is about the sustainability aspect of the production. The future of energy production remains conflicting till this day as carbon emissions and nuclear wastes are the primary concerns for any plans that are being made to operate or scale energy production. With so much prediction and hypothesis what is certain is our ability to make our existing energy production facilities more efficient, which will result in less pollution and more time for researchers to bring a sustainable future in energy production. A huge total of 35.1% of the global energy is derived from coal, any changes to the production methods would have a much more profound impact on the society than arguably any other methods of generation, which is why we have dedicated this study to improve energy efficiency in coal-fired energy production facilities. This study shows how a change in controller can have an effect in efficiency, it further elaborates on using different types of PID control designs to achieve efficiency and differentiates each system's performance. The data for this study was meticulously gathered from a national 500 MW coal-fired thermal power plant in Tuticorin, Tamil Nadu, India. The information gathered was put to the test in our boiler turbine generator station mathematical model, which is a non-linear multi-input, single-output system. The MATLAB software was used to run data in the mathematical model. In the paper, all of the details of simulations and modelling computations are fully defined. Should any of the readers be new with these principles, we've given a brief introduction to efficiency computation and calculations that define the current productivity of the power plant. The study's core compares the performance of popular natural biology-derived algorithms such as GA (Genetic Algorithm), PSO (Particle Swarm Optimization), BFO (Bacterial Foraging Optimization), and BFPSO (Bacterial Foraging Particle Swarm Optimization) to the conventional controller and the QFT (Quantitative Feedback Theory). The rise time (sec), settling time (sec), overshoot (sec), and offset (sec) are all factors to consider. We were able to calculate each controller's efficiency value by comparing their time domains. The calculations and the simulation results provided gives substantial proof for the conclusion we have theorized [1]. The operation of thermal power plants doesn't come without challenges, one of them being to overcome the inherent time delay, non-linearity and continuous load changes caused between the boiler and turbine. Analysing the requirements, research scholars have developed a new fuzzy-based coordinated controller that can precisely match the energy demand of the turbine generator with that of the energy input of the boiler. The proposed model was tested using the data collected from 210 MW thermal power plants [2]. Linearity is a concept mostly used to explain ideal scenarios but real-time operations usually involve non-linear conditions. In the subject of "energy production," linearity and non-linearity can be the difference between high or less efficiency in energy production. Understanding this principle, researchers have proposed analysis and control methods in the boiler-turbine unit that might possibly allow them to operate under linear conditions [3,26]. Another notable work to control the non-linear property in plants comes from studying the genetic algorithm. Scholars have identified this algorithm to be successful in developing PI controllers with state feedback for MIMO plant models [4]. An experimental application of optimal control to a boiler power facility was conducted at the Italian national electricity board. Based on the methods used and the results obtained a short report was formatted. The report ends by concluding possible industrial applications in the near future [5]. Experimenting with hypotheses on real-time models is unnecessary with accurate mathematical models. Given the benefits, researchers are attempting to create models that are as accurate as feasible. Non-linear models for boiler-turbine-alternator systems built to run on fossil fuels are well represented in a report issued by R.D Bell. To ensure ease, it is ensured that these models are managed by the fewest possible mathematical equations [6]. Another notable development of precise mathematical models related to energy plants comes from K.J. Åström. In his work he has published mathematical models for drum boiler, setting of control valves and fuel flow being the primary control variables. To ensure the validity of the model he has tested on a boiler rated for 160 MW [7]. For a subcritical boiler-turbine generator rated for a 32 MW coal-based power production facility, thermodynamic analysis is carried out. The analysis details the distribution of exergy loss in the plant, based on the exergy loss within the system sustainability analysis is performed [8]. To solve the issues caused while controlling non-linear processes PSO algorithm is proposed. Upon experimenting with the hypothesis it has been proven that the PSO algorithm works well both in stable and unstable processes. PID controllers tuned based on this algorithm has been observed to reject supply disturbances, improved time domain specifications, smoothness in tracking reference and have fewer errors overall [9]. To tackle nonlinear systems, the effectiveness of the PSO algorithm is proposed. Furthermore, the study clearly shows how other well-known nature-inspired algorithms, such as GA and AL algorithms, are related [10]. A new hybrid methodology has been created based on GARCH and multiple regression. The report is organised on a comparison between the new method with the VAR model. It also discusses the short-term dynamics of the EEI in reaction to changing indicator factors for thermal power plants in China [11]. A new initiative to increase the efficiency of coal-based thermal power plants was started in India, where 23 units of 210 MW were updated to meet the new standards. The results of the work done have been summarised into a report, which also explains the major auxiliary pieces of equipment involved. Moreover, the report also details how 23,000–32,400 tonnes/year of carbon emissions can be cut by following some of the crucial steps indicated in the report [12]. According to the statistical data made available, only about 20–30% of the heat energy generated in a coal-fired thermal power plant is converted to energy. The report proposes novel approaches for reducing the bulk of heat dissipated into the environment. Energy and energy analysis, which is also published in the study, are used to identify heat losses. MilicaJović [13] analyzed coal based thermal power plant operating in the Republic of Serbia and have proposed low cost changes in the cooling system to improve energy efficiency. Rodrigo Soto [14] has proposed a theory that, when effective, could enhance the efficiency of coastal thermal power plants by about 25–37 MW without any added emissions, simultaneously reducing water temperature and desalinating about 5.8 M tons of water per year. A new proposal to increase energy efficiency of thermal power plants was made public by Tongjun Zhang [15]. Where he suggests that efficiency can be improved when by reducing the temperature of water in the condenser or by increasing the temperature of the steam output of the boiler [16]. A performance evaluation of district heating and cooling systems powered by co-generation and tri-generation systems powered by thermal power plants has been published. The author has used eight thermodynamical models of thermal power plants to simulate the hypothesis. The results suggest that the heating efficiency ranges from 49 to 61%, with a minor decrease in electricity generation. Furthermore, the author claims that this minor change in power plants is advantageous to long-term sustainability and energy efficiency [17]. Scientists have proposed a scheme to increase the efficiency of a thermal plant by studying the impact of temperature and flow rate of cooling water on the performance of condensers. Since the efficiency of a thermal plant highly depends on the turbine-condenser operational mode [18]. A fresh set of recommendations has been proposed in response to the need to upgrade the existing manner of approach. The plan comprises changes to measuring parameters, individual unit energy and heat balances, accuracy assurance method for all important metrics, and the overall energy production facility [19]. The durability of impact plates in the ventilation mill in the coal grinding facility was enhanced in the Serbian power plant Kostolac B, demonstrating an interesting technique to boosting the energy efficiency of coal-fueled thermal power plants. . M. Rafiee [20] proposed to design a thermoelectric generator it is possible to gather power from the high sum of energy that is wasted by escaping to the atmosphere during the condensation process. They further state that, applying this method increases the overall efficiency of thermal plants by about 3.3%. Zarif Aminov [21] has worked on building Combined Cycle Gas Turbine (CCGT) for the coal fired Tashkent power plant in Uzbekistan. They have detailed how this could increase the efficiency of the power plant and also have included plans on how it can be incorporated into existing infrastructure by using some of its features [22]. A team of Chinese research scholars have detailed on evaluating the Total Factor Energy Efficiency (TFEE) evaluation thermal power plants by using Data Envelopment Analysis (DEA), Malmquist and Multiple Regression Techniques. They also have included pointers on how the Chinese government can incorporate their strategy and findings into their existing energy industry infrastructure to maximise the power generation efficiency [23]. Understanding the basic principles of thermodynamics, new direct and indirect techniques of calculating a boiler's efficiency in coal-fired thermal power plants was proposed. The study discusses the direct and indirect techniques of finding, then goes into detail about the direct methods and how they compare to the ASME PTC-41 standards [24]. Published a study explaining capacity control measures for the auxiliary mechanisms in the thermal power plant by developing the mathematical model has enabled them to find control system parameters that provide maximum energy efficiency of the mechanism operation. Rodrigo [25] proposed a scientific study on improving energy efficiency of coal based thermal power plants with Ocean Thermal Energy Conversion (OTEC) and evaluated implementation report in Chilean thermal power plant. Their study suggests that this method has improved the efficiency of the plant by 1.3%.

In this paper, section II describes the details and modelling of thermal power plant; III describes the various steps involved in efficiency calculation. Finally, section IV describes the calculated efficiency using optimization methods like GA, PSO, BFO and BFPSO based controllers and robust controller and also the comparison with the operating efficiency.

2. Real time model

With the acquired data from the 500 MW NTPL boiler turbine generator station a non linear multi input single output system is modeled.

The NTPL coal fueled thermal power plant located at tamilnadu, tuticorin is of 1000 MW capacity it features two 500 MW power generation stations. The cold start up flow data of coal, air, steam and feed water in the measure of Tonnes/hr every minute was recorded starting from 0800 h to 1700 h a day. This data helped was used to model a non linear, three input, one-output system.

The three inputs namely coal flow rate, air flow rate and feed water flow rate are considered. Three process loops tuned using evolution and optimization algorithm is designed for these inputs. The outputs from the process loops will control or maintain the output from the system, generated power.

The mathematical model of the suggested system has been extended by using MATLAB software. In the software the system identification tool box used gives functions, blocks etc., and it is used to find mathematical models of dynamic systems which cannot be easily modeled from first principles. Time domain and frequency domain data can be used to derive mathematical model. The recorded time domain real time cold start up coordinated mode data from NTPL plant is used to develop mathematical model with MATLAB software by using ident tool box. Prediction error method is used. The process loops namely, coal flow, feed water flow and airflow were represented by transfer functions and are given by the following equations

$$G_{11}(S) = \frac{0.0497s^2 + 0.1426s + 0.0118}{s^3 + 0.4908s^2 + 0.2504s + 0.0105} \quad (1)$$

$$G_{12}(S) = \frac{0.0074s^2 + 0.0026s - 0.00008}{s^3 + 0.4908s^2 + 0.2504s + 0.0105} \quad (2)$$

$$G_{13}(S) = \frac{0.0071s^2 + 0.0241s + 0.0017}{s^3 + 0.4908s^2 + 0.2504s + 0.0105} \quad (3)$$

Here, Eq. (1) represents the transfer function of generated electric power and the coal flow rate, Eq. (2) represents the transfer function of generated electric power and the air flow rate and (3) represents the transfer function of generated electric power and the feed water flow rate.

The best fit percentage of the model with the real time cold start up data was 94.43%. Final Prediction Error (FPE) was found to be 62.82%. The value of FPE was found to be decreasing for lower number of data and vice versa. In general optimal model complexity corresponds to minimum value of FPE. The FPE value of 62.82% shows less model complexity and hence the highest best fit of 94.43% has been achieved. At this best fit, the model would yield much closer approximations to the real system. In order to check the stability of the system, stability analysis is carried out. Routh Hurwitz method is used to check the stability of the proposed system.

Uncertainty means the range of possible values within which the true value of the measurement lies. When precision and accuracy are of importance, the uncertainty levels of the system that might have a negative effect must be considered. In this study, uncertainty of the measurements of feedwater flow, airflow and coal flow are lies within the specified uncertainty level prescribed by the manufacturer. For every hour of operation, these valves displace tonnes of material into the system, which makes them easy sections of uncertainty, which in return makes them the most crucial points to be observed in this study. Inspecting the datasheet of these valves we found the uncertainty levels to be approximately 0.075%. All the calculations and designs proposed in this study have been made by taking this value into consideration.

The controller for the three loops was tuned using evolution and optimization techniques like Genetic algorithm, Particle swarm optimization, Bacterial foraging optimization and Bacterial foraging particle swarm optimization. From the results, performance of the plant was analyzed. Further to endorse the robustness, QFT based robust controller was also implemented to control the electric power output [26,27].

3. Efficiency calculation

Efficiency is defined as a level of performance that depicts the use of smallest amount of input to attain the utmost amount of output. It is a quantifiable concept that can be determined using the ratio of valuable output to total input.

The overall efficiency of a TPP depends on the way in which the equipment is operated and controlled. Rejuvenation of controllers for TPP is necessary to improve the performance of the plant and to minimize the consumption of fuel, steam, thermal energy, waste heats etc. Heat rate is one of TPP efficiency which converts a fuel into heat and into electricity as well. The heat rate is the amount of energy used by power plant to generate 1 kW hour (kWh) of electricity. The efficiency of a TPP generally lies in the range from 30 to 50%. This indicates that only half or even less of the heat energy generated in the plant is used for the generation of electric power and the remaining heat is wasted due to heat rejection. Based on this, TPP are inadequate and need to be replaced by 'better' control schemes in order to improve its efficiency.

Efficiency of a TPP is mainly due to the fuel flow and the steam admitted to the turbine. As per the U.S. Energy Information, efficiency of TPP in India is 28%–38%. Thermal efficiency of a TPP is defined as the ratio of the total energy produced as a percent of heat energy generated by coal.

Efficiency is calculated in two different methods:

1. Direct Method – Here, the energy content of the boiler fuel is analyzed with the energy gain of the operational fluid
2. Indirect Method – Here, efficiency is calculated as the difference between the energy input and losses

Operating efficiency of NTPL plant is 37.2%. It is calculated based on the heat flow rate and the steam flow rate to the turbine inlet. This heat flow rate is mainly due to the supply to the steam generator of coal flow, air flow and feedwater flow. In order to achieve increase in efficiency, an efficient controller has been designed. In this study, according to the fuel flow and airflow rate combustion may be controlled or improved. If the combustion process is ideal, there will be better heat generation. This causes better steam generation; hence better steam flow rate to the turbine inlet can be achieved so that efficiency can be improved. The steam flow to the turbine inlet is improved by developing the efficient controller for coal flow, air flow and feedwater flow. Hence the efficiency of the plant has been increased.

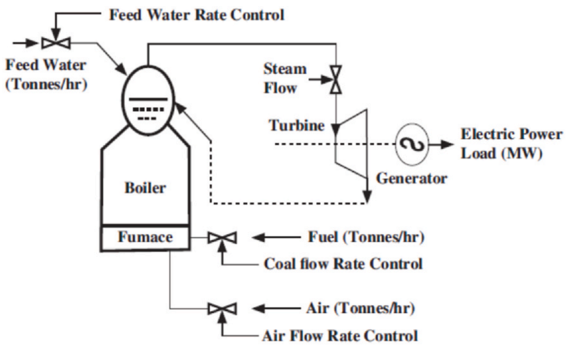

Fig. 1. Three control loops in 500 MW Unit of NTPL plant.

4. Results

In order to control or maintain the generated power by controlling coal flow rate, air flow rate and feed water flow rate PD controller is used in this proposed work. The controller gains are adjusted using optimization and evolution methods. ISE is considered as the optimization function. Controller parameters will be computed for the most minimal Integral Square Error (ISE) value. Controller performance is studied and the efficiency is also calculated.

Fig. 2 shows the electric power generation response of 72 MW (see Fig. 1 shows the three control loops in 500MW unit of NTPL plant). In that, conventional PD controller settled in 82 MW instead of 72 MW. Whereas other controllers like GA-PD, PSO-PD, BFO-PD and BFPSO-PD controller settled with ±3% variation with the set value. BFPSO-PD controller and GA-PD controller settled in 73 MW with less overshoot, BFO-PD controller settled in 76 MW with less overshoot, PSO-PD controller settled in 74 MW with more overshoot than BFPSO-PD controller. Whereas conventional PD controller settled in 82 MW with high overshoot.

From the table it is inferred that for any load change, QFT controller gives less rise time, quick settling time and less overshoot, whereas PSO-PD controller gives less offset. It is proven from the table, that the QFT-based PD controller reaches output response with the required features, faster setting time and significantly less offset and over-shoots than the GA, PSO, BFO and BFPSO-based PD controller.

Plant efficiency is calculated when these sophisticated controllers are used. NLC Tamilnadu Power Ltd (NTPL), a 500 MW capacity plant has operating efficiency of 37.2% is given in Table 2. From Table 2, Load variation is achieved in NTPL plant in the order of 5 MW. As per the plant design, time to achieve 5 MW change was found to be 60sec when the conventional controller was used. When using the robust controller 5 MW change has been achieved in 51sec. This is shown in Table 1. Accordingly, fuel intake, heat flow and steam flow are also regulated simultaneously.

0.0833 MW can be generated per sec when conventional controller was used.

$$\text{Generated power for 1 s} = 0.0833\ \text{MW} \tag{4}$$

(When conventional controller was used)

0.0980 MW can be generated per sec when robust controller was used

$$\text{Generated power for 1 s} = 0.0980\ \text{MW} \tag{5}$$

(When robust controller was used).
For 60 s, the power generated is, 60 X 0.0980 = 5.88 MW

$$\text{Generated power for 1 min} = 5.88\ \text{MW} \tag{6}$$

(When robust controller was used)

$$\text{Generated power for 1 min} = 5.0\ \text{MW} \tag{7}$$

(When conventional controller was used).
Hence while using a robust controller, theoretically 5.88 MW was generated in 60 s.

$$\text{Operating Efficiency of the plant} = 37.2\% \tag{8}$$

(When conventional controller was used)

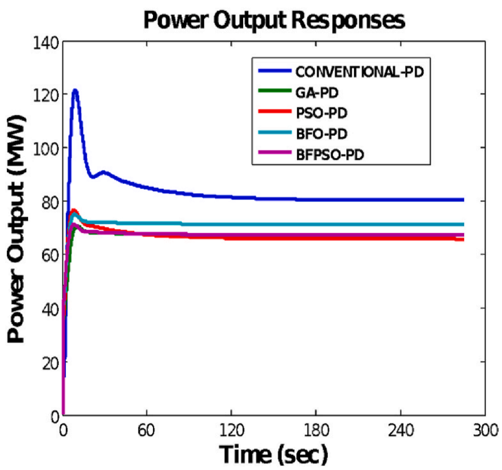

Fig. 2. Output Responses for the set value of 72 MW of Conventional, GA, PSO, BFO, and BFPSO Controllers.

Table 1
Time domain specifications.

Characteristic	Conventional	GA	PSO	BFO	BFPSO	QFT
Rise Time (sec)	1.8	1.3	0.6	0.9	1.2	**0.2**
Settling Time (sec)	60.0	52.3	56.6	54.6	52.0	**51.0**
Overshoot (sec)	13.2	4.8	16.6	13.6	11.8	**3.8**
Offset (sec)	0.4	1.8	0.3	0.6	1.2	**0.3**

Table 2
Efficiency improvement.

Methodology	Conventional	GA	PSO	BFO	BFPSO	QFT
Efficiency (%)	37.2	42.92	39.28	40.85	42.90	**43.75**
Improvement (%)	Ref	5.72	2.08	3.65	5.7	**6.55**

$$\text{Calculated Efficiency of the plant} = 43.75\% \tag{9}$$

(When robust controller was used).

When the conventional controller was used, (i.e., 5 MW in 60sec) operating efficiency resulted with 37.2%. When it was replaced with a robust controller, 5.88 MW was generated theoretically. With these conditions, operating efficiency was improved to 43.75% from 37.2%. On the whole, the improvement in efficiency was found to be 6.55%. The efficiency and improvement in percentage by using different algorithms like GA, PSO, BFO, BFPSO and QFT is shown in Table 2.

It is inferred from the table, the QFT based robust controller gives a higher efficiency and 6.55% improvement with reference to the conventional controller from the operating efficiency for better performance.

5. Conclusion

As of 2020, 61.3% of the global energy was sourced from fossil fuels, among that coal is said to contribute around 35.1%, this would mean that recent decisions to be more tech dependent and reduce global carbon emissions is logically not going to play out evenly. Either the world should choose to regress towards pre technological livelihoods as an attempt to save the planet or become more tech reliant and endure the effects of global warming. To strike a balance between increased tech dependency and reduced carbon emissions, energy must widely be sourced from anything but fossil fuels. Until scientists discover a better energy solution it's in the best interest of everybody that engineers find a way to make our conventional energy conversion process more efficient. Our study has identified that using QFT based controller to control coal, air and water flow rate we can increase the efficiency by about 6.5%. A 660 MW power plant of efficiency 37.96% is observed to use an average of 408 tonnes of coal every hour (not going into the specifics of coal type), with QFT controller in operational we can increase its efficiency up to 44.46% thus saving an average of 71.5 tonnes per hour, 12,012 tonnes per week and 626,340 tonnes per year (considering the plant operates 24/7). The above example is just to give a crude idea of how much coal can be saved, relating the saved coal to the amount of carbon emission avoided will most definitely be of high interest to anyone who is concerned about the future. This approach alone is most certainly not the fix for the rising carbon emissions but most definitely the right step towards fixing it.

A smart control layout for controlling energy generation at NTPL Thermal Power plant by effectively controlling the flow rate of coal, air and feedwater is made operational here. The controller gives the preferred electric output response with small offset and fast settling times observing the fact that it is a real time boiler generator model. The performance of the plant was analyzed. Efficiency of the plant is calculated using all the proposed controllers like GA PD, PSO PD, BFO PD, BFPSO PD and QFT based controllers. Operating efficiency of the plant was compared. The QFT based robust controller gives a higher efficiency and 6.55% improvement with reference to the conventional controller from the operating efficiency for better performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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