LOAD DISPATCH OPTIMIZATION OF OPEN CYCLE INDUSTRIAL GAS TURBINE PLANT INCORPORATING OPERATIONAL, MAINTENANCE AND ENVIRONMENTAL PARAMETERS

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ABSTRACT

Power generation fuel cost, unit availability and environmental rules and regulations are important parameters in power generation load dispatch optimization. Previous optimization work has not considered the later two in their formulations. The objective of this work is to develop a multi-objective optimization model and optimization algorithm for load dispatching optimization of open cycle gas turbine plant that not only consider operational parameters, but also incorporates maintenance and environmental parameters. Gas turbine performance parameters with reference to ASME PTC 22-1985 were developed and validated against an installed performance monitoring system (PMS9000) and plant performance test report. A gas turbine input-output model and emission were defined mathematically into the optimization multi-objectives function. Maintenance parameters of Equivalent Operating Hours (EOH) constraints and environmental parameters of allowable emission (NOx, CO and SO2) limits constraints were also included. The Extended Priority List and Particle Swarm Optimization (EPL-PSO) method was successfully implemented to solve the model. Four simulation tests were conducted to study and test the develop optimization software. Simulation results successfully demonstrated that multi-objectives total production cost (TPC) objective functions, the proposed EOH constraint, emissions model and constraints algorithm could be incorporated into the EPL-PSO method which provided optimum results, without violating any of the constraints as defined. A cost saving of 0.685% and 0.1157% could be obtained based on simulations conducted on actual plant condition and against benchmark problem respectively. The results of this work can be used for actual plant application and future development work for new gas turbine model or to include additional operational constraints.

ABSTRAK

Kos bahan api untuk kuasa penjanaan, kesediaan mesin untuk diguna dan undang-undang alam sekitar adalah merupakan faktor-faktor yang penting dalam kajian pengagihan beban optimum untuk kuasa penjanaan. Objektif kajian ini ialah mencipta model optimasi pelbagai objektif dan optimasi algorithm bagi pengagihan beban optimum untuk tarbin gas kitar terbuka. Ini bukan saja mengambil kira operasi parameter, tetapi juga untuk parameter penyelenggaraan dan alam sekitar yang belum pernah dikaji sebelum ini. Parameter prestasi formula untuk tarbin gas yang berdasarkan kepada ASME PTC 22-1985 telah dihasilkan serta disahkan berbanding dengan sistem prestasi pemantauan (PMS9000) dan laporan ujian prestasi dari stesen. Model tarbin gas dan penghasilan ezkos telah dihasilkan serta dikenalpasti secara matematik ke dalam fungsi optimasi pelbagai objektif. Parameter penyelenggaraan *Equivalent Operating Hours (EOH)* dan parameter alam sekitar bagi had limit pembebasan NOx, CO dan SO2 yang dibenarkan juga diambil kira dalam kajian tersebut. Gabungan kedua-dua kaedah optimasi Extended Priority List dan Particle Swarm Optimization (EPL-PSO) telah digunakan dengan berjaya untuk menyelesaikan model dalam kajian ini. Sebanyak empat simulasi telah dilaksanakan untuk mangaji dan menguji optimasi perisian yang dicipta. Hasil simulasi dalan laporan ini telah berjaya menunjukan bahawa fungsi Kos Jumlah Pengeluaran (TPC) optimasi pelbagai objektif, EOH *constraint*, ekzos gas model dan *constraint* lain telah berfungsi dengan baik bersamaan kaedah optimasi EPL-PSO. Keputusan simulasi juga telah berjaya menunjukkan bahawa keputusan optima dapat dicapai tanpa melampaui sebarang *constraints*. Penjimatan kos sebanyak 0.685% dan 0.1157% telah didapati jika keputusan simulasi dibandingkan dengan data dari stesen dan masalah *benchmark* dari kajian kesusteraan. Hasil usaha kerja ini boleh digunakan untuk applikasi sebenar oleh stesen janakuasa dan kajian masa depan bagi tarbin gas model yang baru, termasuk penglibatan *constraints* yang baru.

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LIST OF SYMBOLS

α	-	thermal time constant for the unit start up (hour)
$a_{i,(1,2,..10)}$	-	Unit *i* input output model polynomial coefficient
β	-	Emissions relative weight
$b_{i,(1,2,..10)}$	-	Unit *i* NOx emission model polynomial coefficient
$c_{i,(1,2,..10)}$	-	Unit *i* CO emission model polynomial coefficient
C_1, C_2	-	Objective function constant parameters
C_c	-	Cold start cost (GJ)
C_F	-	Fixed start-up cost ($)
CO	-	Carbon monoxide emission (ppm)
$d_{i,(1,2,..10)}$	-	Unit *i* SO2 emission model polynomial coefficient
D	-	Dimensional vector $X_{i,d}$ ($X_{i,1}$, $X_{i,2}$, …, $X_{i,D}$)
DCS	-	Distribution control system
DDE	-	Dynamic Data Exchange
EOH	-	Equivalent operating hour (hour)
EOH_{allow}	-	Allowable EOH_{diff} (hour) between units
EOHdiff	-	Remaining EOH before next maintenance work, EOH_N – EOH
EOH_n	-	Next maintenance work equivalent operating hour (hour)
EP	-	Evolutionary Programming
EPL	-	Extended Priority List
EPL-PSO	-	Extended Priority List – Particle Swarm Optimization
E_p	-	Total emissions (ppm)
FC	-	Fuel cost ($/GJ)
$f()$	-	Objective function
f_2	-	NOx emission objective function

f_3	-	CO emission objective function
f_4	-	SO2 emission objective function
f_{ei}	-	Emission objective function for unit *i*
g	-	Constraint function
gbest	-	PSO global best particle
GA	-	Genetic Algorithm
Ho	-	Initial unit status
HPSO	-	Hybrid Particle Swarm Optimization
HR	-	Heat rate (kJ/kWh)
HMI	-	Human Machine Interface
IHR	-	Incremental heat rate (GJ/h)
i	-	i^{th} unit
IO	-	Input output
j	-	j^{th} emission type
KPI	-	Key Performance Indicators
lbest	-	PSO local best particle
LC	-	Load cost ($/kWh)
LC'	-	Differential of LC function / Incremental heat rate (GJ/h)
LCO	-	Allowable CO emission (ppm)
LNOx	-	Allowable NOx emission (ppm)
LSO2	-	Allowable SO2 emission (ppm)
L_T	-	Electrical load / Power demand (MW)
M	-	Total types of emissions
MinDown	-	Minimum down time
MinDownAllow	-	Allowable minimum down time
MinUp	-	Minimum up time
MinUpAllow	-	Allowable minimum up time
N	-	Total unit or U_{max}
NOx	-	Nitride oxide emission (ppm)
OnOffStatus	-	Unit operation status {0,1}
P_i	-	Power output of unit i (MW)
Pbest	-	PSO best particle
PL	-	Priority / Sequence

Pmin	-	Unit minimum power output (MW)
Pmax	-	Unit maximum power output (MW)
ppm	-	Particle per million
PSO	-	Particle Swarm Optimization
$\rho 1$, $\rho 2$	-	PSO constant parameters
R	-	Total spinning reserve
RM	-	Ringgit Malaysia
s	-	PSO penalty factor
s_0	-	PSO initial penalty factor
$S(V_i)$	-	PSO sigmoid function
SdC	-	Shut down cost ($)
StC	-	Start up cost ($)
SO2	-	Sulfur dioxide emission (ppm)
t	-	Time interval
t_{cool}	-	Time in hours the unit has been cooled
T_{max}	-	Total time interval
TPC	-	Total production cost ($)
TPCWE	-	Total production cost with emission ($)
$U_{i,t}$	-	Unit commitment {0, 1} for unit *i* at *t* interval
U_{max}	-	Total unit or N
V	-	PSO particle velocity
V_{max}	-	PSO particle maximum velocity
W	-	Relative weight assigned to the total production cost
w	-	PSO initial weight
$X_{i,d}$	-	PSO particle position for i^{th} particle and d dimension

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The supply of natural energy resources such as natural gas, diesel and coal is decreasing year by year. Malaysia's petroleum resources can only meet the national requirement for another 20 to 30 years (Bernama, 1998). Unless there is an alternative energy source which is cheaper, cost based on fossils fuel would become an even more important consideration. From statistics provided by Department of Electricity and Gas Supply Malaysia, the generation plants in Malaysia mainly 63.4% consist of combined cycle blocks with gas turbine. Approximately 75% of energy generated in the country uses natural gas as fuel, making it the most important fuel in electricity production.

The power generation fuel cost is therefore has become a very sensitive and important parameter to the power generation plant as they cannot effort to waste or inefficiently utilize any energy resources. With reference to Ng (2001), 1% drop of the gas turbine thermal efficiency would lead to 0.065sen/kwh increase of power generation fuel cost (on the basis of the gas turbine running at 30% thermal efficiency). There is therefore a need to ensure the gas turbine always operate at its optimal performance.

On the other hand, the contribution of the gas turbine to environmental pollution raises questions concerning environmental protection and methods of eliminating or reducing pollution either by design or by operational strategies. Pollution affects not only humans, but also other life-forms (such as animals, birds, fish, and plants). It also causes damage to materials, reducing visibility, as well as causing global warming. These effects may be interpreted as costs because it affects life in one way or another. The damage caused by a pollutant depends on its type, meteorological conditions and on our exposure to it. This suggests that each pollutant should be treated on its own merit in assigning cost values (usually referred to as valuing environmental externalities). This represents the potential harm or damage created. The main subtances of the emmisions are Nitrogen Monoxide (NOx), Sulfida Dioxide (SO2) and Carbon Monoxide (CO). Environmental rules and regulations for power generation industries has been implemented extensively and has become an important considerations and even as a regulation. Such regulation are being implemented in developing countries and even in Malaysia that is working towards global environment protection and perservation.

Gas turbine or other electric power plants are currently operating on the traditional basis of least fuel cost strategies (economic dispatch or optimal power flow) without considering the pollutants produced. In order to consider the pollution in the cost function, it is necessary to know the types of pollution produced from power plants, its effects and also requirements of the relevant laws. One of the method to reduce emissions is to dispatch the power generation to minimize emissions or as a supplement to the usual cost objective of economic dispatch. This method requires only minor modification of dispatching programmes to include emissions. Emission dispatching is an attractive short-term alternative in which the primary objective is to minimize the overall emissions by loading the cleaner generating units as much as possible while forcing those with higher emission rates to generate less.

Maintenance parameter such as Equivalent Operating Hours (EOH) are also not currently included to the load dispatch optimization to avoid two or more machines being sent for maintenance at the same time. Insufficient capacity to deliver power as demanded might happen, if wrong decision had been made in manual scheduling.

Industrial gas turbine in most plants do not always operate at their optimum operating conditions to achieve the objectives of minimum cost and minimum emissions, since dependent variables condition like atmospheric pressure, temperature of working fluid, production targets, equipment efficiency, etc. are always fluctuating. Besides, the gas turbine performance degradation may lead to changes of optimal operating points. From time to time, engineers are faced with problem of determining the optimum operating regimes or ways to run a particular machine quickly and accurately in order to obtain maximum benefit from the machine, at all times and under every set of circumstances. It can be very complex and time consuming to generate an accurate mathematical model that represent the machine which optimizes the objective function using suitable optimization techniques.

The primary objective of power dispatch optimization in the past has been concentrated on the minimization of generation cost in meeting the demand on power system – economic dispatch. Few proven mathematical optimization method such as, Extensive Enumeration, Dynamic Programming and Lagrange Relaxation had been used widely in solving such economic dispatch problem. However, the first two methods only work efficiently with small and moderate size system, while Lagrange method suffers from convergence problem, and always trap into a local optimum. Several artificial intelligence (AI) method also had been carried out to solve such optimization problem. Although AI method such as evolutionary computation techniques and genetic algorithm can provide a near-global solution but it takes a very long computation time.

Research work that involves economic load dispatch optimization which includes environmental impact of power generation are very limited. One of the approaches to reduce the emission from thermal power plants is the minimum emission dispatch based on the efficient weight estimation technique as described in El-Keib et al. (1994) and Ramnathan (1994).

This research work therefore attempted to solve the above problems of production scheduling which relates to the determination of the generating units to be service and to meet system demand, while satisfy all the operational and maintenance constraints with minimum cost and minimum emissions. This optimization problem is also commonly known as an economic environmental unit commitment optimization.

1.2 Problem Statement

A direct inference from the previous work reported in the literature review (Chapter 2) showed several evident shortcomings, which are summarized as follows:

a. Maintenance parameter such as Equivalent Operating Hours (EOH) is not included to the load dispatch optimization in preventing two or more machines being sent for maintenance at a time. Insufficient capacity to deliver power as demand might happen if incorrect decision had been made in manual scheduling.

b. Environmental parameters is not included as part of the objective functions in current load dispatch optimization. No load dispatching guidelines at present in meeting environmental regulations (if implemented) in Malaysia

1.3 Objective and Scope

The objectives of this work were:

a. to develop a model for optimizing cost-effective distribution of load demand across units of open cycle gas turbine, incorporating machine operating conditions, maintenance and environmental parameters.

b. to develop a software to validate the developed model and optimization method

The model described in this project aims to provide a flexible framework to evaluate various operational planning options for emission compliance. It can be used to determine the optimum unit commitment and loading levels of each affected unit so as to meet the emission targets. Moreover, it performs multi-objective dispatch considering both the cost and emissions.

This current work was confined to offline optimization. The developed software could honour be upgradeable or scalable for open loop real-time optimization or closed loop real time optimization. No experimental work was done in this work. This means that all experimental data employed for model validation and optimization studies in Chapter 6 and 8, were obtained from existing plant performance monitoring system.

1.4 Methodology

This project was undertaken with an industrial partner TNB Connaught Bridge Power Station, where four of their open cycle ABB 13E gas turbines were studied in this research work. Gas turbine performance parameters in quantify gas turbine performance and its computation technique in accordance to ASME standard was identified before developing the gas turbine efficiency and emissions model. The model that provided a complete representation of the machine behavior could be obtained within the parameters of interest based on a combination of physical principles (thermodynamic) and performance curves. The machine model was then validated against the data acquired from the plant via the installed performance monitoring system (PMS9000), and Gas Turbine Manufacturer's Performance Test Reports.

The cost-based objective functions which represents profit, operating cost energy, yield, etc was developed such that optimization studies could be formulated and make recommendations on operation and maintenance strategy that lead to optimal performance, with considering machine operating conditions, maintenance and environmental parameters. Suitable optimization algorithm was identified to determine the optimal distribution of load demand across the various operating units.

Software coding of above subroutines (both model and optimization) was then undertaken for further studies and validation. Four case studies were carried out to test the program against the benchmark problem and actual field measurement data. Finally, the simulation results were then studied and reported.

1.5 Significance of Research Work

The result of this work will be an essential tool to the plant operation in order to make a plant operate more effectively and competitively. With the development of low price and high performance computer, such software can easily be implemented and routinely applied to improve day-by-day performance of most of the plant operation, typically petrochemical, power generation and water treatment plant with offline simulation and optimization.

It has often been noted that processing facilities are data rich but knowledge poor. The plant DCS system generates an enormous amount of information about the process. This offers scope for such software to be utilized. It is anticipated that the simulation and optimization software can be upgraded to on-line or real-time optimization which leverages the wealth of the information into a range of other benefits. It could convert pure data to information, to knowledge and ultimately, to wisdom, providing the engineers with access to an off-line model which reflects the current plant condition at any point in time and equipment performance indicators.

Recent advances in development of new technology of Advanced Process Control (APC) such as model-based predictive control, shows the potential of the need of simulation and optimization software. In future, the software will incorporate with APC and be implemented to a much greater extent than real-time optimization.

1.6 Thesis Outline

The main body of this thesis begins with a literature study in Chapter 2 that reviews the gas turbine performance calculations and its maintenance practices in general, optimization theory and application, previous work on economic load dispatch problem and selective optimization techniques namely particle swarm optimization. Thereafter, in Chapter 3, the overall methodology of this research is presented.

The formulation of objective function is the one of the crucial steps in the application of optimization to a practical problem and this is illustrated in Chapter 4. The incorporation of both environmental and maintenance parameters into the general objective function is discussed in details. With the developed objective function in Chapter 4, the gas turbine performance and emission model are formulated in Chapter 5. Subsequently, in Chapter 6, the model is validated against actual plant data from the performance monitoring system PMS9000 and machine performance test report.

In Chapter 7, the advanced and recent artificial intelligence technique, namely particle swarm optimization (PSO) is enhanced and tested as the optimization techniques in solving the optimization problem as presented in the previous chapters. The reasons of implementing particle swarm optimization to this problem and comparisons among other techniques are reviewed.

An optimization for load dispatch is of little value unless it is demonstrated that it can give accurate results for known cases. Therefore, in Chapter 8, simulation case studies are made. First, based on the benchmark problem from the literature, the behaviour of the optimization result is validated. Thereafter it is shown that a close agreement was obtained and with the best computation time. After the test with benchmark problem was completed, various studies (by removing some aspects) are carried out with actual plant data for further validation. Finally, the full procedure was implemented on the actual plant model and the resulting optimum solution is found to be superior to the existing solutions used by the plant. After this, general conclusions of the work are drawn in Chapter 9, where also some possible ideas for future work are presented.

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