

POWER SYSTEM SCHEDULING IN PRESENCE OF RENEWABLE ENERGY  
AND ENERGY STORAGE

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A thesis submitted in fulfilment of the  
requirements for the award of the degree of  
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering  
Universiti Teknologi Malaysia

MARCH 2015

To my beloved children Muhammad and Aysha

## ACKNOWLEDGEMENT

Firstly, I would like to thank and praise Almighty Alla'h for giving me the potential and willpower to complete this research work.

While preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners who have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my supervisor, Dr. Mohd Fauzi Othman, for his encouragement, guidance, critics and friendship. I am also very thankful to Professor Nazar Malik and Professor Abdulrehman Al-Arainy for their guidance, advice and motivation. Without their continued support and interest, this thesis would be lacking in some aspects.

I am also indebted to the Universiti Teknologi Malaysia (UTM) for facilitating my Ph.D. study. The Saudi Aramco Chair in Electrical Power, Electrical Engineering Department, College of Engineering, King Saud University, Saudi Arabia also deserves special thanks for supporting me to complete this work.

I also extend my sincere appreciation to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space.

Finally, I am grateful to all my family members for their continuous prayers and support.

## ABSTRACT

Power system scheduling problems like unit commitment and power dispatch methods have a vital role in the operation of electric power industry. Nowadays, global electricity consumption is growing rapidly while the supply of fossil fuels is dwindling and the concern about global warming is increasing. Therefore, power utilities are being forced to use hybrid power systems that consist of both conventional and renewable generation units. Optimum scheduling of such hybrid systems with Energy Storage Facilities (ESF) can ensure a consistent level of renewable power penetration throughout the operation periods, and thus, an economic, clean and energy efficient power generation can be achieved. Modelling of power system scheduling for hybrid power systems with ESF, optimization of such system's scheduling and applications of scheduling under different scenarios are the main scopes of this thesis. The importance and applicability of this research are analyzed and illustrated by MATLAB simulations with the aid of suitable algorithms using the data of several hybrid test systems. It is shown that the proposed scheduling models led to effective utilization of the available resources resulting in significant savings in operation cost and reduction in pollutants emissions, etc. The proposed power dispatches on a hybrid system using IEEE-30 test bus data shows that more than 30% of fuel costs, pollutants emissions and transmission losses can be reduced with 30% renewable penetration. Moreover, more than 10% saving in fossil fuel utilization and above 50% pollutants emissions can be achieved if the proposed approach is applied to energy efficient power generation method with 15% of renewable penetration. This research will help the power utilities to use available energy resources effectively and encourage them to increase the utilization of green energy.

## ABSTRAK

Masalah sistem kuasa penjadualan seperti kaedah unit komitmen dan kuasa penghantaran memainkan peranan penting dalam industry operasi kuasa elektrik. Kini, penggunaan tenaga elektrik secara globalnya telah berkembang dengan begitu pesat malah bekalan bahan api fosil semakin berkurangan dan peningkatan kebimbangan mengenai pemanasan global semakin meningkat. Oleh itu, utiliti kuasa digesa menggunakan sistem kuasa hibrid yang terdiri daripada kedua-dua kaedah konvensional dan unit generasi yang boleh diperbaharui. Penjadualan optimum sistem hibrid dengan Kemudahan Simpanan Tenaga (ESF) boleh memastikan tahap kadar penembusan kuasa boleh diperbaharui yang konsisten sepanjang tempoh operasi justeru penjanaan tenaga yang ekonomik, bersih dan cekap tenaga boleh dicapai. Pemodelan sistem kuasa penjadualan untuk sistem hibrid dengan ESF, pengoptimuman penjadualan sistem berkenaan dan aplikasi penjadualan dalam pelbagai senario adalah skop utama tesis ini. Kepentingan dan kesesuaian kajian ini dianalisis dan diilustrasikan dengan menggunakan simulasi MATLAB dengan bantuan algoritma yang sesuai dengan menggunakan data daripada beberapa ujian sistem hibrid. Ini menunjukkan bahawa cadangan model penjadualan membawa kepada penggunaan sumber sedia ada yang berkesan seterusnya menyebabkan penjimatan yang ketara dalam kos operasi dan pengurangan dalam pelepasan bahan pencemar. Cadangan penghantaran kuasa pada sistem hibrid menggunakan ujian data bas IEEE-30 menunjukkan lebih 30% kos bahan api, pelepasan bahan pencemar dan kehilangan penghantaran boleh dikurangkan dengan 30% kadar penembusan boleh diperbaharui. Selain itu, lebih daripada 10% penjimatan dalam penggunaan bahan api fosil dan lebih 50% pelepasan bahan pencemar boleh dicapai jika pendekatan yang dicadangkan digunakan sebagai kaedah penjanaan kuasa tenaga cekap dengan 15% kadar penembusan boleh diperbaharui. Kajian ini akan membantu utiliti kuasa untuk menggunakan sumber tenaga sedia ada dan menggalakkan penambahan penggunaan tenaga hijau.

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## LIST OF SYMBOLS

$a_c$	-	Aerodynamic coefficient of the wind turbine
$a_i, b_i, c_i$	-	Fuel cost coefficients of $i^{\text{th}}$ thermal unit
$A_c$	-	Solar collector area
$A_{CB}, B_{CB}, C_{CB}, D_{CB}$	-	Bagasse utilization coefficients by co-generation unit
$A_s$	-	Surface swept by wind
$A_{Ti}, B_{Ti}, C_{Ti}, D_{Ti}$	-	Fuel utilization coefficients of $i^{\text{th}}$ tri-generation unit
$B, B_0, B_{00}$	-	Transmission loss coefficients of the system
$C_{he}$	-	Cost coefficient for the health and environmental damages
$C_{re}$	-	Cost coefficient of $e^{\text{th}}$ renewable power generation unit
$C_{sk}$	-	Cost coefficient of $k^{\text{th}}$ storage units
$C_{vfi}$	-	High calorific value in kJ/kg of $i^{\text{th}}$ tri-generation unit
$d_i, e_i$	-	Rippling effect coefficients of $i^{\text{th}}$ thermal unit
$\alpha_{cf}, \beta_{cf}, \gamma_{cf}, \delta_{cf}$	-	Emission coefficients of co-generation unit by $f$ type fuel
$\alpha_i, \beta_i, \gamma_i, \lambda_i, \delta_i$	-	Emission coefficients of the $i^{\text{th}}$ thermal unit
$E_{PL}$	-	Permissible limit of pollutants emissions
$E_{usk}$	-	Unused energy in $k^{\text{th}}$ storage unit after last operation hour
$F_{fc}(P_{ti})$	-	Fuel cost function of thermal plant
$F_{fut}(P_{Ti})$	-	Fuel utilization function of tri-generation plant
$F_{he}(P_{ti})$	-	Cost function for health and environmental damages of thermal plant
$F_{OCH}(P)$	-	Overall generation cost function of hybrid power plant
$F_{OCT}(P_{ti})$	-	Overall generation cost function of thermal plant
$F_{OE}(P_{cf})$	-	Total emission function of co-generation plant
$F_{OEHt}$	-	Total emission function of tri-generation plant



$F_{OEH}(P_i)$	- Overall emission function of hybrid power plant
$F_{OET}(P_{ti})$	- Overall emission function of thermal plant
$F_{re}(P_{re})$	- Generation cost function of $e^{th}$ renewable units
$F_{st}(P_{sk})$	- Cost function of storage units
$F_{WB}(P_{CB})$	- Bagasse utilization function
$F_{ER}(P_{ti})$	- Emission function of renewable units
$F_{ET}(P_{ti})$	- Emission function of thermal units
$\eta_{ci}, \eta_{ei}, \eta_{ti}$	- Cooling, electric and heating power conversion efficiencies of $i^{th}$ tri-generation unit.
$IBP_i$	- Boiler input power of $i^{th}$ tri-generation unit
$IBP_f$	- Boiler input power by f-type fuel in co-generation unit
$N_r$	- Number of renewable power generation units.
$N_s$	- Number of energy storage units
$N_t$	- Number of thermal units
$\chi_{re}$	- Emission coefficients of the $e^{th}$ renewable unit
$P_{cf}$	- Power output of co-generation unit by $f$ type fuel
$P_D^A$	- Actual demand
$P_D^T$	- Total demand
$P_{dl}$	- Delivered power
$P_{dk}$	- Power delivered from $k^{th}$ storage unit
$P_L$	- Transmission loss of the system
$P_{ms}$	- Power rating of solar panel
$P_s$	- Solar power
$P_{st}$	- Stored power
$P_{sk}$	- Power stored in $k^{th}$ storage unit
$P_{Ti}$	- Power output of $i^{th}$ tri-generation unit
$P_{ti}$	- Power output of the $i^{th}$ thermal unit
$P_{usk}$	- Unused power in $k^{th}$ storage unit after last operation hour
$P_{cf}$	- Power output of co-generation unit by $f$ type fuel
$P_r^d$	- Total dispatched renewable power

$P_{re}^d$	- Power dispatched by the $e^{th}$ renewable unit
$P_r^g$	- Total generated renewable power
$P_{re}^g$	- Power generated by the $e^{th}$ renewable unit
$P_{Cf}^{\min}, P_{Cf}^{\max}$	- Output power limits of $f$ type fuel in co-generation plant
$P_{re}^{\min}, P_{re}^{max}$	- Output power limits of the $e^{th}$ renewable unit
$P_{sk}^{\min}, P_{sk}^{\max}$	- Output power limits of the $k^{th}$ storage units
$P_{ti}^{\min}, P_{ti}^{\max}$	- Output power limits of the $i^{th}$ thermal unit
$P_{Ti}^{\min}, P_{Ti}^{\max}$	- Output power limits of the $i^{th}$ tri-generation unit
$P_s$	- Solar power
$P_{ti}$	- Power output of the $i^{th}$ thermal unit
$P_{Ti}$	- Power output of $i^{th}$ tri-generation unit
$P_{usk}$	- Unused power in $k^{th}$ storage unit after last operation hour
$\rho$	- Air density.
$RdR_i$	- Ramp down rates of $i^{th}$ thermal
$RuR_i$	- Ramp up rates of $i^{th}$ thermal
$S$	- Solar irradiation
$Sc_i$	- Start cost of $i^{th}$ thermal unit
$t$	- Operation hour
$T_{cell}$	- Solar cell temperature
$T_{dl}$	- Power delivering period
$T_{sa}$	- Solar unavailable period
$T_{st}$	- Power storing period
$T_{su}$	- Solar available period
$u_{re}$	- State of the $e^{th}$ renewable power generation unit
$u_{sk}$	- State of the $k^{th}$ storage unit
$u_{ti}(t)$	- State of the $i^{th}$ thermal unit
$V_w$	- Wind speed in m/s.
$W_{fi}$	- Weight of fuel (ton/h) at boiler of $i^{th}$ tri-generation unit
$x_{tci}$	- Share of heat used to produce cooling power
$x_{te}$	- Electric power share of the total demand
$\tau$	- Drift in solar panel output due to temperature per °C.

## LIST OF ABBREVIATIONS

BESS	- Battery energy supply system
CASE	- Compressed air energy storage
CCHP	- Combined cool heat and power
CEEPD	- Clean and energy efficient power dispatch
CHP	- Combined heat and power
CSP	- Concentrated solar power
ECED	- Emission constraint economic dispatch
ED	- Economic dispatch
EDV	- Electric drive vehicles
EED	- Economic and Environmental dispatch
EEDL	- economic and environmental dispatch with minimum transmission loss
EEOPD	- Energy efficient optimum power dispatch
EFD	- Environmental friendly dispatch
EFDOB	- Environmental friendly power dispatch with optimum bagasse
EIA	- Energy information administration
EJ	- Exajoul
ESC	- Energy storage cost
ESF	- Energy storage facilities
FC	- Fuel cost
FFs	- Fossil fuels
GA	- Genetic algorithm
GA-SQP	- Genetic-sequential quadratic programming
GBG	- Green Budget Germany
GHG	- Greenhouse gases

GVEA	- Golden Valley electrical association
HC	- Cost paid for health and environmental damages
HES	- Hybrid energy system
IU	- Indian utility
KSU	- King Saud University
MC	- Moisture content
MSW	- Municipal solid waste
NTPS	- Neyveli thermal power station
OPD	- Optimum power dispatch
OPDM	- Optimum power dispatch management
PD	- Power dispatch
PHS	- Pumped hydro storage
PV	- Photovoltaic
RES	- Renewable energy sources
SC	- Start-up cost
SMES	- Superconducting magnetic energy storage
SPC	- Solar power cost
SQP	- Sequential quadratic programming
TCNH	- Total generation cost without cost paid for health and environmental damage
TCWH	- Total generation cost with cost paid for health and environmental Damage
TGC	- Total generation cost
UC	- Unit commitment
UCHREES	- Unit commitment for hybrid power system including renewable energy and energy storage units
UCP	- Unit commitment problem
WPC	- Wind power cost

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## CHAPTER 1

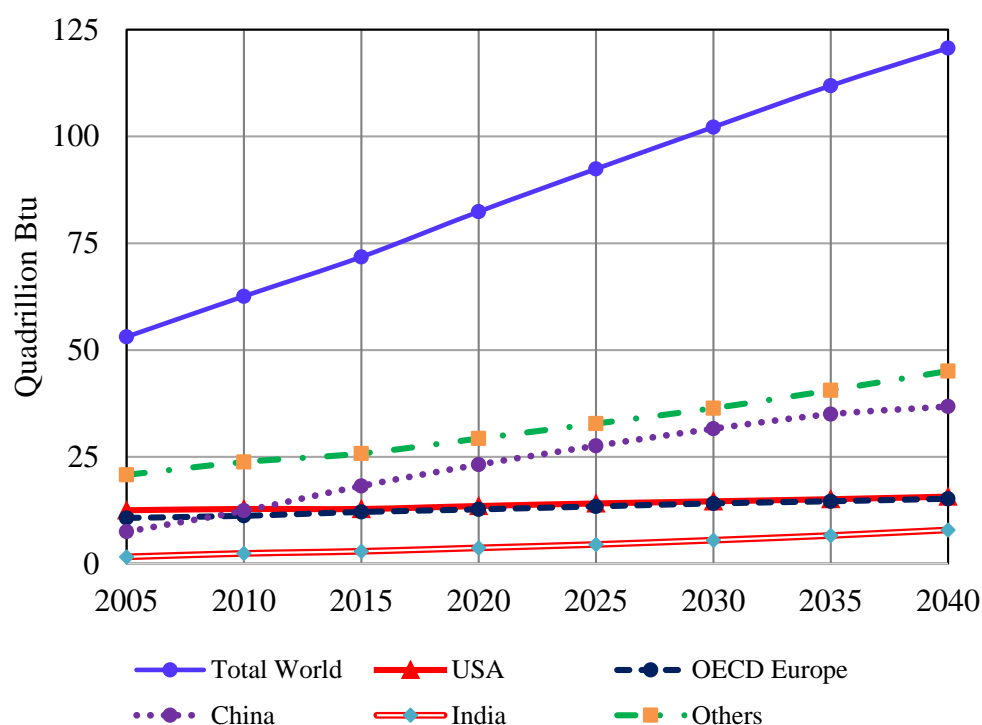
### INTRODUCTION

#### 1.1 Background

For current and future economic and social needs, the optimal use of conventional and renewable energy resources is essential in order to minimize the lifecycle costs of generation units as well as the environmental impacts. Proper power system scheduling helps to utilize the energy resources in an optimal manner. The scheduling procedure of power stations involves two steps: the first step is called unit commitment (UC) while the latter is known as power dispatch (PD). It is not economical and reliable to run all the available generating units all the time. Instead only the units of a plant that should operate to meet a particular load demand are selected, and the selection process is known as unit commitment. However, the power dispatch problem attempts to produce optimal outputs from the committed units corresponding to the demand without violating the unit or the system constraints [1-3]. Optimal UC and PD problems schedule the generation units in the most efficient, economical and environmental friendly manner in order to meet the forecasted demand.

Due to the population growth and increasing industrialization, urbanization, modernization and income growth, the global electricity consumption is expected to continue to increase significantly in years to come. According to the international energy outlook 2013 by the US Energy Information Administration (EIA), the current global primary energy demand is 546.8 Quadribillion Btu ( $546.8 \times 10^{15}$  Btu) and is projected to reach almost 820 Quadribillion Btu by 2040 [4]. It is expected that the

global consumption of electrical energy will be doubled in the next 15-20 years [5]. Figure 1.1 shows the expected global electrical energy consumption growth from 2010- 2040. At present, fossil fuels like coal, oil and natural gas contribute approximately 80% of the global primary energy needs [6]. Reserves of these fuels are decreasing rapidly and projected depletion times for coal, natural gas and oil reserves are estimated as 103, 33 and 31 years, respectively [7]. The increased dependence on fossil fuels is resulting in severe damage to the environment. Due to the effect of pollutants from the fossil fuel burning plants, millions of people are facing health disease and many people die annually worldwide [8].



**Figure 1.1** Global electrical energy consumption growth during 2010-2040 [9].

A rapid rise in global temperature has occurred in the 21<sup>st</sup> century due to the increase in the concentration of greenhouse gases (GHG) in the atmosphere. In 2011, global CO<sub>2</sub> emission reached more than 31.6 gigatonnes with an increase of 3.2% on 2010 levels and coal-fired power plants accounted for about 43% of this emission [10]. Approximately 960 kg/MWh of CO<sub>2</sub>, 6 kg/MWh of SO<sub>2</sub> and 2.6 kg/MWh of NO<sub>x</sub> are the quantities of the main pollutants emitted during the generation of electricity from coal fired power plants [11]. CO<sub>2</sub> contributes the highest proportion of greenhouse

effect mainly due to its higher concentration in the atmosphere. The upper safe limit of CO<sub>2</sub> concentration is suggested to be 350 parts per million (ppm) so as not to harm the environment whereas CO<sub>2</sub> level exceeding 450 ppm is expected to cause severe damage to the environment [12]. In May 2013, the global CO<sub>2</sub> concentration reached almost 400 ppm and its current growth rate is more than 2 ppm/year [13]. It is projected that doubling of the CO<sub>2</sub> concentration from the current value will cause an increase in global temperature of 1.5°C to 3°C [14]. Rapid depletion of fossil fuel reserve, awareness on carbon footprint and effect of global warming have thus forced a policy of accelerated utilization of renewable energy sources (RES) for electricity generation.

Electricity production using RES is thus growing rapidly across the world. Global renewable power generation in 2011 reached 4540 Tetra-Watthour (TWh) and is expected to become 6400 TWh within the next 5 years with a growth rate of 5.8% per year [15]. Presently, about half of the newly added power generation capacities use the renewable power technologies [16]. If the current developments in renewable industry continue, then a major share of global electricity production in the future would be supplied by the renewable power technologies. In order to ensure high penetration to grids, power generation with intermittent renewable resources require back-up or storage facilities. Production and storage of renewable energy at times when there would be a surplus of its availability or at off-peak hours and the reuse of such stored energy during its unavailable periods help to utilize RES more effectively. Energy storage facilities (ESF) guarantee reliable power management for hybrid power plants [17, 18]. The current global storage capacities have exceeded 127.9 GW. Pumped hydro storage (PHS) facilities alone account for 95% of the storage capacities [19, 20]. Batteries, flywheels, compressed air and super capacitors, etc. are some of the other technologies used for energy storage. RES and ESF based power production can play an important role in the installation of hybrid energy systems especially in remote areas where the grid extension and fuel transportation are costly due to the remoteness of the location. The supplementary contribution of RES and ESF based power to conventional power generating systems can help to meet the increasing load demands under varying natural conditions with reduced overall lifecycle costs and pollutants emissions [18, 21, 22].



In the early scheduling problems, only fossil fuel based thermal units were considered [1]. Hence, the modelling and formulation of thermal units based scheduling problems were well studied and analyzed. However, the dwindling supplies of fossil fuels and rapid growth in renewable energy technologies have forced the modification of the scheduling problems to consider renewable power generation units along with thermal units. Such modified approach helped to achieve economic and environmental benefits from power stations. Meanwhile, the proper utilization of renewable resources without energy storage facilities are not easy due to their uncertainty and variation even when there is high potential of renewable energy. Currently, energy storage technologies and renewable power generation methods are being developed and widely used for clean and economic power production. In such applications, the renewable generation and energy storage systems are effectively interconnected with the existing power plants. Hence, a novel approach for power system scheduling is mandatory in such interconnected plants in order to operate storage and renewable power units effectively along with the thermal units.

The modelling and analysis of scheduling problems for hybrid power plants that consist of thermal, renewable and storage based units under various conditions are the main contribution of this research work. Moreover, the importance of co-generation and tri-generation is also increasing nowadays, since these are more energy efficient power generation methods compared to the conventional power generation systems. Optimum power dispatches for co-generation and tri-generation based thermal units with RES and ESF based units are also formulated and analyzed in this research. The proposed scheduling methods are analyzed using MATLAB simulations. Dynamic programming approach is used to investigate the proposed UC problem while sequential quadratic programming (SQP) and genetic and sequential quadratic programming (GA-SQP) based hybrid algorithms are used to study the proposed PD problems. Sequential quadratic programming algorithm based optimization is the best method to find local optimum results [23]. However, SQP is not preferred to find the global minimum solution since it is a gradient dependent method and is sensitive to the initial points. Hence, for the optimization of objective functions that contain more complicated terms such as exponential and complex functions, etc., a GA-SQP hybrid algorithm is used for finding global minimum values. In GA-SQP algorithm, the

optimum results of GA is used as the initial points to SQP and thereby SQP acts as tuner algorithm to the GA based optimization results. IEEE 30 bus test system as well as other test systems which are used to demonstrate the scheduling models are modified in order to interconnect the RES and ESF based units. The data of these modified test systems are used here to illustrate the proposed scheduling problems for hybrid power plants with thermal, RES and ESF units.

## 1.2 Objectives

The main goal of this research work is to present a clean, efficient and economic power plant scheduling for hybrid power plants consisting of thermal, renewable and energy storage based generation units. The modelling and formulation of power plant scheduling like unit commitment and power dispatch in the presence of renewable energy and energy storage facilities are the objectives considered in this work. The analysis carried out here is for various scenarios that encourage an environmental friendly and optimal fuel utilization in power generation schedules while supplying customer's power demand. The main objectives of this work can be enumerated as:

1. To model power system scheduling such as power dispatch and unit commitment issues in the presence of renewable energy and energy storage facilities.
2. To formulate optimum scheduling problems for conventional, cogeneration and tri-generation based thermal units along with the RES and ESF units.
3. To analyze the benefits of proper scheduling such as savings or reduction in generation cost, pollutants emissions and transmission loss, etc., in hybrid power plant consisting of thermal, RES and ESF units under various conditions.
4. To prove that the efficient use of RES and ESF in hybrid power plants help to achieve the most economical, and reliable power operation scheduling with reduced pollutants emissions.

### 1.3 Scope and Contributions

Electricity demand is increasing rapidly. Meanwhile billions of people still lack electricity for their primary needs. The vast use of fossil fuels for electricity generation decreases their reserves and increases their harmful environmental effects. Most of the countries have now implemented emission trading policies to limit the pollutants emissions from the thermal power plants. The awareness on carbon footprint and dwindling supply of fossil fuels has encouraged the electrical power utilities to increase the utilization of renewable energy resources and to install hybrid power systems consisting of both conventional and renewable based power generation units. Energy storage facilities are essential in such hybrid power plants in order to ensure proper renewable power penetration levels to the grid. Rapid advances in renewable energy and energy storage technologies thus increase the needs and role of optimum operation policies for such hybrid power plants which can thus help to provide a major part of electricity demand in the future.

Mathematical modellings and formulations of power scheduling problems in the presence of renewable energy and energy storage facilities, optimization of such power system scheduling, application of scheduling under different scenarios and modification of scheduling algorithm are the contributions of this research. Unit commitment and power dispatch problems in the presence of renewable energy and energy storage facilities is firstly introduced in this research. Hence, this work has a vast scope to fulfill both national and international interests for clean, economic and reliable electricity generation methods. The future lies with energy efficient power generation and utilization. Therefore, the modelling of scheduling problems in this research are also extended to the energy efficient generation methods like co-generation and tri-generation. Hence, the scope of this research is not only limited in the scheduling of generation units for providing clean and economic power generation but also in scheduling energy efficient generations. The following optimum scheduling

problems for hybrid power plants in presence of renewable energy and energy storage facilities are formulated and analyzed in this research.

1. Unit commitment problem
2. Economic dispatch problem
3. Environmental friendly power dispatch issue
4. Economic and environmental power dispatch method
5. Power dispatch with minimum transmission loss approach
6. Emission constrained economic dispatch method
7. Power dispatch at multi-fuel cogeneration plants
8. Clean and energy efficient dispatch by tri-generation, etc.

#### **1.4 Thesis Outline**

The remaining chapters of the thesis are organized as follows:

CHAPTER 2 gives a comprehensive review on previous researches and literatures related to this research topic. It includes the review on unit commitment and power dispatch problems, their solution methods and the algorithm used to solve the scheduling problems, pollutants emission from conventional plants, global renewable and storage potential, etc.

Methodology of the research is explained in detail in CHAPTER 3. It includes the criteria for the selection of renewable resources and formulation of actual demand supplied by thermal generation units with renewable and storage power. The modelling of scheduling problems like optimum unit commitment, power dispatch and energy efficient dispatch for various scenarios are explained and discussed in this chapter as well.

CHAPTER 4 discusses simulation and analysis of optimum unit commitment problem for hybrid power plant consisting of thermal, RES and ESF based generation units.

Simulation and analysis of optimum dispatch problems such as economic dispatch, environmental friendly dispatch, economic environmental dispatch as well as economic and environmental dispatch with minimum transmission loss are investigated and reported in CHAPTER 5.

The importance of the emission constrained economic dispatch (ECED) and a case study on ECED optimization are discussed in CHAPTER 6. MATLAB simulations of this optimization are carried out using the SQP and hybrid GA-SQP methods. Their results are compared and analyzed in this chapter as well.

CHAPTER 7 explains energy efficient generation methods such as tri-generation and co-generation for hybrid plants in the presence of renewable energy and energy storage facilities. Simulation and analysis of optimal power scheduling for the proposed energy efficient generation methods are also explained and discussed in this chapter.

CHAPTER 8 discusses the conclusions and scope of future work of this research.

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