SOLVING UNIT COMMITMENT PROBLEM USING MIXED INTEGER LINEAR PROGRAMMING

A thesis submitted in partial fulfillment of the requirements for the award of the degree of

Master of Engineering

In

Power Systems

Submitted by

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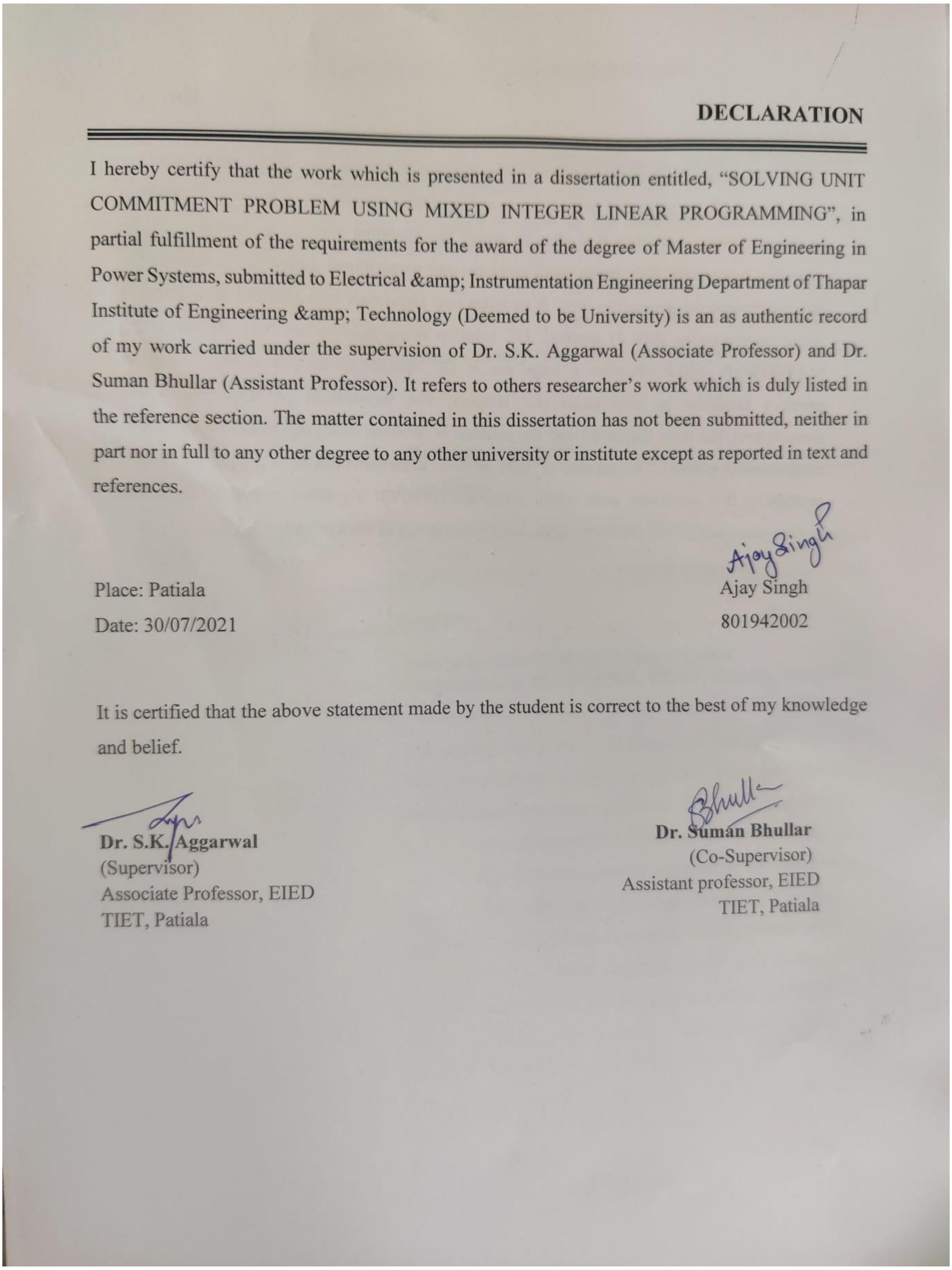

DECLARATION

I hereby certify that the work which is presented in a dissertation entitled, "SOLVING UNIT COMMITMENT PROBLEM USING MIXED INTEGER LINEAR PROGRAMMING", in partial fulfillment of the requirements for the award of the degree of Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar Institute of Engineering & Technology (Deemed to be University) is an as authentic record of my work carried under the supervision of Dr. S.K. Aggarwal (Associate Professor) and Dr. Suman Bhullar (Assistant Professor). It refers to others researcher's work which is duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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Abstract

Unit commitment involves the process of preparing a schedule for electrical generator units at every hour interval, subjected to the system and operating constraints. It is a critical problem in power system operations that aims to utilize the operating cost while satisfying all the operating constraints. This thesis work proposes unit commitment algorithms to achieve the target of minimum generation cost. It includes two algorithms based on the Mixed-integer linear programming (MILP) method: UC solution using *fmincon* and UC solution using MATPOWER. MILP observes a large use in UC operations, as this strategy considers problem functions as continuous and integers. The formulation of deterministic unit commitment has been discussed and the solution is obtained using the mixed integer linear programming method. The success of these *fmincon* algorithms has been tested on a system containing four generator units while using MATPOWER algorithm tested the three bus system containing three generator units, wind generator, and storage unit.

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Nomenclature

Indices

i , H	indices of generators
j , N	indices of load loss
t , T , τ	indices of time
k , K	indices of piecewise linear approximation

Constants

SU_i	start-up cost of unit i
SD_i	shut down cost of unit i
$F_i(.)$	fuel cost function for generator i
p_{it}	the amount thermal power generation/dispatch of unit i at time t
$VOLL$	value of loss load in $/MWh
δ_{jt}	load loss at but j at time t
a , b , c	are the cost coefficients
α_k , β_k	are the coefficient used to approximate the quadratic curve

Decision Variables

u_{it}	startup action of unit i at time t
d_{it}	shut off action of unit i at time t
M_i	commitment status of generator i
M_{it}	commitment decision of generator i at time t

$M_{i(t-1)}$	commitment decision of generator i at time $\mathrm{t}-1$
L_i	the minimum-on duration
l_i	the minimum-off duration
$\lvert T\rvert$	the duration of the planning horizon
P_i^{min}	the minimum generator limit of unit i at time t
P_i^{max}	the maximum generation limit of unit i at time t
p_{it}	generation of unit i at time t
RU_i	ramp-up rate of unit i
RD_i	ramp-down rate of unit i
S_{it}	spinning reserve of unit i at time t
S_i^{max}	maximum spinning reserve of unit i
RS_{jt}	spinning reserve requirement for bus i at time t
f_{jht}	a bi-direction flow between bus j and bus h
A_j^+	the set of flow start at bus j
A_j^-	the set of flow end at bus j
R_{jt}	renewable power output at bus j at time t
D_{jt}	load demand at bus j at time t
F_{jh}^{min}	the minimum transmission flow between bus j and h
F_{jh}^{max}	the maximum transmission flow between bus j and h
γ_{jt}	a phase angle at interconnected bus j
B_{jht}	susceptance of an transmission line $(j\,, h)$

Q_i^{min}	lower limit of reactive power generation of unit i
Q_i^{max}	upper limit of reactive power generation of unit i
q_{it}	reactive power generation of unit i at time t
D_t^Q	Reactive power demand at time t

List of Abbreviations

UC	Unit Commitment
ED	Economic Dispatch
MIP	Mixed Integer Program
MILP	Mixed Integer Linear Programming
ACS	Ant Colony System
GA	Genetic Algorithm
PL	Priority List
LR	Lagrangian Relaxation
DP	Dynamic Programming
BD	Benders Decomposition
SCUC	Security Constrained Unit Commitment
PBUC	Price Based Unit Commitment
HUC	Hydro Unit Commitment
RES	Renewable Energy Sources
SR	Spinning Reserve
MOST	MATPOWER Optimal Scheduling Tool

Chapter 1

Introduction

1.1 Overview

In the power systems, the scope of operational scheduling and planning is very important for its secured and economic operation. To reach an economic operation, it is necessary to meet load demand and optimize generations which varies on an hourly basis over the whole day. The generators are constricted by many constraints. These constraints limit their operation and it's impossible to encounter the load demand and reserve specifications. Therefore, it is necessary to commit the units in advance for an operation horizon to fill the load demand and reserve conditions. The unit commitment (UC) schedules the power production levels of every generating unit intending to diminish the absolute production cost while fulfilling a set of unit constraints and the system operational constraints over the defined time. UC problem determines the startup or shutdown (On/Off) status of each generator unit for an operation horizon.

UC plays an important role to address a fundamental decision that is taken while scheduling a power production for every generating unit over the specified period. The decision is exposed to several system and operational constraints, such constraints are crew constraints, constraints ranging from the minimum up and minimum downtime constraints, ramp-rate limits, unit capacities, to reserve requirements, and power balance constraints. The unit commitment problem is scheduled on an hourly basis over a day or a week and considers a number of generators and transmission systems over many buses and lines. The large size and complex structure of the system can make difficulty in solving unit commitment problem. Therefore, it is more suitable to consider a small group of transmission or system constraints for the UC problem scheduling.

The UC system at a large scale has several non-linear equations and continuous or integer variables, which is the main reason for the unit commitment scheduling problem to be considered computationally challenging. UC is also called the non-linear mixed-integer minimization problem. It contains many integers and continuous variables i.e. on/off status units and the output power units. The techniques that handle unit commitment problems try to minimize the production cost which is expressed using non-linear equations.

The mixed-integer linear programming (MILP) strategy has become most popular in recent years because it gives a feasible solution. The given cost functions in the UC problem are carved as either a linear function or quadratic function for shortening the problem. The mixed-integer linear programming strategy converts the non-linear, non-differentiable, and non-convex cost function into integer form to solve the given problem. It provides a relatively rough calculation for the UC problem and several MILP commercial solvers are available for solving non-linear or combinatorial UC problems. The MILP solvers can solve the UC problem with high speed and accuracy.

1.2 Classification of Unit Commitment Problem

The following section discusses the different types of unit commitment problems based on different parameters.

1.2.1 Based on Security

- Traditional Unit Commitment - It is criteria for planning various generating units concerning a network load to accomplish the lowest operating charges. The traditional unit commitment includes startup and shutdown time, the ramp rates of the units, the upper and lower bounds of power output, and the power balance limits for each limit.
- Security Constrained Unit Commitment (SCUC) - It is an authoritative scheduling strategy employed in the power markets for planning daily. SCUC strategy combines two common problems such as unit commitment (UC) and economic dispatch (ED) while adding a new dimension called security.
- Price Based Unit Commitment (PBUC) - It is a scheduling strategy used to attain maximum profit. This will include the pricing of various services and materials used in generation operations. In the PBUC, the fuel purchase price, ancillary service sale, and energy sale price are the planning components.

1.2.2 Based on Scheduling in Market’s Operations

- Vertically Integrated Environment - In a vertically integrated environment structure, the component such as customers of power companies, are predefined.
- Deregulated Environment - It is a scheduling strategy where the task changes from cost minimization to maximizing profit. This scheduling strategy uses the components such as transmission companies, distribution companies, and generation companies to create generation offers.

1.2.3 Based on UC Future Events

- Deterministic Unit Commitment- It is a traditional solution strategy that considers simple operating constraints such as reserve constraints, start-up constraints, and demand constraints. The approaches such as ‘dynamic programming’, ‘priority list method’, ‘Lagrangian relaxation’, and ‘mixed-integer linear programming’ methods are used to concern with unit commitment having deterministic nature.
- Stochastic Unit Commitment - In stochastic unit commitment, the sequence of making decisions is segregated into two stages. The first one includes day-ahead decisions, while the second one includes real-time decisions. It is a better way to handle factors of uncertainties. The stochastic unit commitment uses approaches such as ‘genetic algorithm’, ‘particle swarm optimization’, ‘simulated annealing’, ‘tabu search’, ‘evolutionary programming’, and ‘ant colony strategy’ to overcome the shortcomings of traditional UC.

1.3 Evolution of Unit Commitment Problem

The unit commitment scheduling is an effortful topic for electric utilities. In general, the system operator schedules the operation of generating units while fulfilling the corresponding power demand. Research on the unit commitment scheduling problem started in the 1940s in the last century and has continued until today as shown in Figure 1.1 Several optimization strategies to work out the UC scheduling problem are outlined. The different considerations for UC in both regulated and deregulated situations are pointed out. Although significant contributions were made in this field and an enormous volume of papers have been published.

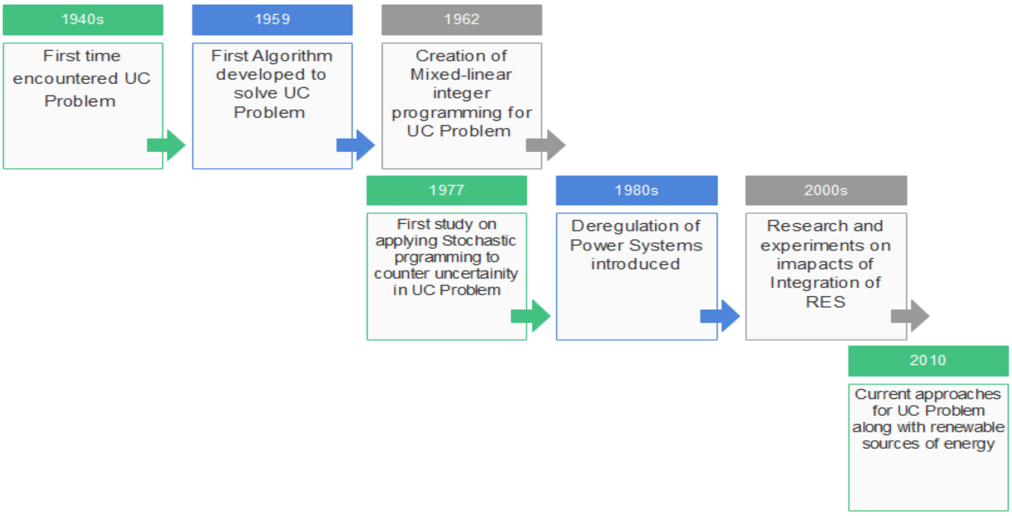


Figure 1.1 Evolution of UC problem

1.4 Objectives of Proposed Work

The objectives of this research are listed as follows:

1. Solving unit commitment problem for a simple 4 generator system using *fmincon.*
2. Solving deterministic unit commitment problem for 3 bus test case systems (without considering wind and storage) using mixed-integer linear programming.
3. Solving deterministic unit commitment problem for 3 bus test case systems (considering wind and storage) using mixed-integer linear programming.

1.5 Thesis Outline

Chapter1: Introduction

Chapter1 introduces the concept of unit commitment problem, classification, and work objectives to solve the UC problem.

Chapter 2: Literature Survey

A survey about the recent research on the Unit Commitment Problem is contained in chapter 2.

Chapter 3: Deterministic Unit Commitment Using Mixed Integer Linear Programming

It describes the state-art of unit commitment problem in the power system. Problem formulation and solution methods to deterministic unit commitment are discussed in chapter 3.

Chapter 4: Methodology

In this chapter, the methodology is described to achieve the objectives listed in Chapter 3.

Chapter 5: Results and Discussions

This section of the thesis discusses the results and the performance of the proposed method.

Chapter 6: Conclusion and Future Perspective

This chapter summarizes the thesis and future perspective of the proposed work.

Chapter 2

Literature Survey

Unit commitment is a nonlinear mixed-integer optimization problem to schedule the power generator's unit status at each hour of the planning period while satisfying the system demand and constraints. Generally, uncertain data such as the generator outage contingencies, forecasting error demands, and renewable energy generation are the main reason for getting difficulty in solving unit commitment problems. So it is best to use optimal or sub-optimal solution strategies to solve the problem unit commitment. The authors presented a large variety of solution strategies to deal with complex problems of unit commitment.

Lauer *et al.* [1] discussed the solution of large-scale unit commitment problems, developed an optimization method based on branch and bound strategy. Results were given and analyzed for the given problem. The solution obtained tells the effectiveness of the proposed method. Gupta *et al.* [2] presented an application of a Genetic Algorithm (GA) to solve the short-term unit commitment problem by deciding the decision order of units for a whole day in advance. The genetic-based system evaluated the priority of the units while considering the system parameters, constraints, and system load profiles at each period. The work target is to find the best schedule from a set of good decisions.

Lowery [3] solved the unit commitment problem with Dynamic Programming (DP) and determine the feasibility of this method to solve the UC problem. The test results showed the power of this method to produce a feasible solution in a small computation time. Hence, dynamic programming is a feasible method. Kazarlis *et al.* [4] studied a Genetic Algorithm (GA) Solution to the unit commitment problem and discussed that the importance of defining a standard GA performance with varying quality function strategy and problem-specific operators for obtaining a satisfactory problem solution. Results are compared with a predefined algorithm and showed that there is a small difference (0.74%) between the worst and the best GA-provided solution.

Chang *et al.* [5] explored mixed-integer linear programming to solve Hydro Unit Commitment (HUC) by expressing the problem with integer variables. The proposed solution algorithm was solved by a CPLEX solver, also the LP solver based on the interior barrier point method was used to provide a quick solution. The results of the given problem are obtained and showed the effectiveness of the proposed strategy to deal with HUC. Arroyo *et* *al.* [6] proposed a solution method to develop a piece of suitable information to produce bids to the electricity spot market, this proposed method aimed to maximize the unit's profit.

Cheng *et al.* [7] solved the problem of unit commitment with the Genetic Algorithm and Lagrangian Relaxation method and discussed simulation results of two cases which showed the effectiveness of this technique in terms of its solution quality. Kavitha *et al.* [8] described a fuzzy dynamic programming approach to obtain a UC solution. It was used as the basic approach to handle objective function and constraints, by providing fuzzy preference. The results were obtained for three units system and later for five units system, which showed that the fuzzy dynamic programming could be extended to large-scale systems and no modification was required. Padhy *et al.* [9] presented the bibliography survey of the unit commitment problem, also discussed the mathematical formulations of the problem and its general background and its historical developments.

Pandian *et al.* [10] had implemented a new approach called the Fuzzy Logic Algorithm for solving unit commitment problems and elaborate the use of fuzzy logic in taking logical decisions for a given problem. It could be effectively implemented for the aging of machines, line losses, and the uncertainties in load demands. Chang *et al.* [11] proposed another procedure to express the unit commitment problem in MILP manners and evaluated the proposed methodology to solve the UC problem in a traditional and deregulated environment. Results were obtained and tested for the problem of having six plants and 27 thermal units. They discussed the precision of the proposed method while dealing with the problem in a reasonable time.

Simon *et al.* [12] stated an Ant Colony System (ACS) method to the unit commitment with a spinning reserve and ramp rate constraints. The aim was to produce the minimum cost path for the decision of thermal units in a given period. ACS model was very effective and acceptable for optimizing problems because they had the potential to produce a near-global optimal solution. Carrion *et al.* [13] examined and studied the salient features of computationally efficient mixed-integer linear formulation to solve the unit commitment problem containing thermal units. The proposed methodology was applied to the given test case problem and results depicted the effective performance of this approach.

Wu *et al.* [14] described a solution to security-constrained in unit commitment, the model named as a stochastic model was presented. It deals with the problem of representing uncertainties. The method based on Monte Carlo simulation was used to simulate the outage of components and also the Lagrangian relaxation was used to convert the given problem into many deterministic long-term SCUC problems. Numerical results and tests showed that this methodology could obtain better decisions on energy allocation, fuel consumption, and long-term usage of generating units. Kadam *et al.* [15] proposed applications of a fuzzy logic methodology to determine short-term UC. The authors discussed that the proposed methodology is a powerful tool for solving highly non-linear problems and multiple constrained optimization problems.

Logenthiran *et al.* [16] proposed a theory to solve unit commitment problems in regulated and deregulated power markets, discussed the concept of solving UC problems with power systems renewable energy sources. Abedi *et al.* [17] used the differential evolution algorithm to solve risk constraints associated with the UC problem, discussed the impact of the unknown behavior of solar and wind power as well as examined the dispatch level of the thermal unit system. The optimal day-ahead scheduling of units was obtained. In this, they studied the risk-constraint of renewable in simulation and corresponding results showed the success of the proposed method for the solution of a given problem.

Bhardwaj *et al.* [18] described different ways to solve unit commitment to fill the load demand. It explained brief ideas about the unit commitment problem. The various solution strategy such as priority list, dynamic programming, Lagrangian relaxation, and genetic algorithm, mixed-integer linear programming was described in this study. Tuffaha *et al.* [19] proposed a MIP formulation strategy to solve the problem of unit commitment while observing start-up costs. The proposed methodology could solve a UC of 14 or 60 units over 24 periods, and results showed the requirement of fewer constraints and tightness of start-up costs. Saravamman *et al.* [20] elaborated the various aspects of unit commitment problem in power systems, also discussed the newly evolved hybrid solution techniques procedure for unit commitment problem. Bruninx et al. [21] have described the working state-art overview of solving large-scale UC problems.

Siface *et al.* [22] were concerned with the continuous stochastic linear programming models to resolve large-scale mixed-integer linear programming (MILP) and discussed that the proposed model handles complicated uncertainties. The results are obtained for the given UC problem and show the effectiveness of the proposed model. Bergh *et al.* [23] implemented a mixed-integer linear program model to solve UC problems, using the MATLAB-GAMS model coupling. The model was able to solve problems having inelastic demand and also discussed that this model resulted in a feasible solution.Gentile *et al.* [24] discussed the UC description while considering primary constraints such as system generation limits, its startup and shutdown, and minimum up and downtimes and concluded that the proposed constraints help in tightening the final UC.

Mustafa *et al.* [25] reviewed the different UC models to deal with Renewable Energy Sources impact, discussed that the high penetration of intermittent RES brought new difficulties to the UC process, and suggest the need to produce novel UC models in order to reduce the system variability and uncertainties. Hua *et al.* [26] have presented a practical demonstration to solve mixed-integer linear programs with MATLAB using YALMIP to find its solutions by defining an objective function, variables and constraints. Abdou *et al.* [27] have presented a survey of the unit commitment problem, also discussed the different techniques and their applications to solve the unit commitment problem. This paper provides an advancement in the UC problem over the past years.

Der *et al.* [28] have explored the UC by considering the high dispersion of ramp rate and renewable energy of thermal units. To solve problems, the ramp rate was applied with a power shortage of 30 and 10 min because the intermittent renewable energy destabilizes power outputs when the huge amounts of PV and wind power are integrated into power grids. This study includes the advanced priority list strategy to solve large-scale nonlinear MIP unit commitment problems which are capable to produce a feasible solution.

Knueven *et al.* [29] have described the detailed overview of mixed-integer linear programming formulation to the unit commitment problem, also discussed the various mathematical formulations. Zimmerman *et al.* [30] have presented the framework called MOST for solving electric power scheduling problems and discussed that the proposed tool can solve problems as a deterministic, stochastic, security-constrained, combined UC, multi-period optimal power flow. The work is based on mixed-integer linear programming for building various program structures.

Chapter 3

Deterministic Unit Commitment using Mixed Integer Linear Programming

3.1 Unit Commitment in Power System

In the power system, the possibility of operations scheduling and planning is very important for its secured and economic operation. Many electric services have day-to-day load patterns that show a large difference between peak and off-peak hours, as the consumption of electricity is less on Sunday than any other working day and the low cost at midnight and early morning. To reach economic operations, it's necessary to meet load demand and optimize generations that differ from hour to hour over the day. So it is best to use an efficient operation scheduling strategy based on economic criteria. Moreover, the management of the fuel cost component has a significant impact on electric services as reducing the fuel cost by 0.5 % can pay off in huge savings of millions of dollars per year. The unit commitment is a principal criterion in a power system to fill the load demand by determining the operational scheduling of system generating units with the objective of cost minimization at a given period, subject to network and operating constraints. The UC problem depends upon the mix generating units and systems operational constraints. It is a decisive problem through which scheduling of units is to be done online or offline while satisfying specified operating criteria. Thus it is acknowledged that the unit commitment scheduling (generally on an hourly basis) results in large savings for electric services.

3.1.1 Functions of Unit Commitment

Unit commitment provides a versatile working environment for scheduling purposes. The input for the commitment is either the load forecast or trading power. The unit commitment functions provide three execution modes, which help the operator to combine the results of an optimized algorithm with its judgment.

- Basic Mode: The basic model involves the task of determining a minimum generation cost issue with the specified input data.
- Operator Participation Mode: In operator participation mode, the operator may initiate a UC execution to adjust a previously determined schedule.
- Fixed Dispatch Mode: Later, the fixed dispatch mode simply analyses the generation schedule.

3.1.2 Benefits of Unit Commitment

The following parameters describe the benefits of unit commitment.

1. The total production cost can be reduced to the minimum.

2. The fuel can be used optimally.

3. It is an effective technique that covers limitations such as power generation of each power plant, fuels, losses, operating cost, and employees.

4. It helps in huge savings of units being used in power system operations.

3.2 Unit commitment Problem Constraints

3.2.1 Spinning Reserve (SR) Constraints

In the given model, the spinning reserve constraints are used to stabilize the active power from unpredictable losses or interruptions. In general, the basic job of spinning reserve constraints in the UC model is to chart the planning of power generation and set out the respective output with minimum cost to meet the power load and various operational conditions.

3.2.2 Unit Constraints

In thermal units, due to gradual temperature changes, it is required to consider the crew in the functioning of plants, generally at on and off state.

The following constraints parameter arises in the functioning of plants, such:

Minimum up time: It is the functioning time of the unit, once it has been turned on. In other words, it describes a minimum online time of a unit in working operation.

Minimum down time: It is the stopping time of the unit, once it has been turned off. In other words, it describes a minimum offline time of a unit in working operation.

Crew Constraints: If a plant has more than one's unit, it is not possible to turn on all units at one time because there are insufficient crew members to address all units at the startup. In addition, it is essential to set up these constraints according to their startup and shutdown time requirements.

Operation and Maintenance costs: It comprises the labor cost of the operating set and the cost for the maintenance of the plant.

3.2.3 Load Balance Constraints

The load balance constraints require that there is an equality between the total power outputs from the available plants to the load demand in each hour.

3.2.4 Generation Units Constraints

It describes the generating units as lie between the maximum and minimum power produced by generating units and the power output will not exceed these limits.

3.2.5 Generation Ramping Constraints

The power output of the generator cannot change immediately as ramp rate limits determine these variations. When the ramp rate limits are ignored, it will provide a reasonable state configuration, to take commitment decisions in corresponding hours.

3.2.6 Other Constraints

The following parameters describe the other constraints that need to be considered in the unit commitment decision.

Fuel consumption constraints

A power plant system in which few generating modules have limited fuel or also have the motive to use or burn a fixed amount of fuel given by a fuel supplier in a given time. Thus it is required to establish the upper and lower limits for fuel usage over the study period.

Must Run Units

At some point in the year, few units are given must run stature which supports voltage on the transmission network or sometimes for other purposes.

Must off Units

It involves the criteria of turning off the specific units during the maintenance period and forced outage.

Transmission Constraints

It is used to fulfill the customer load demand, maintain transmission follows, and bus voltage limits consideration. Usually, the linear DC transmission Constraints are used for UC problems with the purpose of system security consideration.

3.3 Unit Commitment Algorithm

UC involves the calculation of operating fuel costs, maintenance costs, and startup costs, the following parameters state the step required to solve unit commitment. Step by step procedure to solve unit commitment problem is shown in figure 3.1.

1. Draw the required possible combination of n number of generators.

2. State the feasible combination according to specified load.

3. Notice the various units combination having the least production cost.

4. Calculate the total production cost and produce all United States.

5. Save the lowest-cost plans.

6. Track down the optimal schedule for the specified problem.

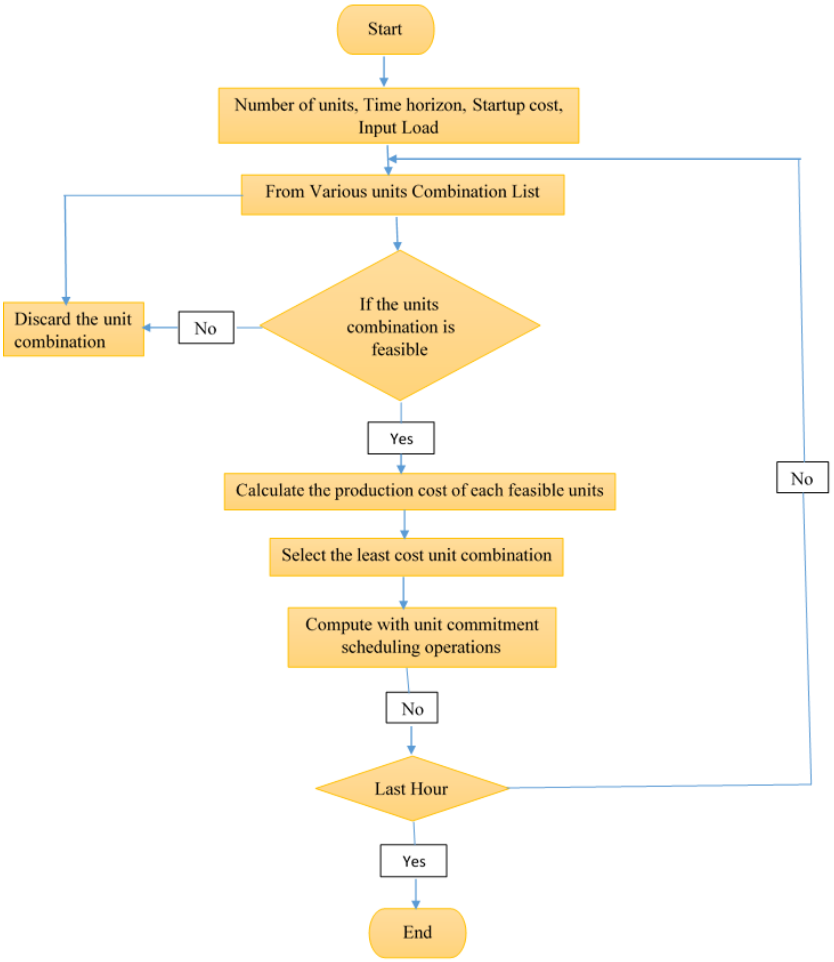


Figure 3.1 Step by step diagram of unit commitment algorithm

3.4 Solution Methods to Deterministic Unit Commitment

The following section summarized a study of several solution methods to deal with the deterministic unit commitment.

3.4.1 Priority List

This solution approach consists of creating a priority list of committed generators to schedule the most economic primary load having the least cost unit at first and units that have large costs at last. The usage of this approach is very simple but it is highly heuristic. Priority list involves a very fast computation process to produce starting solutions which will experience the improvement procedure with the fast heuristic method to obtain the total generation cost and an economic dispatch scheduling.

3.4.2 Dynamic Programming Method

Dynamic programming (DP) is the key solution strategy to solve a particular class of problems. It involves extract mathematical optimization procedures to solve UC problems that have the properties of overlapping sub-problems. This solution strategy decomposes a given problem into several sub-problems, then solves these sub-problems and results in an optimum solution. In its elemental form, the DP solution strategy for the unit commitment problem will go through all possible combinations in each period. Some of these combinations are found to be infeasible and are required to reject instantly. This solution approach has many advantages over the various schemes. Suppose we have n generator units in a system, then the possible combinations for the testing are 2n-1.

The dynamic programming solution approach cannot be applied to large-scale systems, as its computation time increases exponentially. Therefore, it is best to use dynamic programming with other methods to improve its computation performance in case of a large-scale problem.

3.4.3 Mixed Integer Linear Programming

This solution strategy is used as a reformulation to the UC problem to get relief from some computation barriers such as nonlinear dimensions. It is the most promising solution approach applied to UC problems, which targets better solution procedures as well as obtaining an optimal solution.

$$[P]:\ min\, r_1^T x + r_2^T \mathrm{y} \tag{3.1}$$

$$s.t.\ W_1 x = c_1 \tag{3.2}$$

$$W_2 x + Ey = c_2\ \ , x \in \{0,1\}^{\sigma_1} \tag{3.3}$$

$$y \in R_+^{\sigma_2} \tag{3.4}$$

where $r_1 \in R^{\sigma_1}$, $r_2 \in R^{\sigma_2}$, $c_1 \in R^{\theta_1}$, $c_2 \in R^{\theta_2}$, $W_i \in R^{\sigma_1 \times \theta_i}\ where\ (i = 1,2)$ $\mathrm{E} \in \mathrm{R}^{\sigma_2 \times \theta_2}$, and θ_1 , θ_2 are scalars.

The above equations show that the MIP contains an integer variable (x) and a continuous variable (y), involving UC constraints as binary variables.

In the given UC problem, the fuel cost is generally formed as a quadratic function where directly solving may give rise to a solution with the computational burden. So it is required to state a piecewise linear approximation strategy to develop a closer value for generation variables.

Generally, the branch-and-cut solution method is suitable for MILP problems, which involves the breaking of the problem into several smaller MILP problems.

3.4.4 Lagrangian Relaxation

The Lagrange relaxation solution approach has been used for UC scheduling at large-scale power systems. It will provide approximate solutions to mixed-integer programming problems by solving binary UC problems. This solution approach can replace the complex constraints of the objective function with optimal terms, which are expressed by the violation of constraints and with its Lagrangian multipliers.

3.4.5 Benders Decomposition

This solution approach reduced the optimization barriers, as a basic single problem is decomposed into a master problem (MP). This solution process involves the following steps:

1. It starts with solving the master problem to attain a lower bound.

2. Then, pass the obtained solution to the corresponding sub-problem and solve it to attain the upper bound.

3. Construct the cut for the master problem to converge the corresponding lower bound and upper bound.

The linear or non-linear sub problems are capable of providing feasible solutions as well as allow the MP to consider all discrete variables.

3.5 Deterministic Unit Commitment Problem Formulation Considering MILP

Unit Commitment process schedule the generator's status (on/off) to provide the least cost for power production. The UC problem generally involves a process of scheduling generator units under physical conditions. The various parameters such as minimum on/off time, ramp up/down rate, generation costs, and generation capacity are required to optimize to meet the corresponding load demands. Moreover, real-time scheduling is also subject to load demand changes and transmission conditions. The following section contains the deterministic UC problem formulation considering MILP.

3.5.1 Objective Function

The objective function is associated with two-stage decisions. These decisions claim two cost components to reach the minimum operating cost over the specified planning periods. The first cost component is determined by day-ahead decisions, which involve each generator startup and shutdown and the second cost component is a fuel cost and non-served energy penalty produced by load-shedding losses.

$$Min \sum_{i\in H} \sum_{t\in T} (SU_i u_{it} + SD_i d_{it}) + \sum_{i\in G} \sum_{t\in T} F_i\,(p_{it}) + VOLL \sum_{j\in N} \sum_{t\in T} \delta_{jt} \qquad (3.5)$$

From the above equation, it is observed that the objective function involves total fuel cost as a quadratic function of the dispatch and production states.

$$F_i(p) = a + bp + cp^2 \qquad (3.6)$$

It is very difficult to solve quadratic MIP when large numbers of generators are involved. So it is good to solve the problem with linear approximation strategies to get a very close solution for computational confidence. This means that it is required to reformulate the primary objective function to generate a piece-wise linear approximation, named a MILP problem.

$$\{p_i = \sum_{k=1}^{K} \alpha_k \beta_k\,, \sum_{k=1}^{K} \beta_k = u_i\,, \beta_k \geq 0, k = 1, \ldots\ldots, K\}$$

(3.7)

Eq. 3.7 uses the sum of squares strategy for gaining the linear piecewise approximation. This involves the substitution of the fuel cost function $F_I(p)$ by $\sum_{k=1}^{K} C_k\, \beta_k$ along with some additional constraints.

$$p_i = \sum_{k=1}^{K} \beta_k = M_i$$

(3.8)

In Eq. 3.8 when the unit is in the "On" mode, i.e. $M_i = 1$, then the UC equation will be found with the following constraints,

$$p_i = \sum_{k=1}^{K} \alpha_k \beta_k$$

(3.9)

$$\sum_{k=1}^{K} \beta_k = 1,$$

(3.10)

$$\beta_k \geq 0, \qquad k = 1, \ldots\ldots, K$$

(3.11)

Or when the unit is in the "Off" mode, i.e. $M_i = 0$, then there is no operational cost and the p_i become zero.

3.5.2 Constraints

The following section describes the detailed formulation of unit commitment constraints from mixed-integer linear programming models.

3.5.2.1 Unit commitment Constraints

The operation action requires a minimum on-time, minimum off-time, startup, and shutdown that will cause restrictions to generator status. The below Eq. 3.12 and Eq. 3.13 describes the shortest ON/Off period, needed before shut down or startup.

Minimum ON time constraint:

$$M_{it} - M_{i(t-1)} \leq M_{i\tau} \qquad \forall i \in H,\ t \in T,\ \tau = t, \ldots\ldots min\{t + L_i - 1, |T|\} \qquad (3.12)$$

Minimum OFF time constraint:

$$M_{i(t-1)} - M_{it} \leq M_{i\tau} \qquad \forall i \in H,\ t \in T,\ \tau = t, \ldots\ldots min\{t + l_i - 1, |T|\} \qquad (3.13)$$

The Startup action u_{it} and the shutdown action d_{it} are describes by Eq. 3.14 and Eq. 3.15

Startup action Constraints:

$$u_{it} \geq M_{it} - u_{i(t-1)} \qquad \forall i \in H,\ \ t \in T, \qquad (3.14)$$

Shutdown action Constraints:

$$d_{it} \geq -M_{it} + M_{i(t-1)} \qquad \forall i \in H,\ t \in T, \qquad (3.15)$$

3.5.2.2 Thermal Generation Constraints

Unit commitment scheduling requires the power generation to provide the minimum cost generation output through available generation resources. Eq. 3.16 states the generator output with a minimum generation limit P_i^{min} and the maximum generation limit$\mathrm{P}_{\mathrm{i}}^{\mathrm{max}}$.

$P_i^{min} M_{it} \leq p_{it} \leq P_i^{max} M_{it}$ $\forall i \in H, \; t \in T,$

(3.16)

$p_{it} \geq 0$ $\forall i \in H, \; t \in T,$

(3.17)

When M_{it}=1, the generator active to give corresponding bounds on dispatch levels.

When M_{it}=0, the generator outcome is forced to zero.

$-RD_i \leq p_{it} - p_{it-1} \leq RU_i$ $\forall i \in H, \quad t \in T,$

(3.18)

Eq. 3.19 presented the increasing or decreasing periods of generator output.

$p_{it} - p_{it-1} \leq P_i^{min}\left(2 - M_{it} - M_{i(t-1)}\right) + RU_i\left(1 + M_{i(t-1)} - M_{it}\right)$ $\forall i \in H, \; t \in T,$

(3.19)

$p_{it-1} - p_{it} \leq P_i^{min}\left(2 - M_{it} - M_{i(t-1)}\right) + RD_i\left(1 + M_{i(t-1)} - M_{it}\right)$ $\forall i \in H, \; t \in T,$

(3.20)

The Eq. 3.19 and Eq. 3.20 constraints describe the following conditions:

- If a unit is ON at time $(\mathrm{t}-1)$ and ON at time *t*, the corresponding value isRU_i
- If a unit is OFF at time $(\mathrm{t}-1)$ and ON at time t, the corresponding value isP_i^{min}
- If a unit is ON at time $(\mathrm{t}-1)$ and ON at time t, the corresponding value isRD_i
- If a unit is ON at time $(\mathrm{t}-1)$ and OFF at time t, the corresponding value isP_i^{min}

3.5.2.3 Operating spinning reserve constraints

$0 \leq S_{it} \leq S_i^{max}$ $\forall i \in H, \quad t \in T,$

(3.21)

$\sum_{i \in I_j} S_{it} \geq RS_{jt}$ $\forall j \in H, \quad t \in T,$

(3.22)

3.5.2.4 Transmission Generation Constraints

$$\sum_{(j,h)\in A_j^+} f_{jht} - \sum_{(j,h)\in A_j^-} f_{jht} = \sum_{i\in I_j} p_{it} + R_{jt} - D_{jt}^0 + \delta_{jt} \qquad \forall j \in N,\ \ t \in T, \tag{3.23}$$

$$-F_{jh}^{max} \le f_{jht} \le F_{jh}^{max}\ , \qquad \forall (j,h) \in A\ ,\ \ t \in T, \tag{3.24}$$

The above Eq. 3.24 describes the flow limits of the power transmission line from bus j to h. In many cases, load-shedding is not allowed and δ_{jt} is restricted to be zero.

$$l_{jt} \ge 0, \qquad \forall j \in N,\ \ t \in T, \tag{3.25}$$

$$\left(f_{jht} - f_{hjt}\right) - B_{jht}\left(\gamma_{jt} - \gamma_{ht}\right) = 0 \qquad \forall (j,h) \in A\ ,\ \ t \in T, \tag{3.26}$$

$$\gamma_{jt}\ \ \textit{Unrestricted}, \qquad \forall j \in N,\ \ \ t \in T, \tag{3.27}$$

3.5.2.5 Reactive Power Constraint

The equation Eq. 3.28 and Eq. 3.29 introduce the load bus balance, reactive generation limits, and operating reserve conditions.

$$Q_i^{min} M_{it} \le q_{it} \le Q_i^{max} M_{it} \qquad \forall i \in H, \qquad t \in T, \tag{3.28}$$

$$\sum_{i\in I} Q_i^{max}\, M_{it} \ge D_t^Q \qquad \forall t \in T \tag{3.29}$$

Chapter 4

Methodology

4.1. Software Description

The following software were used to solve the UC problem:

4.1.1 MATLAB

It is a high-performance programming language and numeric computing domain which permits the user with matrix manipulation, design of user interfaces, plotting to various functions, algorithm implementation, and associating with programs written in other languages. MATLAB is a mixed laboratory that allows you to solve many technical computing problems by managing the variables in your workspace. It features a family of toolboxes with a broad group of MATLAB functions for developing, managing, debugging, importing, and exporting data.

4.1.2 GUROBI

GUROBI is the fastest and powerful optimizer used to solve all major type problems, in addition to supporting features to solve algorithms with multiple objectives. It can optimize models with non-convex and piecewise linear objective functions and construct the models in min/max or if/then form.

4.1.3 YALMIP

It is a powerful tool for MATLAB that automatically locate the problems defined by the individual and pick a suitable solver based on this analysis. YALMIP includes the “sdpvar” command to define variables, “sdpsettings” to define options within the problems, and “optimize” to solve the problems.

4.1.4 MATPOWER

Zimmerman *et.al* developed the MATPOWER for the Cornell university project called PowerWeb. It is an online tool for power flow simulations and analysis. MATPOWER is a MATLAB-based simulation package for researchers and educators that facilitates a high-level set for solving power flow and optimal power flow situations. It includes the

MATPOWER Optimal Scheduling Tool (MOST) cases for solving electric power systems scheduling problems.

4.1.5 MOST

MOST is a tool for solving any deterministic, stochastic, and multi-period problems for power systems. It can be used to solve various problems that involved uncertain renewable generation sources, energy storage systems, ramping costs, ramping constraints, localized contingencies, and generation reserves, and combined unit commitment. Moreover, it can only consider network DC models to solve problems.

This tool is used to solve the unit commitment problem. In order to solve UC problems with MOST, the user is required to install high-performance mixed-integer solvers such as GUROBI, CPLEX, MOSEK, and GLPK.

4.2 Proposed Methodology

The following section describes the methodology to solve the unit commitment problem using *fmincon* and MATPOWER.

4.2.1 UC Solution Using *fmincon*

In the proposed methodology Figure 4.1 describes the following steps to achieve the solution of the unit commitment problem with *fmincon*.

Step1: The first step is to define the given problem with YALMIP.

Step2: This step involves the representation of declaring variables such as binary variables, continuous variables, and generator variables.

Step3: The third step defines the problem constraints into vector form. In addition, this step involves the bounds constraint for power outputs, logical constraints between startup and on/off variables, and power balance constraints.

Step4: This step defines the objective function of a given problem. The target is to minimize the total unit operating cost subjected to various constraints.

Step5: This step involves the solver options using "*sdpsettings*" and optimizing the unit commitment problem to produce corresponding solutions.

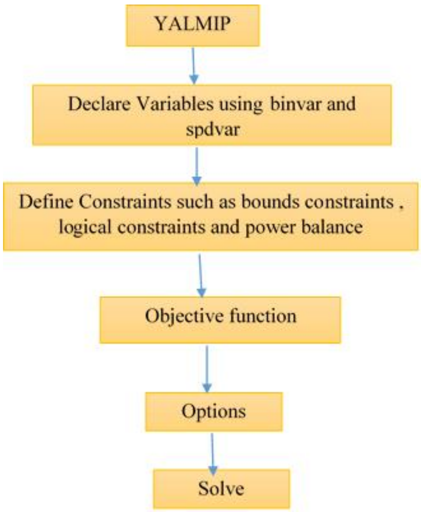


Figure 4.1 UC solution using *fmincon*

4.2.2 UC Solution using MATPOWER

In the proposed methodology Figure 4.2 different classifiers were used to obtain results that are presented in this study. The first step is to define the MATPOWER case file that contains all the network data or load profile data. The MATPOWER file consists of files of bus data, generator data, branch data, generator cost data, wind data, load data, and storage data. Then add to this step, this file is loaded into the MOST using the *load case* function. The addition generator parameters were loaded using the *loadxgendata* function. This procedure involves the modification in MATPOWER by adding wind generators or storage units using *add wind* and *add storage* function. The user can also introduce the additional storage parameters to *Storage data*. The profile data file containing time-varying parameters is loaded using the *get profile* function. After the data preparation and introduction, the next step is to set the options using the *mpopt* function, and then the next thing to do is run MOST for the initial loaded data. The MOST initial run aims to define the profiles for generators data, buses data, and wind data and do a first DC power flow for the deterministic unit commitment problem. This run provides an initial picture of how the system will behave, namely when a wind generator or storage exists. It also helps in defining how the system will work during the 24 hours. The results for this run are obtained using the *mdo* function. In addition to this run, the MOST data struct involves the introduction of additional input fields and offers within the system requirements.

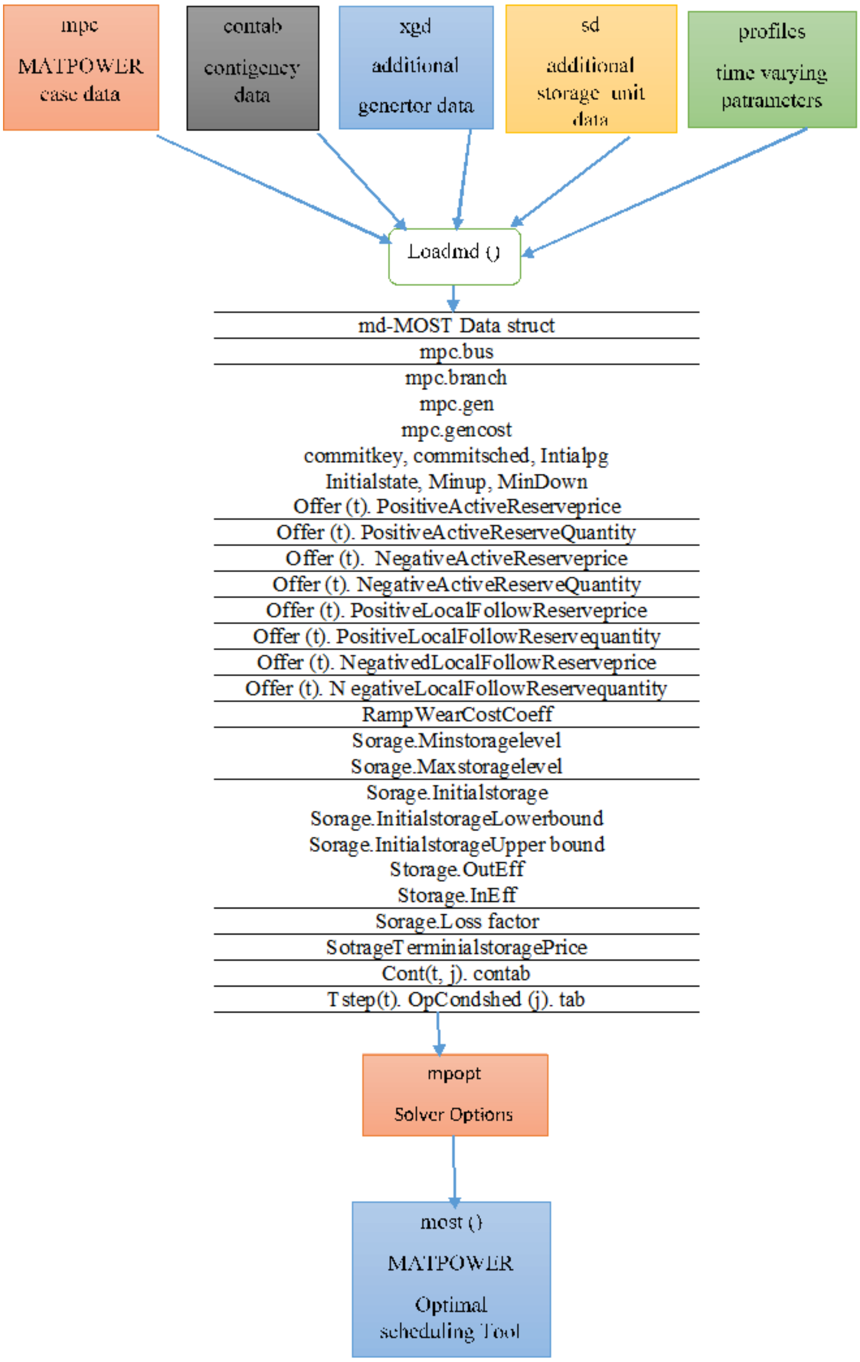


Figure 4.2 UC solution using MATPOWER

Chapter 5

Results and Discussion

5.1 Test case system 1

Four generator units are to be committed for 4 hours. The Data on the units, startup costs, production costs, and load is contained in the given Table 5.1 The detail of minimum and maximum generation limits are given in Table 5.2.

Table 5.1 Data of generator units

Unit (k)	Startup costs ($)	Production costs ($/p.u.-hour)	Load (p.u.)
1	100	25	1.50
2	100	35	1.60
3	100	45	1.70
4	100	55	1.90

Table 5.2 Minimum/Maximum generation limits

Unit (k)	Minimum generation	Maximum generation
1	0	0.50
2	0	0.55
3	0	0.60
4	0	0.65

5.2 Test case system 2

Three bus systems consist of three generators, wind, and energy storage unit respectively. The detail of the generators, load, wind, and storage unit are contained in the given Table 5.3. The detail of branches and adequacy conditions are given in Table 5.4.

Table 5.3 Details of generator, load, wind, and storage

Bus No.	Bus 1	Bus 2	Bus 3
Generators	250 MW gen 1 and gen 2	500 MW gen 3	....

Load	……………………	……………………	550 MW curtailable at 1000 $/MWh
Wind	100 MW		
Storage	……………………	……………………	300 MWh 80MW max charge and discharge rate

Table 5.4 Details of branches and adequacy conditions

Branches	340 MW limit on lines 1-2 260 MW limit on lines 1-3 300 MW limit on lines 2-3
Condition for Adequacy	1: 160 MW system demand 2: contingencies that gen 2 at bus 1

Tables 5.5 Details of wind profiles and load profiles

Time (Hours)	Wind Profile Data	Load profile Data
1	0.80	370
2	0.65	450
3	0.60	490
4	0.82	440
5	1.00	470
6	0.70	395
7	0.50	360
8	0.85	340
9	1.00	300
10	1.10	380
11	1.06	250
12	0.95	200
13	0.72	220

14	0.88	250
15	0.85	350
16	0.95	300
17	0.88	325
18	0.81	340
19	0.60	390
20	0.54	420
21	1.64	435
22	1.66	375
23	1.55	475
24	1.40	485

5.3 UC Solution Using *fmincon*

The following section described the detailed discussion for the test case system 1 using the f min con method. This section provides the results of 4 unit systems which have 4 hour time period with the configuration mentioned in test case 1.

Results: Gurobi gives an objective function value of 542.500 $.

Gurobi > display solution variables-

Table 5.6 Solution of all the variables in 4 hour period

Time (Hours)	**1**	**2**	**3**	**4**
P1	0.5	0.5	0.5	0.5
P2	0.5	0.5	0.5	0.5
P3	0.55	0.55	0.5	0.55
P4	0.45	0.55	0.6	0.6
Z1	1	1	1	1

Time (Hours)	1	2	3	4
Z2	1	1	1	1
Z3	1	1	1	1
Z4	1	1	1	1

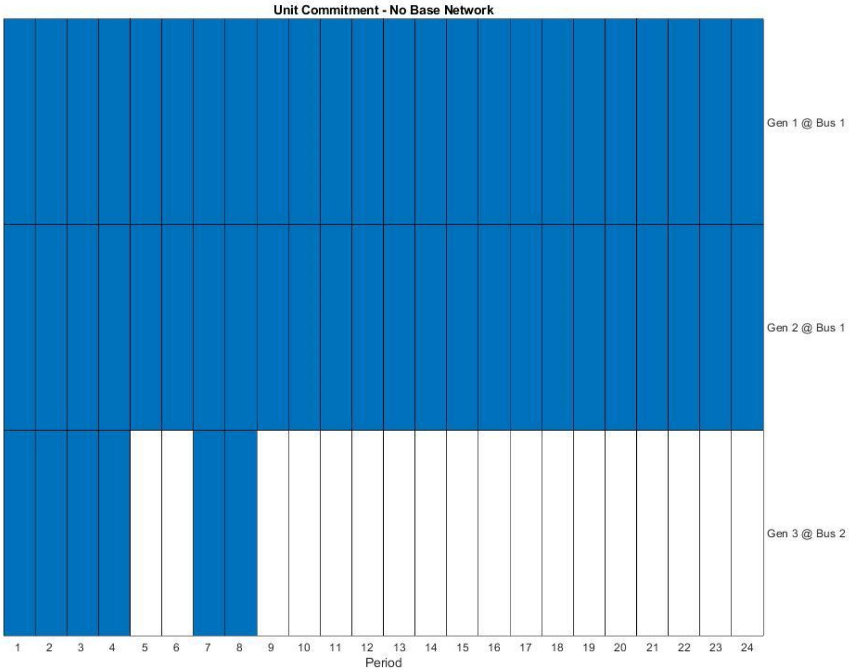
Where P1, P2, P3, P4 are the power generation in each hour andZ1, Z2, Z3, Z4 are the decision variables

5.4 UC Solution without Wind Generator and Storage Unit

The following section described the detailed discussion for the 3 bus systems without considering wind generators and storage units. The results for the 3 bus systems using mixed-integer linear programming are described in this section. This section provides the results of 3 bus systems that have three generators with the configuration mentioned in test case 2.

5.4.1 Scheduling of Generators without Network Model:

Figure 5.1 described the graphical information of scheduling of three buses, three generator systems when there are no network constraints, no minimum up and downtime constraints, no startup and shutdown costs, no ramp costs, and ramp constraints.



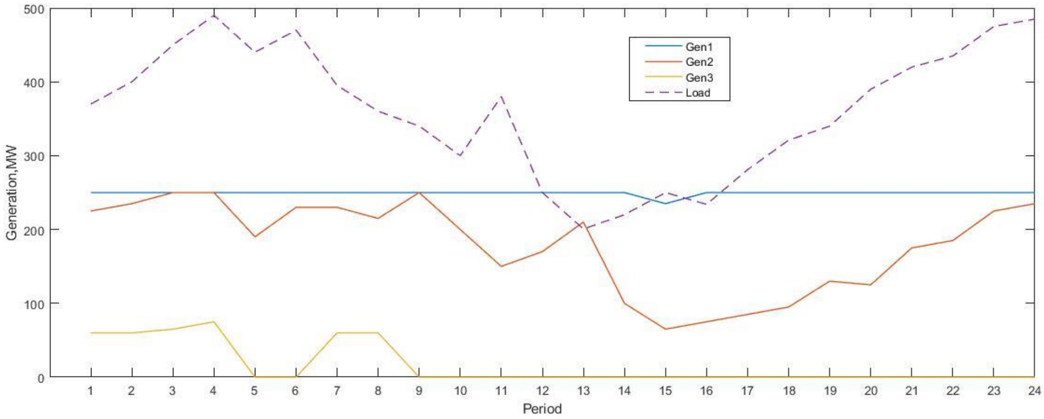


Figure 5.1 Graph showing scheduling without network model

The results obtained from no base network are detailed in Table 5.7 consisting of 24 hours' time horizons for three bus systems and Table 5.8 describes the corresponding value of three generators at each hour.

Table 5.7 On/Off state without network model

Gen	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24
1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
2	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
3	**1**	**1**	**1**	**1**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 5.8 Generators value without network model

Gen	T_1 T_{13}	T_2 T_{14}	T_3 T_{15}	T_4 T_{16}	T_5 T_{17}	T_6 T_{18}	T_7 T_{19}	T_8 T_{20}	T_9 T_{21}	T_{10} T_{22}	T_{11} T_{23}	T_{12} T_{24}
1	250 250	250 250	250 235	250 250	250 250	250 250	250 250	250 250	250 250	250 250	250 250	250 250
2	225 210	235 100	250 65	250 75	190 85	230 95	230 130	215 125	250 175	200 185	150 225	170 235
3	60 0	60 0	65 0	75 0	0 0	0 0	60 0	60 0	0 0	0 0	0 0	0 0

5.4.2. Scheduling of Generators with Addition of DC Network Model:

Figure 5.2 described the graphical information of scheduling of three buses, three generator systems when a DC network model is added to the corresponding system.

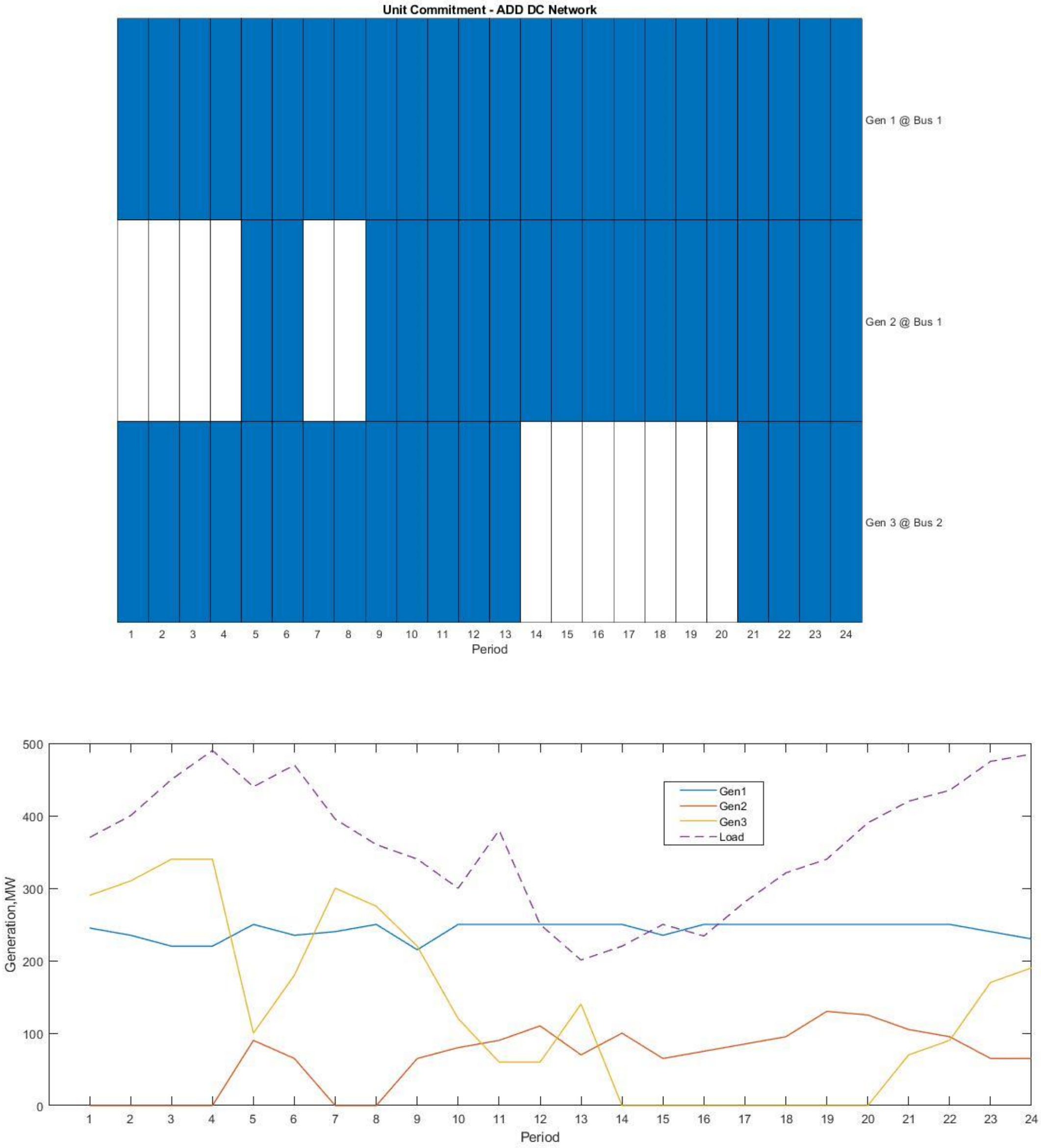


Figure: 5.2 Graphs showing scheduling with addition of DC network model

The results obtained from the DC network model are detailed in Table 5.9 consisting of 24 hours' time horizons for three bus systems and Table 5.10 describes the corresponding value of three generators with a DC model at each hour.

Table 5.9 On/Off State with addition of DC network model

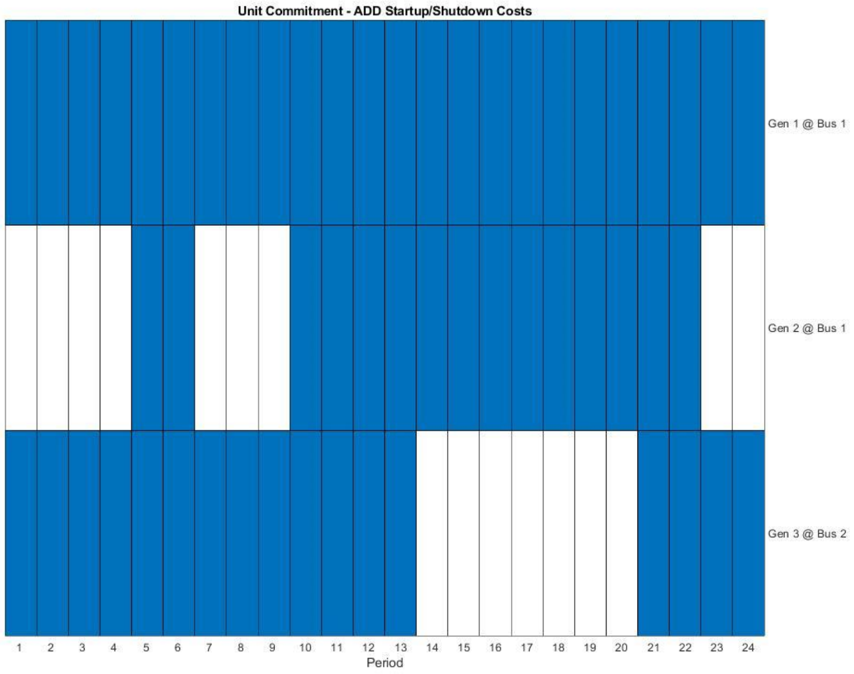
Gen	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24
1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
2	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
3	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**1**

Table 5.10 Generators value with addition of DC network model

Gen	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}
	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}	T_{20}	T_{21}	T_{22}	T_{23}	T_{24}
1	245	235	220	220	250	235	240	250	215	250	250	250
	250	250	235	250	250	250	250	250	250	250	240	230
2	0	0	0	0	90	65	0	0	65	80	90	110
	70	100	65	75	85	95	130	125	105	95	65	65
3	290	310	340	340	100	180	300	275	220	120	60	60
	140	0	0	0	0	0	0	0	70	90	170	190

5.4.3. Scheduling of Generators with Addition of Startup and Shutdown Costs:

Figure 5.3 described the graphical information of scheduling of three buses, three generator systems when startup and shutdown costs are added to the system.



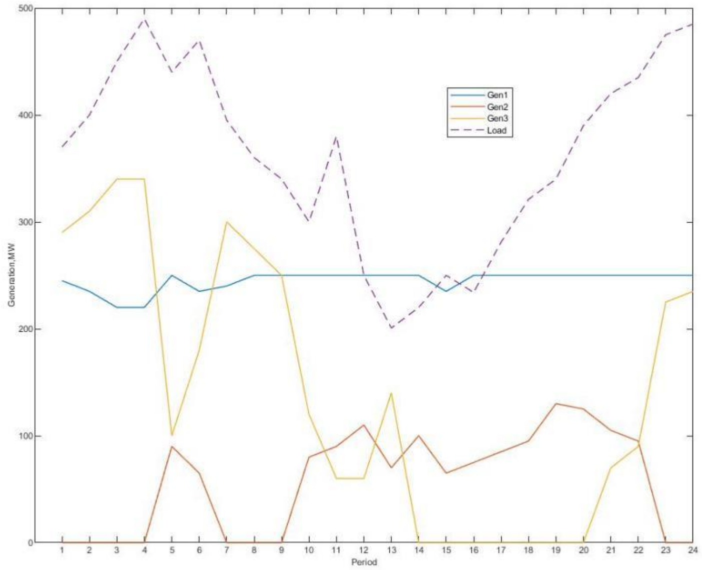


Figure: 5.3 Graphs showing scheduling with addition of startup/shutdown costs

The results obtained from the startup/shutdown costs are detailed in Table 5.11 consisting of 24 hours' time horizons for three bus systems and Table 5.12 describes the corresponding value of three generators with Startup and Shutdown at each hour.

Table 5.11 On/Off state with addition startup/shutdown costs

Gen	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
3	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1

Table 5.12 Generators value with addition startup/shutdown costs

Gen	T_1 T_{13}	T_2 T_{14}	T_3 T_{15}	T_4 T_{16}	T_5 T_{17}	T_6 T_{18}	T_7 T_{19}	T_8 T_{20}	T_9 T_{21}	T_{10} T_{22}	T_{11} T_{23}	T_{12} T_{24}
1	245 250	235 250	220 250	220 250	250 250	235 250	240 250	250 250	250 250	250 250	250 250	250 250
2	0 70	0 100	0 65	0 75	90 85	65 95	0 130	0 125	0 105	80 95	90 0	110 0
3	290 140	310 0	340 0	340 0	100 0	180 0	300 0	275 0	250 70	120 90	60 225	60 235

5.4.4 Scheduling of Generators with Addition of Minimum Up/Down Time Constraints:

Figure 5.4 described the graphical information of scheduling of three buses, three generator system when minimum up/downtime time constraints is added to the system.

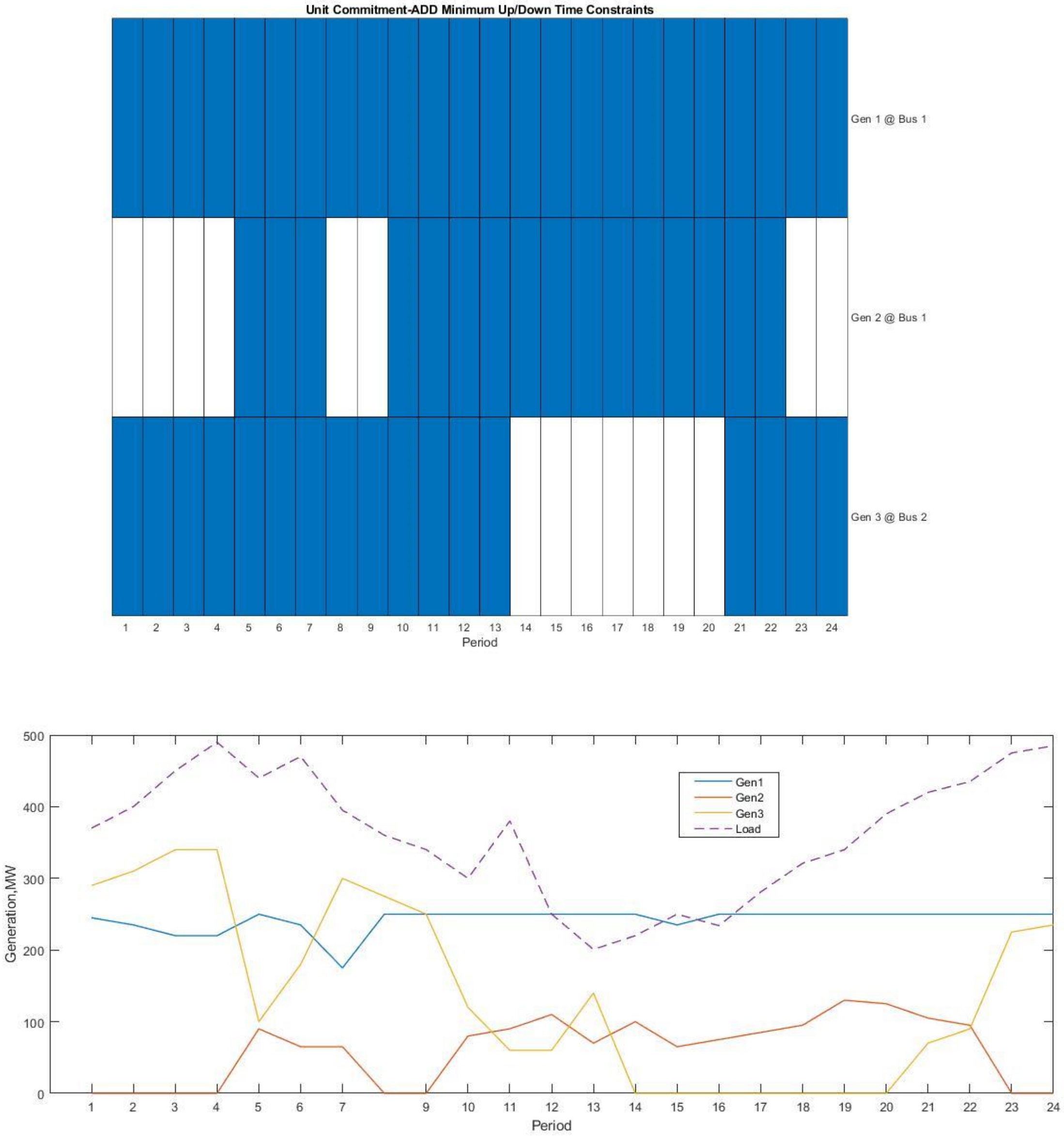


Figure: 5.4 Graph showing scheduling with addition of minimum up/down time constraints

The results obtained from the Minimum Uptime/Downtime constraints are detailed in Table 5.13 consisting of 24 hours' time horizons for three bus systems contains minimum up/downtime constraints and Table 5.14 describes the corresponding value of three generators that contain minimum up/downtime constraints.

Table 5.13 On/Off state with addition of minimum up/down time constraints

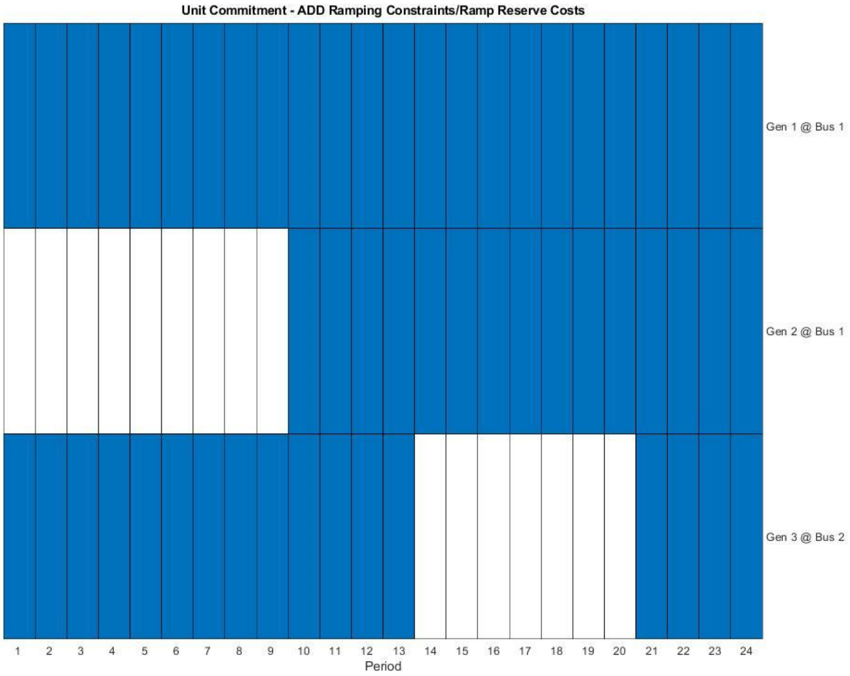
Gen	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24
1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
2	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**0**
3	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**1**

Table 5.14 Generators value with addition of minimum up/down time constraints

Gen	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}
	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}	T_{20}	T_{21}	T_{22}	T_{23}	T_{24}
1	245	235	220	220	250	235	175	250	250	250	250	250
	250	250	235	250	250	250	250	250	250	250	250	250
2	0	0	0	0	90	65	65	0	0	80	90	110
	70	100	65	75	85	95	130	125	105	95	0	0
3	289	309	340	340	100	180	300	275	250	120	60	60
	60	140	0	0	0	0	0	0	70	90	225	235

5.4.5 Scheduling of Generators with Ramping Constraints and Ramp Reserve Costs:

Figure 5.5 described the graphical information of scheduling of three buses, three generator system when ramping constraints and ramp costs is added to the system.



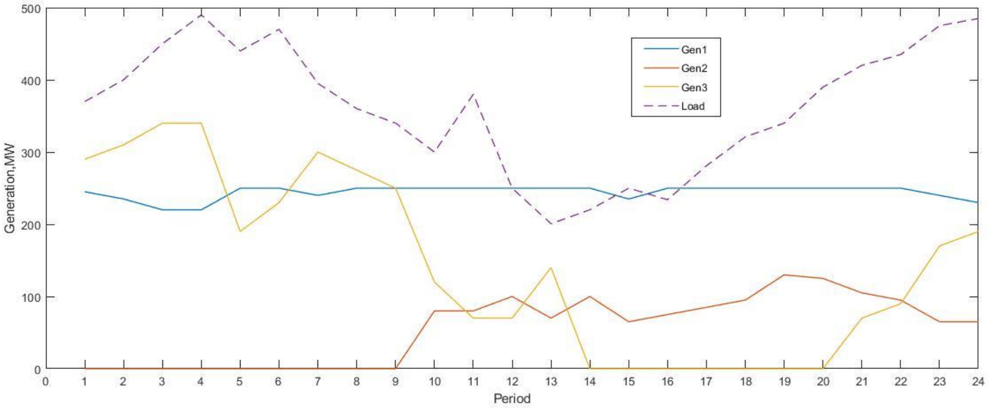


Figure: 5.5 Graph showing scheduling with addition of ramping constraints/ ramp reserve costs

The results obtained from the ramping constraints and reserve costs are detailed in the Table 5.15, consists of 24 hours' time horizons for three bus system and Table 5.16 describes the corresponding value of three generators contain ramp costs and ramping constraints.

Table 5.15 On/Off state with addition of ramping constraints/ ramp reserve costs

Gen	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1

Table 5.16 Generators value with addition of ramping constraints/ ramp reserve costs

Gen	T_1 T_{13}	T_2 T_{14}	T_3 T_{15}	T_4 T_{16}	T_5 T_{17}	T_6 T_{18}	T_7 T_{19}	T_8 T_{20}	T_9 T_{21}	T_{10} T_{22}	T_{11} T_{23}	T_{12} T_{24}
1	245 250	235 250	220 235	220 250	250 250	250 250	240 250	250 250	250 250	250 250	250 240	250 230
2	0 70	0 100	0 65	0 75	0 85	0 95	0 130	0 125	0 105	80 95	80 65	100 65
3	290 140	310 0	340 0	340 0	190 0	230 0	300 0	275 0	250 70	120 90	70 170	70 190

5.5 UC Solution Considering Wind Generator and Storage Unit

The following section described the detailed discussion for the 3 bus systems while considering wind generators and storage units. The results for the 3 bus systems using mixed-integer linear programming are described in this section. This section provides the results of 3 bus systems which have three generators, wind generators, and storage units with the configuration mentioned in test case 2.

5.5.1 Scheduling of Generators without Network Model:

Figure 5.6 described the graphical information of scheduling of three buses, three generator systems including wind generator and storage unit system when there are no network constraints, no minimum up and downtime constraints, no startup and shutdown costs, no ramp costs, and ramp constraints.

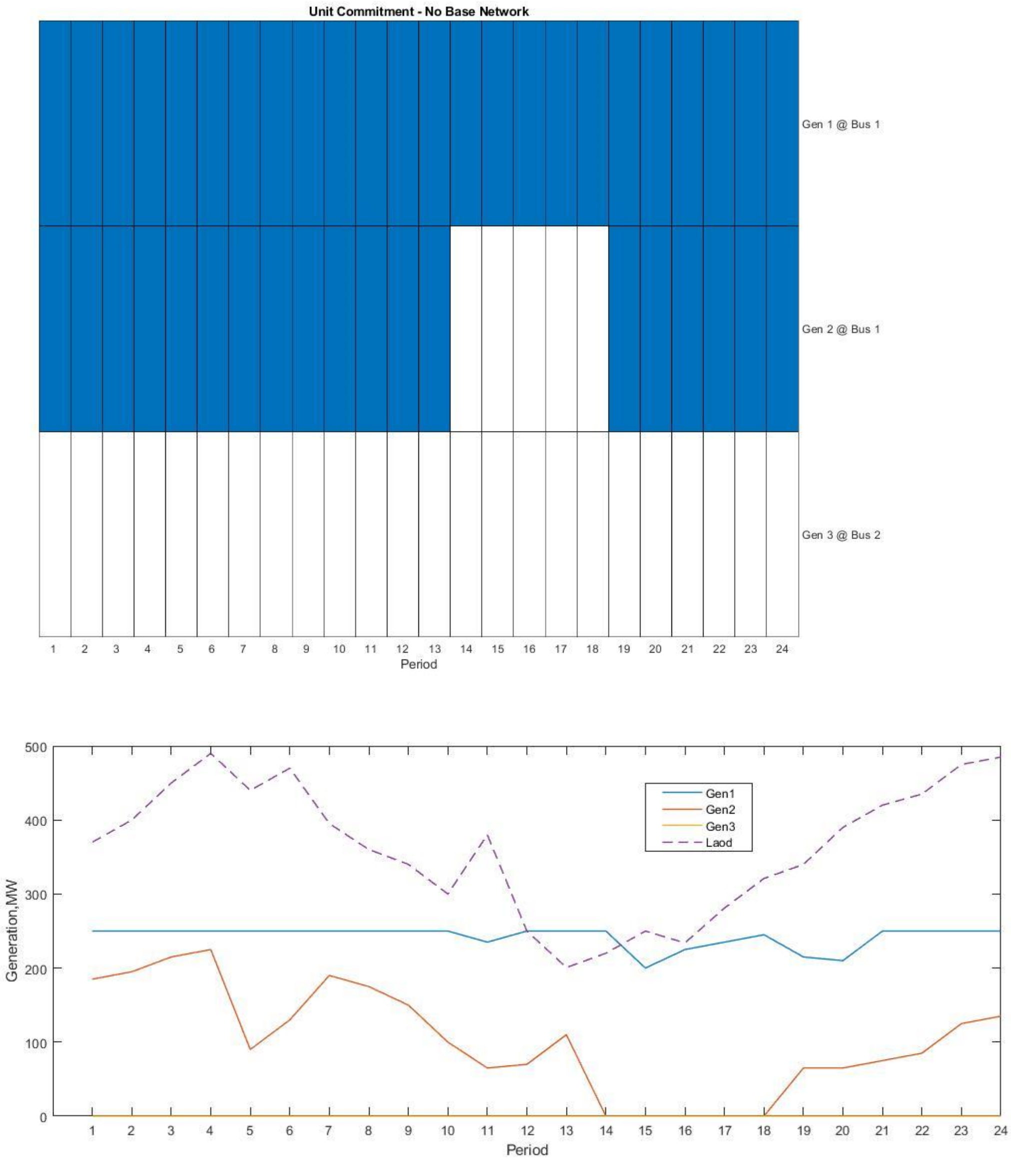


Figure: 5.6 Graph showing scheduling without network model

The results obtained from the no base network are detailed in Table 5.17 consisting of 24 hours' time horizons for three bus systems and Table 5.18 describes the corresponding value of three generators at each hour.

Table 5.17 On/Off state with no base network

Gen	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24
1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
2	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**1**	**1**	**1**
3	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 5.18 Generators value without network model

Gen	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}
	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}	T_{20}	T_{21}	T_{22}	T_{23}	T_{24}
1	250	250	250	250	250	250	250	250	250	250	235	250
	250	250	200	225	235	245	214	210	250	250	250	250
2	185	195	215	225	90	130	190	175	150	100	65	70
	110	0	0	0	0	0	65	65	75	85	125	135
3	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	

5.5.2 Scheduling of Generators with Addition of DC Network Model:

Figure 5.7 described the graphical information of scheduling of three buses, three generator systems including wind generator, and storage unit when a DC network model is added to the corresponding system.

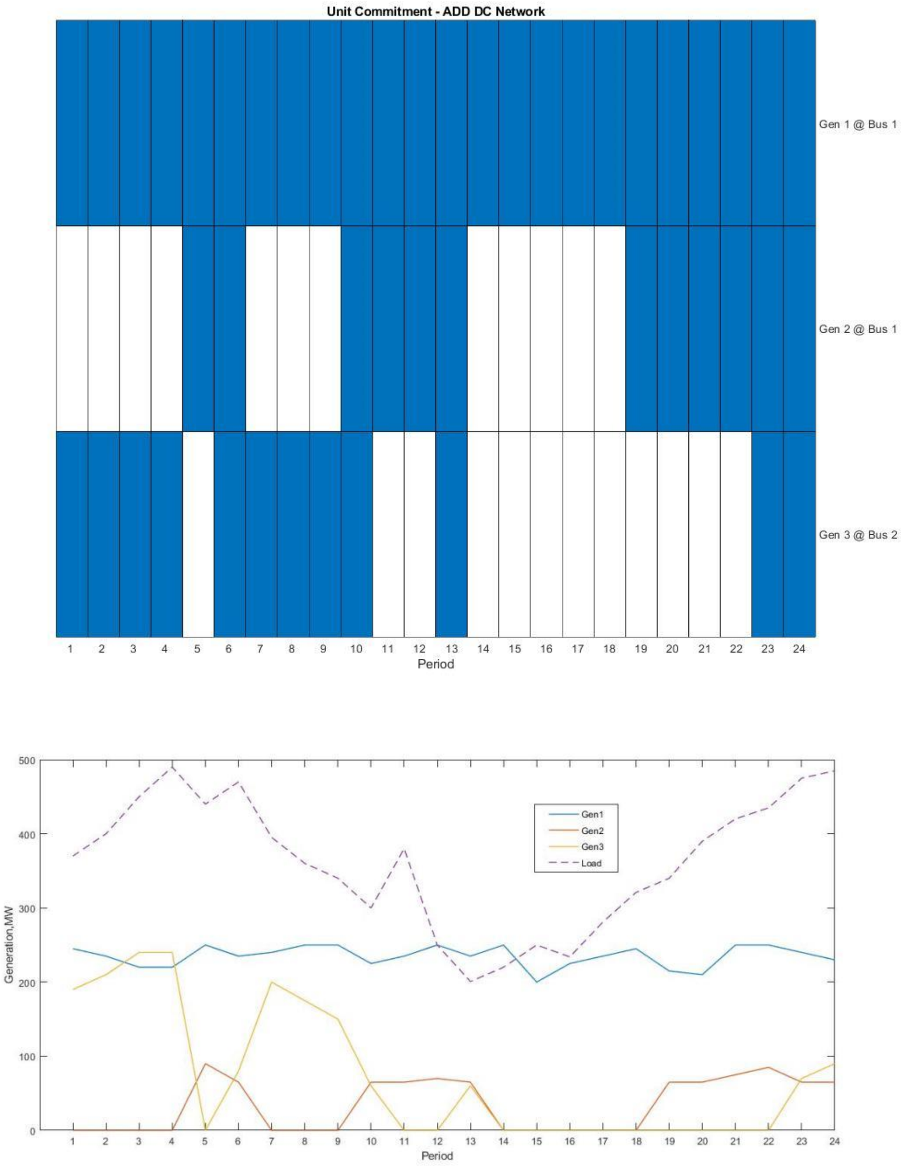


Figure: 5.7 Graph showing scheduling with addition of DC network model

The results obtained from the DC network model are detailed in Table 5.19 consisting of 24 hours' time horizons for three bus systems with DC model, and Table 5.20 describes the corresponding value of three generators at each hour when the DC model is added to it.

Table 5.19 On/Off state with addition of DC network model

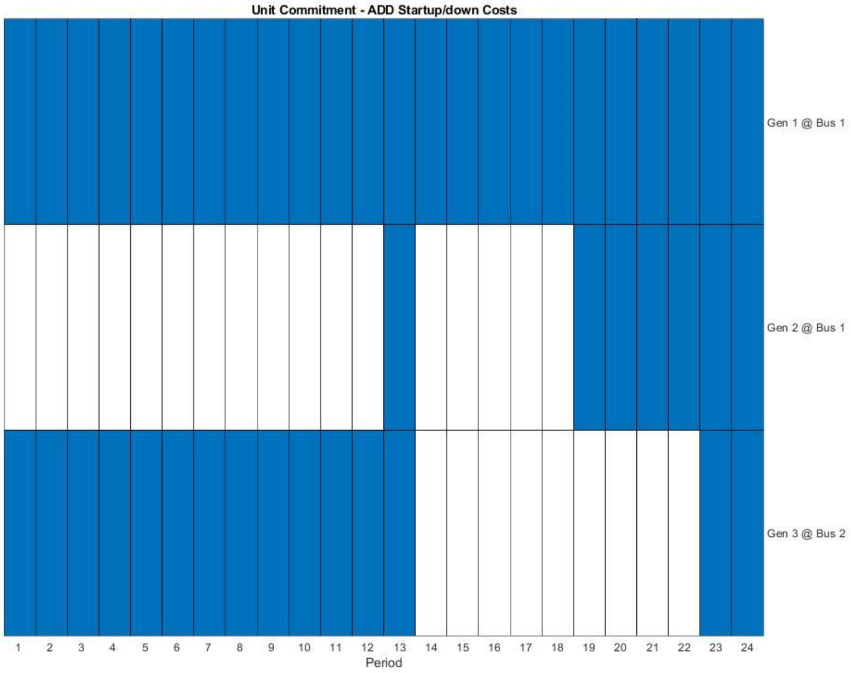
Gen	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24
1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
2	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**1**	**1**	**1**
3	**1**	**1**	**1**	**1**	**0**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**

Table 5.20 Generators Value with addition of DC Network model

Gen	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}
	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}	T_{20}	T_{21}	T_{22}	T_{23}	T_{24}
1	245	235	220	220	250	235	240	250	250	225	235	250
	235	250	200	225	235	245	215	210	250	250	240	230
2	0	0	0	0	90	65	0	0	0	65	65	70
	65	0	0	0	0	0	65	65	75	85	65	65
3	130	210	240	240	0	80	200	175	150	60	0	0
	60	0	0	0	0	0	0	0	0	0	70	90

5.5.3 Scheduling of Generators with Addition of Startup and Shutdown Costs:

Figure 5.8 described the graphical information of scheduling of three buses, three generator systems including wind generator and storage unit when startup and shutdown costs are added to the system.



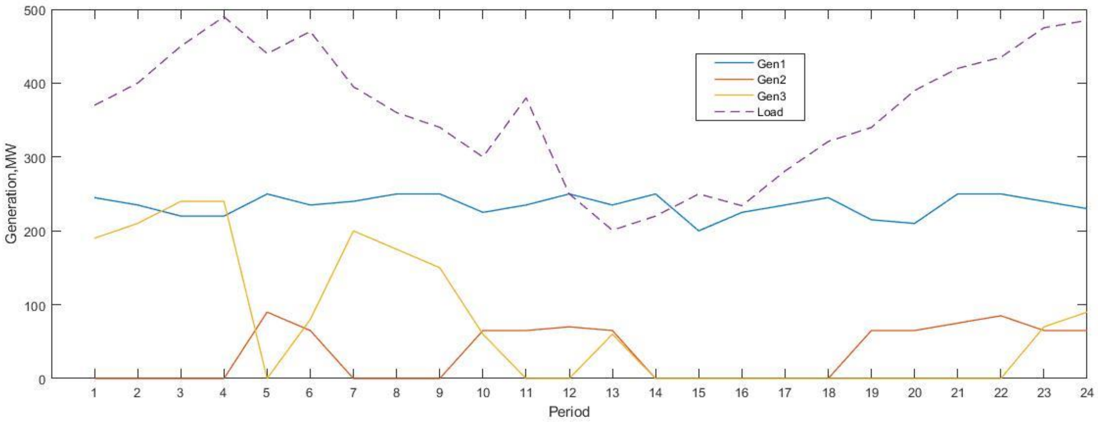


Figure: 5.8 Graph showing scheduling with addition of startup/shutdown costs

The results obtained from the startup/shutdown costs are detailed in Table 5.21 consisting of 12 hours' time horizons for three bus systems and Table 5.22 describes the corresponding value of three generators with Startup and Shutdown at each hour.

Table 5.21 On/Off state with addition of startup/shutdown costs

Gen	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1

Table 5.22 Generators value with addition of startup/shutdown costs

Gen	T_1 T_{13}	T_2 T_{14}	T_3 T_{15}	T_4 T_{16}	T_5 T_{17}	T_6 T_{18}	T_7 T_{19}	T_8 T_{20}	T_9 T_{21}	T_{10} T_{22}	T_{11} T_{23}	T_{12} T_{24}
1	245	235	220	220	250	250	240	250	250	250	240	250
	235	250	200	225	235	245	215	210	250	250	240	230
2	0	0	0	0	0	0	0	0	0	0	65	70
	65	0	0	0	0	0	65	65	75	85	65	65
3	190	210	240	240	90	130	200	175	150	100	60	70
	60	0	0	0	0	0	0	0	0	0	70	90

5.5.4 Scheduling of Generators with Addition of Minimum Up/Down Time Constraints:

Figure 5.9 described the graphical information of scheduling of three buses, three generator systems including wind generator, and storage unit when minimum up/downtime constraints is added to the system.

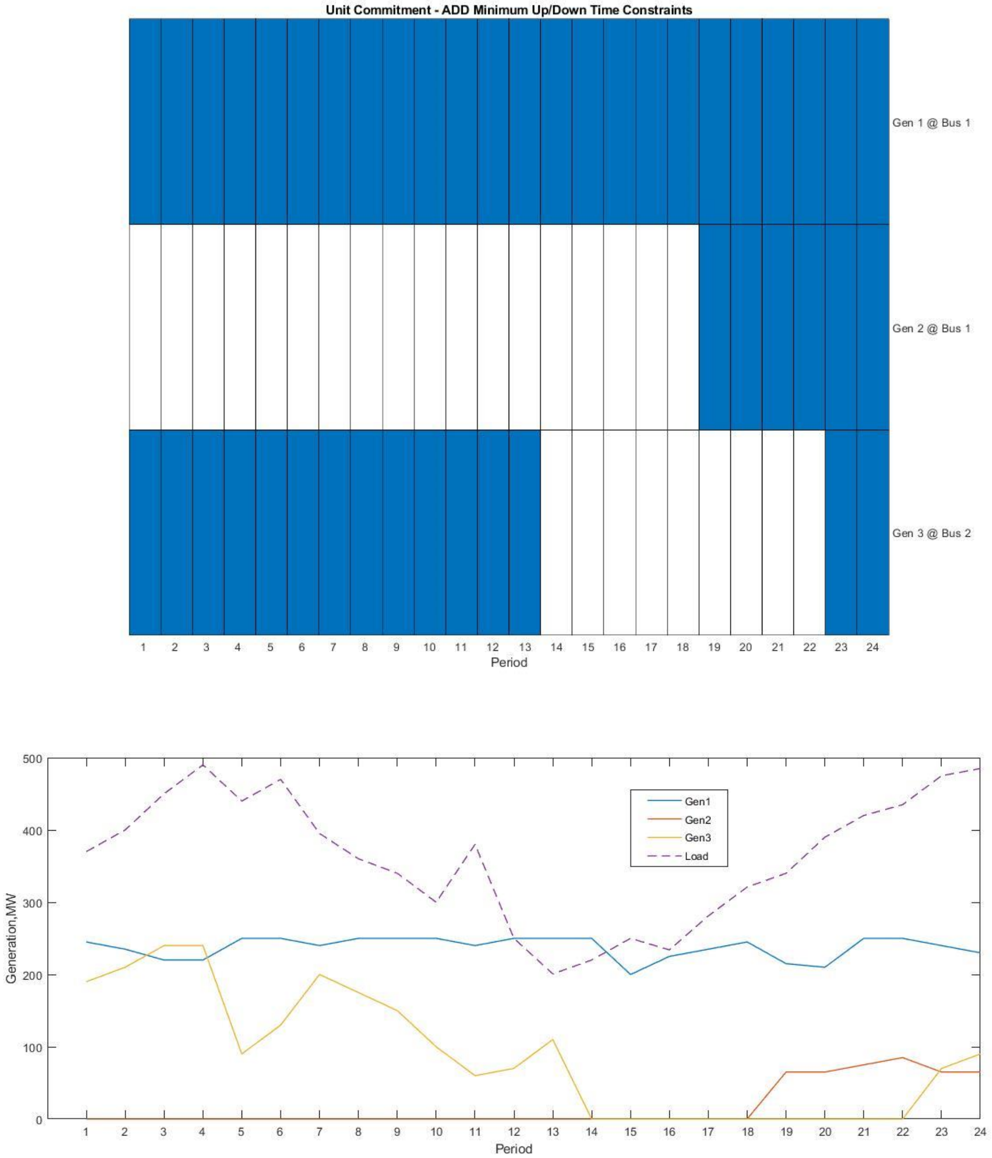


Figure: 5.9 Graph showing scheduling minimum up/down time constraints

The results obtained from the minimum uptime/minimum downtime are detailed in Table 5.23 consisting of 24 hours' time horizons for three bus systems. Table 5.24 describes the corresponding value of three generators that contain minimum up/downtime constraints.

Table 5.23 On/OFF State with addition of Minimum Up/Down Time Constraints

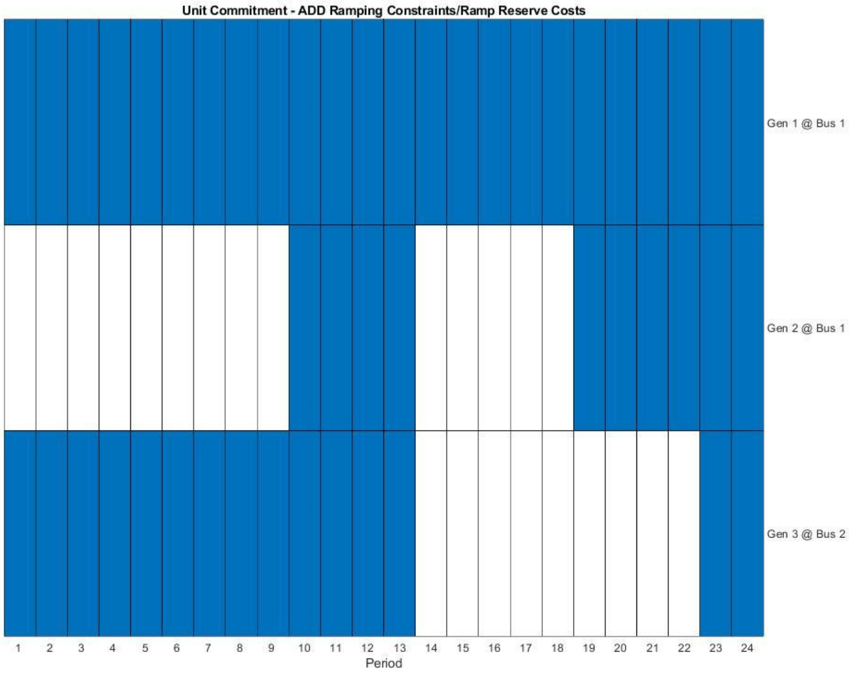
Gen	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1

Table 5.24 Generators Value with addition of Minimum Up/Down time constraints

Gen	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}
	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}	T_{20}	T_{21}	T_{22}	T_{23}	T_{24}
1	245	235	220	220	250	250	240	250	250	250	240	250
	250	250	200	225	235	245	215	210	250	250	240	230
2	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	65	65	45	85	125	135
3	190	210	240	240	90	130	200	175	150	100	60	70
	110	0	0	0	0	0	0	0	0	0	70	90

5.5.5. Scheduling of Generators with Ramping Constraints and Ramp Reserve Costs:

Figure 5.10 described the graphical information of scheduling of three buses, three generator systems including wind generator and storage unit when ramping constraints and ramp costs are added to the system.



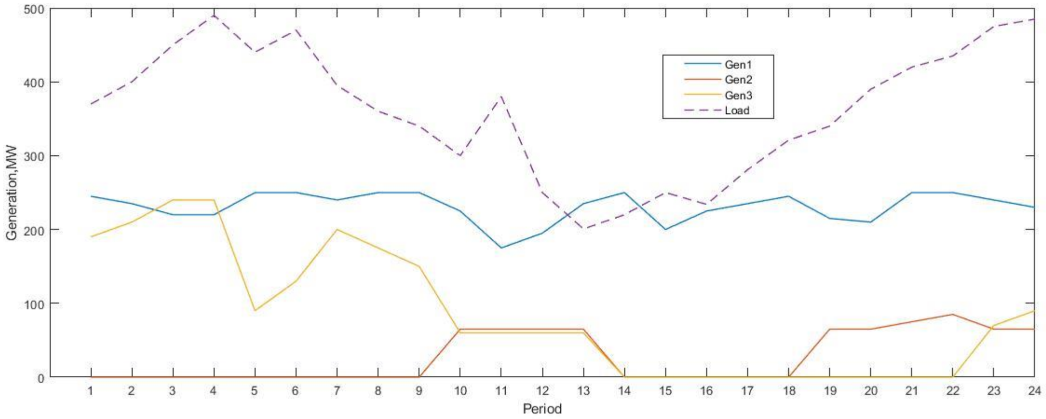


Figure: 5.10 Graph showing scheduling with ramping constraints and ramp reserve costs

The results obtained from the ramping constraints and ramp reserve costs are detailed in the Table 5.25 consists of 24 hours' time horizons for three bus systems and Table 5.26 describes the corresponding value of three generators contain ramp costs and ramping constraints.

Table 5.25 On/OFF State with ramping constraints and ramp reserve costs

Gen	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**	**T19**	**T20**	**T21**	**T22**	**T23**	**T24**
1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
2	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**1**	**1**	**1**
3	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**

Table 5.26 Generators value with ramping constraints/ramp reserve costs

Gen	T_1 T_{13}	T_2 T_{14}	T_3 T_{15}	T_4 T_{16}	T_5 T_{17}	T_6 T_{18}	T_7 T_{19}	T_8 T_{20}	T_9 T_{21}	T_{10} T_{22}	T_{11} T_{23}	T_{12} T_{24}
1	245 235	235 250	220 200	220 225	250 235	250 245	240 215	250 210	250 250	225 250	175 240	195 230
2	0 65	0 0	0 0	0 0	0 0	0 0	0 65	0 65	0 75	65 85	65 65	65 65
3	190 60	210 0	240 0	240 0	90 0	130 0	200 0	175 0	150 0	60 0	60 70	60 90

5.5.6. Scheduling of Generators with Addition of Storage Unit:

Figure 5.11 described the graphical information of scheduling of three buses, three generator systems including wind generators, and storage units when storage is added to the system.

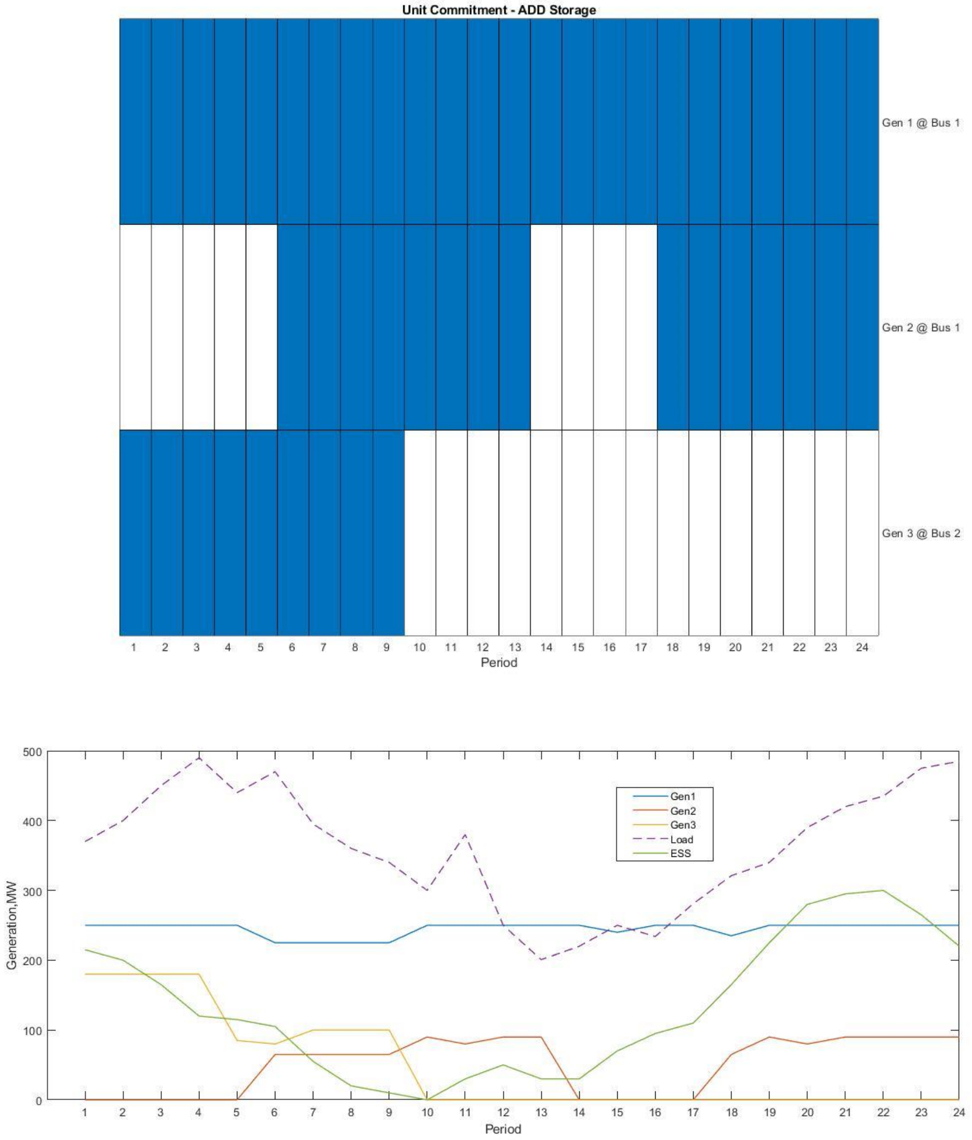


Figure: 5.11 Graph showing scheduling with addition of storage unit

The results obtained from the storage unit are detailed in Table 5.27 consisting of 24 hours' time horizons for three bus systems and Table 5.28 describes the corresponding value of three generators containing storage units.

Table 5.27 On/Off state with addition of storage unit

Gen	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24
1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
2	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
3	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 5.28 Generators value with addition storage unit

Gen	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}	T_{20}	T_{21}	T_{22}	T_{23}	T_{24}
1	250	250	250	250	250	225	225	225	225	250	250	250	250	250	240	250	250	235	250	250	250	250	250	250
2	0	0	0	0	0	65	65	65	65	90	80	90	90	0	0	0	0	65	90	80	90	90	90	90
3	180	180	180	180	85	80	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Chapter 6

Conclusion and Future Perspective

6.1 Conclusion

It is understood that the unit commitment results in minimum generation cost. The unit commitment problem involves the process of preparing a schedule for generating units at every hour interval, subjected to the system and operating constraints. This work proposed two algorithms, UC solution using *fmincon* in MATLAB and UC solution using GUROBI optimization algorithm. Both the algorithms based on mixed-integer linear programming have been studied on two test case systems. While *fmincon* may be used for smaller problems; GUROBI is efficient in handling large-scale UC problems. The results are obtained using two algorithms and their effectiveness has been shown while solving given unit commitment problems.

6.2 Future Perspective

This work has been carried out on three bus systems, in the future, it can be standard to IEEE test case having more buses *i.e.* 30 bus, 39 bus, 118 bus.

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