MODERN TRANSMISSION EXPANSION PLANNING CONSIDERING RENEWABLE RESOURCES

BY

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To my beloved parents and mentors

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In the name of Allah, the most Gracious and ever-Merciful. All praise is due to Allah; we praise Him, seek His help and ask for forgiveness. Peace be upon the Prophet Muhammad his family, his companions and all those who follow him until the Day of Judgment.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

TEP	:	Transmission Expansion Planning
RES	:	Renewable Energy Sources
PEM	:	Point Estimation Method
HVDC	:	High Voltage Direct Current
TSO	:	Transmission System Operator
SW	:	Social Welfare
CWE	:	Curtailed Wind Energy
OPF	:	Optimal Power Flow
ENS	:	Energy Not Supplied
HVAC	:	High Voltage Alternating Current
DE	:	Differential Evolution
EA	:	Evolutionary Algorithm

ABSTRACT

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With an increasing demand for electric power, there is a need for construction of new transmission lines to guarantee a reliable and economic operation. The aim of this research is to demonstrate the methodology based on the deterministic concept by considering the technical and market economic regulation principles. In this research work both single and multi-objective functions are considered. Single objective function called social welfare is maximized. For multi-objective functions which are investment cost and wind curtailment optimum location of transmission line is found by considering intermittent nature of wind and variable load data. The multi-objective functions are solved using non-dominated sorted differential evolution algorithm. To obtain the desired results based on decision maker preference fuzzy logic approach is utilized. Effect of the uncertainty in wind and load forecast is performed. The results obtained show the variation in costs based on the variation in random error percentage. The proposed methodology is illustrated on different IEEE bus systems.

ملخص الرسالة

الاسم الكامل: كامران محمد ظافر

أطروحة العنوان: حديث التخطيط نقل التوسع بما في ذلك المصادر المتجددة

كبير الميدانالكهربائية: الهندسة

تاريخ الدرجة العلمية: ديسمبر **2016**

ع تزايد الطلب على الطاقة الكهربائية، وهناك حاجة لبناء خطوط نقل جديدة لضمان عملية موثوقة واقتصادية والهدف من هذا البحث هو للتدليل على منهجية تقوم على مفهوم حتمية من خلال النظر في المبادئ الفنية وتنظيم اقتصاد السوق. في هذا البحث تعتبر وظائف على حد سواء واحد ومتعدد الأهداف. إلى أقصى حد ممكن وظيفة موضوعية واحدة تسمى الرعاية الاجتماعية. لوظائف متعددة الهدف والتي وجدت التكلفة الاستثمارية وتقليص الرياح المكان الأمثل لخطوط النقل من خلال النظر في طبيعة متقطعة من تحميل البيانات المتغيرة الرياح و. تحل وظائف متعددة موضوعية استخدام غير التي يهيمن عليها التفاضلية فرزها تطور الخوارزمية. للحصول على النتائج المرجوة على أساس يستخدم صانع القرار تفضيل نهج المنطق الضبابي. يتم تنفيذ تأثير حالة عدم اليقين في توقعات الرياح والحمولة. وأظهرت النتائج التي تم الحصول عليها من الاختلاف في التكاليف على أساس الاختلاف في نسبة خطأ عشوائية. ويتضح المنهجية المقترحة على أنظمة حافلة IEEE مختلفة.

CHAPTER 1

INTRODUCTION

Transmission Expansion Planning (TEP) has received extensive attention in recent years and a large amount of research work has been conducted and proposed with the purpose of simplifying the problem and alleviating computational burden.

The purpose of transmission expansion planning is to find out where, when, and how many transmission elements should be constructed in the network to meet the future demand [1]. Nevertheless, transmission expansion planning is a large-scale, mixed integer, nonlinear and non-convex optimization problem [2].

The objective of the TEP is to minimize the cost of constructing new lines or operational cost of the equipment over a planning horizon. The constraint relationship ensure that system is modeled while satisfying or complying to all power flow relationships and stability.

Transmission expansion planning problem is linked with different type of uncertainties such as load, price, market, sources and others. Due to its complexity, TEP problems are difficult to solve. Different technical, economical and society oriented issues should be considered in TEP according to the interests of system operators such as generation capacity of resources and the availability of a transmission line.

Recently the integration of renewable energy resources in power system has increased because of their environmental, social and economic benefits. Due to irregular or discontinuous nature of renewable sources, it can cause a power fluctuation on transmission lines when connected to power system resulting in redundant investments. New techniques shall be proposed to find economically justified transmission investments while continuing to increase the renewable energy usage.

Different multi-objective TEP methodologies have been proposed in the past to minimize investment, risk and congestion cost but the introduction of renewable energy resources has added a complex dimension[3].In recent years, many transmission expansion planning formulations attempt to address the issues related to presence of wind turbines.

TEP problem has been formulated using non-linear and linear programming respectively to refrain from involving integer variables[4-5]. A number of papers formulate TEP as a mixed integer linear problem [6-9], where nonlinear constraints are replaced by equivalent linear constraints. Although the AC model describes power system most accurately, it can always lead to a large and complicated nonlinear programming requirement. As a result, on basis of certain assumptions DC model, ignoring reactive components, is widely adopted to reduce the size of TEP [7-10].

In recent years, with more attention given to the non-linear and non-convex property of TEP, a diversity of heuristic techniques are introduced to solve TEP such as particle swarm optimization [11], genetic algorithm [12], and chaos optimal algorithm [13]. Although these heuristic algorithms are able to provide a rational and feasible solution without much computational time, it is obvious that that an optimal solution cannot be ensured because no mathematical indicator is involved in heuristic methods when the solution is generated.

On account of these challenges, it is not realistic to formulate and calculate TEP directly according to its own natural properties. As a consequence, it is essential and significant to simplify a TEP problem so as to achieve relatively accurate results in an acceptable computation time.

1.1 Motivation

Electrical energy plays an increasingly vital role in this rapidly growing society. People rely heavily on a power supply almost in every aspect of a daily life. The electric power system should have the ability to supply enough electricity reliably and steadily.

In order to meet this requirement, it seems that the problem can be tackled merely by increasing the capacity of the existing generation units or building a new power plant and transmission elements. However, extra generation will correspondingly give a rise to the power flow on transmission lines and hence may lead to overloading. This would put the power system at a risk since overload on transmission lines could subsequently result in more transmission losses, overheating and even burning out. In order to transfer the added electric power, a rational transmission expansion planning is highly required.

1.2 Thesis Objectives

The general objective of the work is to develop transmission planning methodology with long term focus on technical and economic regulation principles. The specific objectives are:

1. To maximize the social welfare by minimizing the investment cost.
2. To find out the optimum location of transmission lines in the network with and Without load curtailment.
3. To find the effects of error or uncertainty in wind speed and load forecast on Transmission Expansion Planning.
4. To apply the decision making approach for determining the final optimum solution.

1.3 Organization of the Thesis

Chapter 2 includes the comprehensive review of a literature which covers the work done in the past on transmission expansion planning, how the work was accomplished and what were the assumptions or shortcomings. It also reviews different techniques and methods utilized to solve the optimization problems for transmission expansion planning.

Chapter 3 is dedicated to problem formulation and algorithm. Formulations for maximizing the social welfare and minimizing the investment cost, load and wind curtailment along with algorithms and solution techniques are defined.

Chapter 4 is related to the simulation results and discussion. In section 4.1.1 results for different scenarios of maximizing the social welfare are presented and discussed.

Similarly in section 4.2.1 results for finding optimal placement of transmission line for multi-objective functions are discussed. Section 4.2.2 is associated with the results for decision making based on the preference. Section 4.2.3 represents the results for the effect of different percentages of error/uncertainty in wind forecast. Section 4.2.4 represents the results for the effect of different percentages of error/uncertainty in load forecast. Section 4.2.5 displays the effect of combined uncertainty in load demand and wind speed forecast on the objective function values.

Chapter 5 concludes the outcome of the work.

The thesis also contains the list of references and relevant appendices.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The transmission expansion planning (TEP) problem has been addressed in different ways by using various solution methods, objective functions and constraints. Although TEP is a general phenomenon, the concrete formulations and computational algorithms can be extraordinarily distinctive from each other depending on the practical issues and interests of operators.

Zhang, H, Heydt, G.T., Vittal, V [14] solve both network loss and investment costs of transmission lines optimization algorithm. In addition, Jing Qiu , Zhao and Yan [15] propose a risk based approach to multi-stage probabilistic transmission expansion planning. The probabilistic load curtailment degree is quantified by a capped load curtailment probability, which is incorporated into a multi-stage TEP model. Moreover, the system dynamic performance including security and stability is also realistically considered. It also assists network planners in making a trade-off between the most flexible and cost effective planning schemes.

Transmission planning under generation uncertainty was developed by Goran and Ioannis in [16].The potential for non-conventional assets to accommodate new resources of power generation is investigated and their benefits are analyzed.

To handle the intermittent characteristics of renewable energy resources which can affect the TEP, Rongrit and Surachi presented a new problem formulation and solution procedure[17]. Moreover, a new parameter called “Renewable Energy Leak” was introduced to evaluate the unutilized or leaked renewable energy in TEP.

Due to the non-convex nature of AC power flow, the majority of TEP work is performed on DC power flow. A novel based TEP using AC power flow has also been developed [18].Furthermore, second order programming and the conic relaxation method were formulated to solve the optimal power flow and AC power flow equations respectively. This paper has considered both the voltage limit and network loss. The simulation results show the effectiveness of the conic relaxation of AC power flow while additionally comparing the solution with DC power flow.

TEP for multi-area power system was proposed by Amin and Mohsen in reference [19].Using the local characteristics of an area, TEP and power flow equations are formulated. Next, a decision making algorithm is employed to handle local TEP problems and find an overall solution to the power system.

Multi-objective functions for TEP using different constraints and Genetic Algorithm was optimized in [20]. These constraints include power flow node balance, power flow limit, generator outage, transmission line outage, load uncertainty, power generation limit and bus voltage phase angle limit.

Only a few transmission expansion planning studies produced have dealt with contingency conditions due to its complexity. Although any plan for a transmission extension should be robust enough to handle both normal and abnormal conditions of line outage. It is a vital evaluation to maintain a reliable and stable operation. Also, TEP methodology is proposed to minimize investment cost and curtailed wind energy by considering both normal and N-1 contingency conditions in reference [21].

A new hybrid DEA(Distribution of Estimation algorithm)/DE algorithm approach was developed by Wenxia Liu [22] to improve the speed of simulation and precision of solving approach. This paper also considered the smart grids and security constraints for TEP incorporating wind power. However, the obtained algorithm based on the static TEP model under deterministic condition is not suitable for uncertain factors in the future.

J.M. Barroso used a hybrid algorithm for TEP[23]. Objective functions were minimization of investment, system operation and load shedding costs. However, this method didn’t consider the integration of renewable energy. A stochastic approach was used to consider the uncertain behavior of solar and wind generation. An efficient probabilistic method called the Point Estimation Method (PEM) was applied for modeling the uncertainties linked with wind and solar power generation[24].

Jabr proposed a methodology to minimize load and wind curtailments in order to find out the optimum location of the transmission line without considering hourly data [25].Moreover, when it comes to computation algorithms, a variety of methods have been applied and developed. Branch and bound algorithm were proposed to directly deal with mixed integer non-linear problem[25].

Different solution techniques used are Genetic Algorithm, Particle Swarm Optimization and Differential Evolution[26]-[28].Due to its efficiency and effectiveness, Differential evolution has gained more attention in recent times. The stochastic technique is needed for considering the uncertain nature of renewable energy sources(RES).The most common approaches used in mathematical optimization are linear programming, non-linear programming, dynamic programming and mixed integer programming [29].

The main mathematical optimization approaches used for TEP include the transportation model, the DC model, the AC model or a combination of all three. The AC model is more accurate compared to other two as it considers reactive power and power losses but this model is computationally complex due to non-linear and non-convex formulation. Moreover, the DC and transportation model are less complicated to solve and ensure an optimum solution due to linearized system constraints.

Uncertainty in wind energy and load demand on the transmission network have been probed[30]. Probabilistic methods, Fuzzy decision making and a Monte Carlo Simulation have been used to cater for these kinds of uncertainties in TEP problem.

Some works proposed a probabilistic approach for TEP with wind power integration but without considering the risk involved in transmission investments [31].In recent years, more research has been conducted on addressing the financial aspects of a transmission lines which is a vital factor for private investments.

There are different techniques to model uncertainty in wind such as time series model[32], data mining algorithm [33], clustering approach [34] or the Weibull

Probability density function. Considering wind uncertainty in TEP is vital, and without it, results can be unsuitable under certain circumstances.

In the latest research, more work has been developed on HVDC links due to the reduction in investment cost and power losses as compared to HVAC links. Even though some simplifications and computational techniques have been applied, it is still a difficult task to solve the TEP problem when it comes to a large-scale power system and when many aspects have to be considered.

Some of the optimization studies done in the past don't consider the cost function of generators in their formulations .However, for better transmission expansion planning operational cost should be considered.

Many research works and publications have addressed the TEP using various techniques. Few of the publications had addressed the TEP problem under market constraints and the joint participation of renewable energy.

2.2 Solution Methods for Solving TEP Problem

As a result of research performed on TEP, solution methods can be categorized into mathematical optimization, heuristics and meta-heuristics approaches.

The mathematical optimization solution method uses a mathematical model technique for TEP problem. This method finds an optimum solution by working on the mathematical formulation of a problem which is given by an objective function and set of constraints.

This method has an advantage that we can obtain accurate optimal solutions and fast convergence. Constraints used are limited and refer to technical, reliability and economic issues. The most common approaches used in mathematical optimization are linear programming, non-linear programming, dynamic programming and mixed integer programming.

Another method of solving a TEP problem is by using heuristics. Heuristic methods as name implies are creative methods based on human experience. The experience is used for defining a set of rules to be used for defining a step by step solution for the TEP problem. Heuristic methods have advantage that computational time and convergence rate are faster as compared to the mathematical models. Furthermore, they provide good solution but not proven to be optimal. Meta-heuristic methods combine heuristics with mathematical optimization. These algorithms are inspired from theory of evolution (such as genetic algorithm, differential evolution), from animal collective behavior (Ant Colony Optimization, Particle Swarm Optimization), from processes and phenomena(Simulated Annealing)[35]-[36].

An evolutionary algorithm (EA) technique is easy to implement, doesn't require a derivative information and can monitor a large number of optimal solutions. The disadvantage of this approach is that it is not reliable as it cannot guarantee achieving a global optimal solution.

2.3 Transmission Planning Considerations

Transmission planning can be classified as static or dynamic based on the task. In case of a static planning, planner looks for the optimal value for single time period focusing on the final optimal state of a network however, in case of dynamic planning, planner consideration is on the multiple years for optimal development strategy.

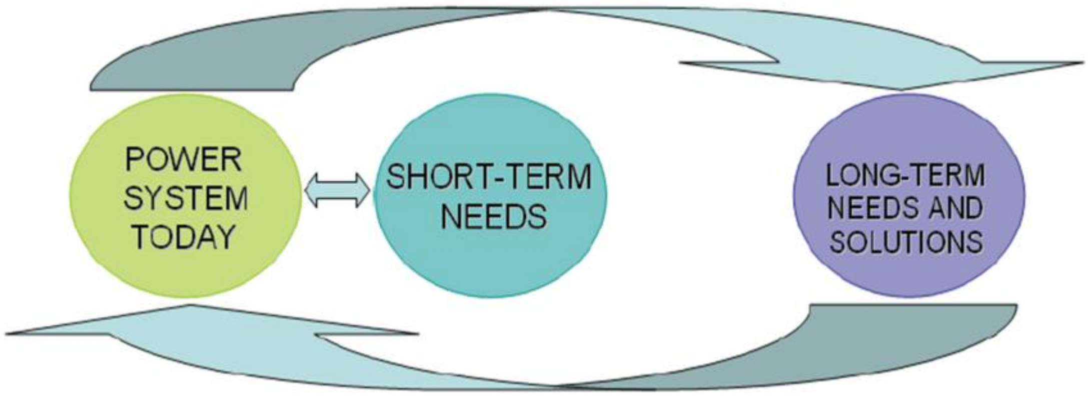

Figure 2.1 Planning Horizons

The optimal development strategy focuses on system analyses and dynamic multi step optimization methods in order to look for the interconnection of system elements over time. During network analysis, various parameters must be investigated during the development process.

The basics of power system development approach are established from following main factors[37]:

- Decision making for advanced stage in uncertain condition only for nearest time period of 2-5 years.
- Estimation period shall correspond to the average life cycle period, approximately within 20 to 30 years.

This thesis takes into an account both single and multi-objective functions. These are the cost function of generation together with the integration of renewable sources .

CHAPTER 3

PROBLEM FORMULATION AND ALGORITHMS

This chapter defines the problem using mathematical formulation and explains the algorithm utilized to find the optimum solution. Firstly, single objective function is defined which is a Social Welfare. For short term transmission expansion planning including the effect of discontinuous or periodic generation, market conditions and subject to initial information availability, AC optimal power flow model can be used. Due to complex dimensions of the optimization task, network and uncertainty conditions appropriate method mostly utilized is DC optimal power flow. While using DC network assumptions, the complex OPF problem is simplified to a quadratic program with linear constraints by doing number of approximations. This is usually a technique considered for long term TEP.

3.1 Single Objective Function

The objective function in equation3.1 represents the social welfare. The social welfare is expressed as aggregated utility demand bid function minus generation cost function. The expression in 3.2 represents the cost of power generation[38].

The aim is to maximize the social welfare and to minimize the cost of production[41].

$$\max F(T,g) = \max_{g \in \{G\}} \sum_{t=1}^{T} (SW(t, e(t)) - IC(t, e(t))$$

(3.1)

$$CG_g = a_g PG_g^2 + b_g PG_g + c_g \tag{3.2}$$

where

t: Development step serial number

T: Number of development steps in a period

SW: Social Welfare criteria in development step t

IC: Investment cost in development step t

g: Development process

G: Set of development plans

a_g, b_g, c_g = Coefficient of generator costs

Subject to,

$$-_{ref} \le - \le -_{ref}$$

$$V_{\min} < \mathrm{V} < \mathrm{V}_{\max}$$

$$\mathrm{P}_{g\min} < \mathrm{P}_g < \mathrm{P}_{g\max}$$

$$Q_{g\ \min} \angle Q_g \angle Q_{g\ \max}$$

$$0 < \mathrm{P}_{\mathrm{d}}^{load} < \mathrm{P}_{\mathrm{d}}^{demand}$$

$$0 \le Q_L \le Q_{L\ \max}$$

$V_{\min}, V_{\max}$ = Upper and lower limit on Bus voltage magnitudes

The constraints include reference bus angle, upper and lower limits on all bus voltage magnitudes, real and reactive power generator and load.

Social welfare can also be described by Figure 3.1 which shows that consumer surplus

Plus supplier's profit is equal to social welfare. Social welfare is maximum when Consumer surplus is equal to supplier's profit. If consumer surplus is smaller and supplier's profit is larger then social welfare is smaller. Similarly, if consumer surplus is higher and supplier's profit is smaller even then social welfare is smaller.

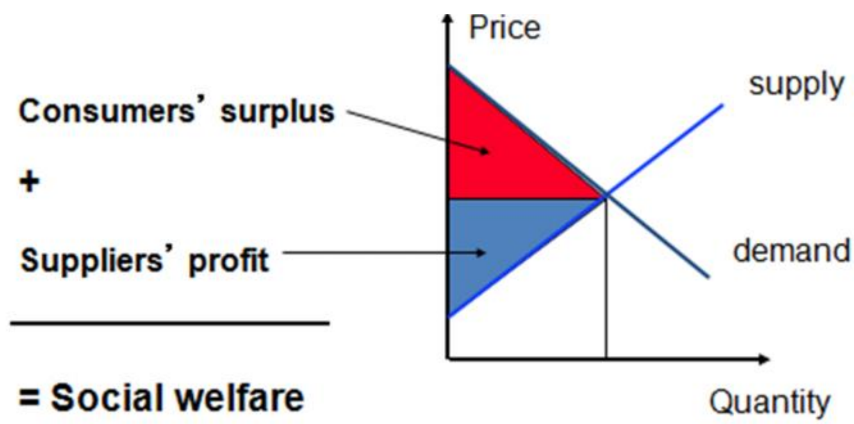

Figure 3.1 Social Welfare

The algorithm used for maximizing the social welfare is shown in Figure 3.2

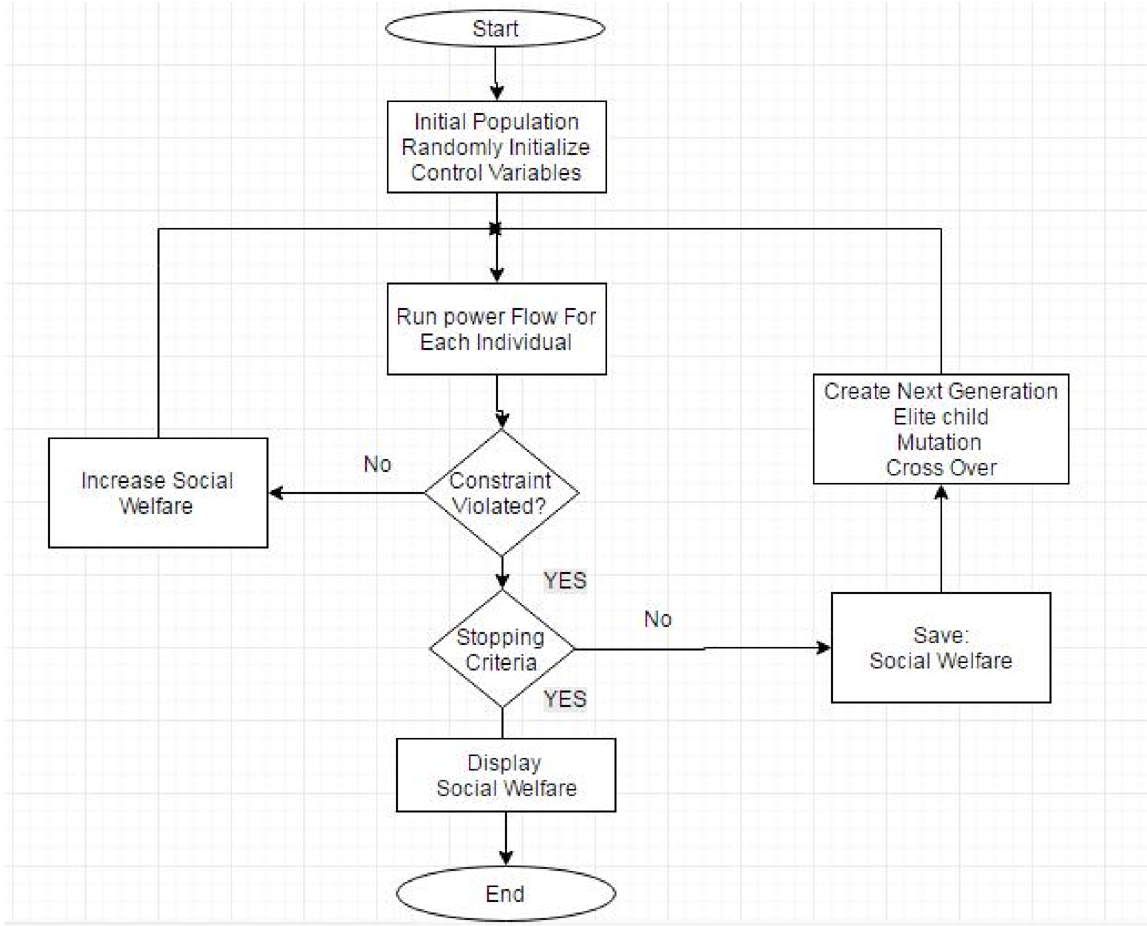

Figure 3.2 Algorithm for Maximizing Social Welfare

Initial population of control variable which in this case is Social Welfare is randomly generated. For all random combination of control variable power flow is run and constraints are checked. If no constraint is violated SW is increased until any one of the constraints is violated. Stopping criteria in this algorithm is the maximum number of generations. Stopping criteria is checked, if not met, best value of SW is saved and next generation is created. The process is repeated for next generation and it continues until stopping criteria is met.

In the following section multi-objective functions using mathematical formulations and solution technique are defined. One of the objective function considered is sum of investment cost plus load curtailment and other is wind curtailment. To obtain the values of both wind and load curtailment DC power flow equation based OPF is formed and solved using a optimization technique. Non-dominated sorting differential algorithm approach is applied to cater non-linear nature of multi-objective problem. The proposed methodology is composed of following stages:

- Hourly processing of variable load and wind data.
- Optimization framework to find the location of optimal investment in a transmission network.
- Decision making approach using Fuzzy logic is implemented on obtained non-dominated solutions by taking into consideration different decision maker preferences.
- To find the effect of uncertainty in wind and load forecast.

3.2 Multi-objective Functions

The objective function in expression 3.3 represents the sum of investment cost and penalty for energy not supplied which in actual is load curtailment. The objective function in 3.4 represents the sum of curtailed wind energy in case of wind turbine.

Curtailed wind energy is compensated by the production cost of a generation. The difference between demand and supplied power to the load means load curtailment and the difference between wind power capacity and dispatched wind power defines wind curtailment[39].

The aim is to reduce the investment cost by using load and wind curtailments[42].

$$\min f_1 = \sum_{n \in N_{line}} C_n x_n + \sim \sum_{d \in N_{bus}} ENS_d \qquad (3.3)$$

$$\min f_2 = \sum_{w \in N_{WT}} CWE_W (P_{dr}, P_{wr}) \qquad (3.4)$$

Where,

C_n = Investment Cost
X_n = Length of T.L
CWE = Curtailed Wind Energy
ENS= Energy Not Supplied
N_{wt} = Number of wind turbines
N_{bus} = Number of buses in Power System
@ = Load Penalty factor = 10^6 \$/MWH
= Average production cost of generator = 200 \$/MWH

ENS and CWE values are calculated as a result of Optimum power flow which is given in equation 3.5. This is called as lower stage optimization and is used to calculate ENS and CWE values by performing OPF for different load and wind power over a period of time.

$$f_{OPF} = \sum_{g \in N_{gen}} (a_g P_g^2 + b_g P_g + c_g) - \sim \sum_{d \in N_{bus}} P^{load} \qquad (3.5)$$

Where,

$$P_{g\min} < P_g < P_{g\max}$$

$$0 < P_d^{load} < P_d^{demand}$$

$$-_d = 0 \;\; d \in Slackbus$$

The constraints consist of minimum and maximum active power generation, load demand and phase angle at buses.

Figure 3.3representsthe flow chart for optimization of Multi-objective functions to Minimize the investment cost and wind curtailment.

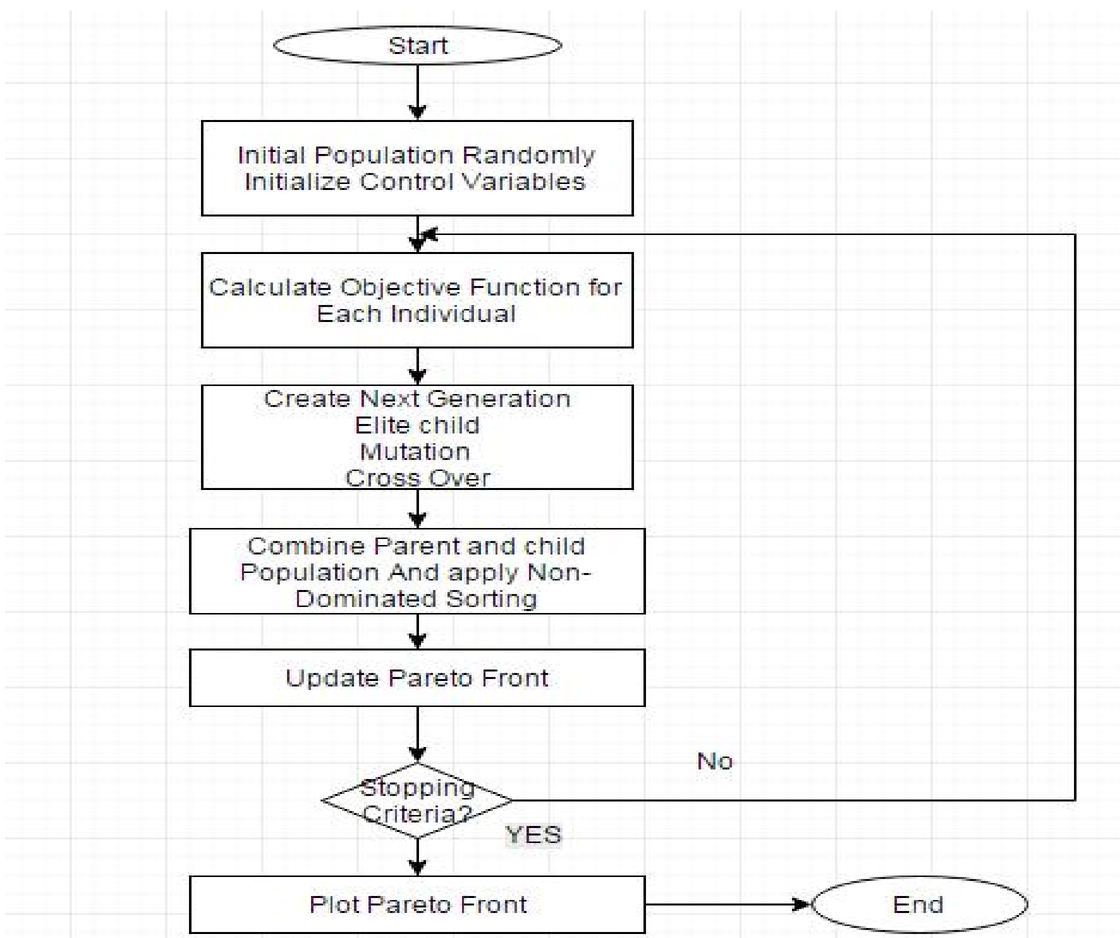

Figure 3.3 Algorithm for Multi-Objective Functions

Initial population of control variables, which in this case are, investment cost and Wind curtailment are generated. For all random combination of control variables all objective functions are evaluated. Using mutation and cross over, next generation is created and objective functions are evaluated for them. Both parents and offspring are combined to make an intermediate generation. All the members of intermediate generation are sorted out in ranks using non-dominated sorting. Top “N” candidates are selected to be the next generation. Stopping criteria is checked, if not met, again the objective function is evaluated for this new generation. The process continues until stopping criteria is met and petro front is plotted.

3.3 Methodology and Assumptions

1. This research focuses on a perspective development strategy, which is explained by methodology that can contribute to a future electric power supply.
2. Time horizon of 10 years is considered for which the net social welfare needs to be maximized.
3. Generators cost changes for every year such that gas price increase by 1% , coal price by 2% and load by 0.5% every year.
4. Results for single objective function called Social Welfare are obtained under four different scenarios:
    - Without Wind Power plant and investment in new line
    - Without Wind Power plant but with investment in new line
    - With Wind Power plant and without investment in new line
    - With Wind Power plant and investment in new line

5. Multi-objective TEP problem has been formulated to achieve trade-off between different objective functions.
6. In the first configuration, Optimum location of transmission line is found by achieving balance between investment cost and wind curtailment.
7. In the second configuration, load curtailment is added in investment cost and power flow limits are multiplied by 50% to obtain optimum solution.
8. Decision making approach is applied using Fuzzy logic on the optimum solutions to obtain the results based on the decision maker preference.
9. Effect of uncertainty in wind speed forecast is checked on the system for different percentages of negative and positive random error.
10. Effect of different percentages of negative and positive random error in load forecast is also applied.

3.4 Solution Method

The algorithm used consists of DC OPF model and was realized by simulation in Matlab software. Differential evolution which is a meta-heuristic approach is developed for simulation along with Fuzzy satisfying method.

3.4.1 Differential Evolution

Differential evolution is a population based optimization algorithm. Differential evolution is used to find feasible solutions for a problem having objective functions which are non-differentiable, non-linear and multi-dimensional. Different stages of this algorithm include initialization, mutation, re-combination and selection. Differential evolution makes very few assumptions of a given problem to be optimized and can search for a numerous different optimal solutions. The DE problem is optimized by maintaining a population of possible solutions and creating a new feasible solutions by combining existing solutions using different formulae. Finally, solution which best fits the conditions is obtained.

3.4.2 Fuzzy Logic Approach

Fuzzy logic is a form of many-valued logic in which truth values can be any real number between 0 and 1 unlike Boolean logic in which value of variable can be either zero or one. This technique has been utilized in many fields like artificial intelligence, neural networks, expert systems and control theory etc.

Fuzzy logic process:

1. Fuzzify all input values into fuzzy membership functions.
2. Execute all applicable rules in the rule base to compute the fuzzy output functions.
3. De-fuzzify the fuzzy output functions to get "crisp" output values.

Fuzzy logic starts and builds on a rule set by human beings. It is designed to solve problems in same manner as humans do: by taking into account all the available data and by making a best possible decision from the given input data. The fuzzy system converts the rule into mathematical equations which makes the job trivial for programmer and designer. It is a simple and flexible approach. It can handle non-linear function equations, imprecise and incomplete data.

A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1.

CHAPTER 4

SIMULATION RESULTS

4.1 Garver’s 6 Bus Sytem

To check and verify the performance of a proposed algorithm, different test cases with and without integration of wind power on single objective function have been studied using Garver’s 6 Bus system given in figure 4.1. Data for 6 bus system is given in Appendix A. This modified 6 bus system has 14 existing lines, 5 loads and 3 generators. There are 2 Coal generators installed at bus no. 3 and 6 of 370 and 610 MW respectively. One Gas generator is installed at bus no.1 of 160 MW. Wind generator of 100 MW is installed at bus no.2 later to check the effect of integration of renewable energy. The total base load of the system is 760 MW distributed between bus no.1 to 5.

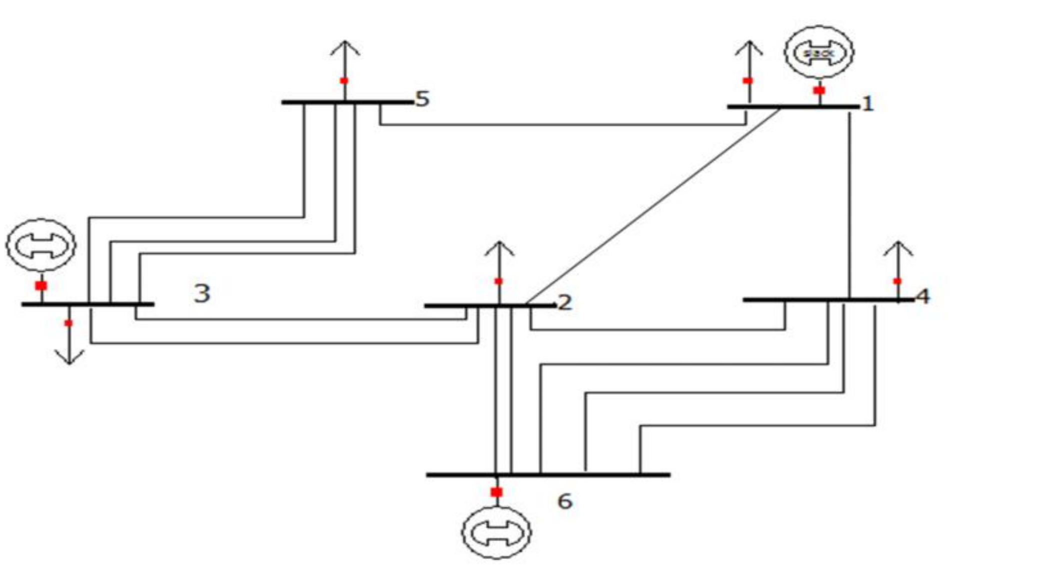

Figure 4.1 Garver’s 6 bus System

4.1.1 Social Welfare Maximization

Figure 4.2 represents the monthly wind power production which is calculated using equation 4.1 and based on the provided monthly wind variable speed. One wind turbine has the capacity to produce 6MW power. Seventeen wind turbines are used to produce 100 MW power. Wind power is installed at Bus no.2.

$$P_{avail} = \frac{1}{2} \circ A v^{3} c_{p} \tag{4.1}$$

r: Blade length= 40m

v: Wind Speed

ρ : Air Density = 1.23 kg/m^3

C_p: Power Coefficient = 0.59

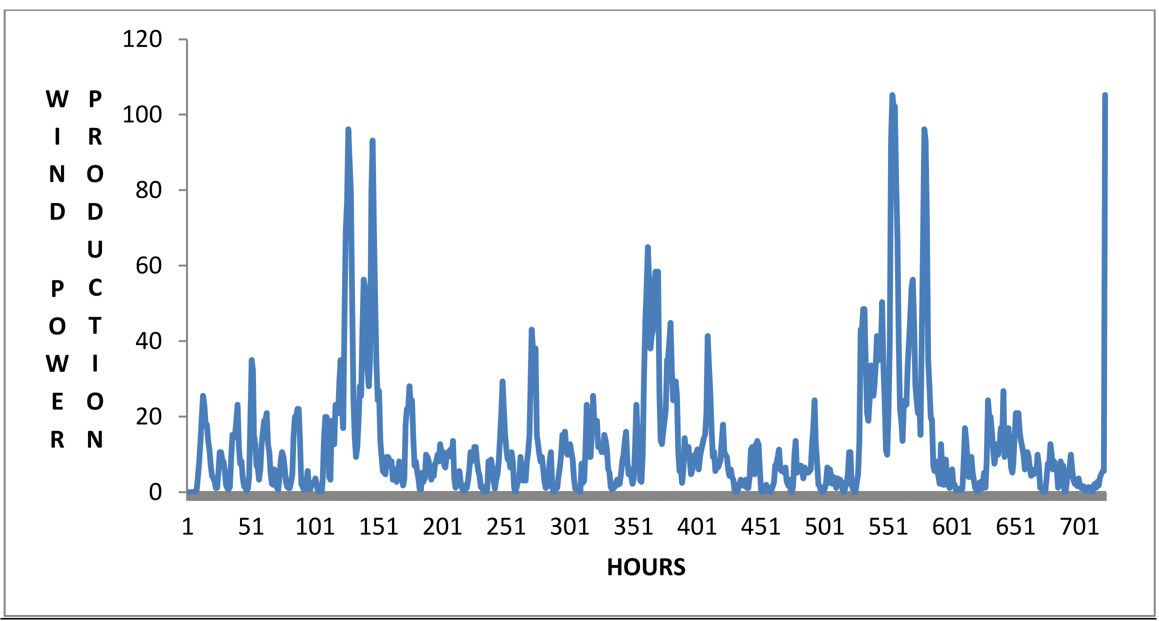

Figure 4.2 Wind Power Production Curve

Figure 4.3 represents the monthly load variation curve of the system load.

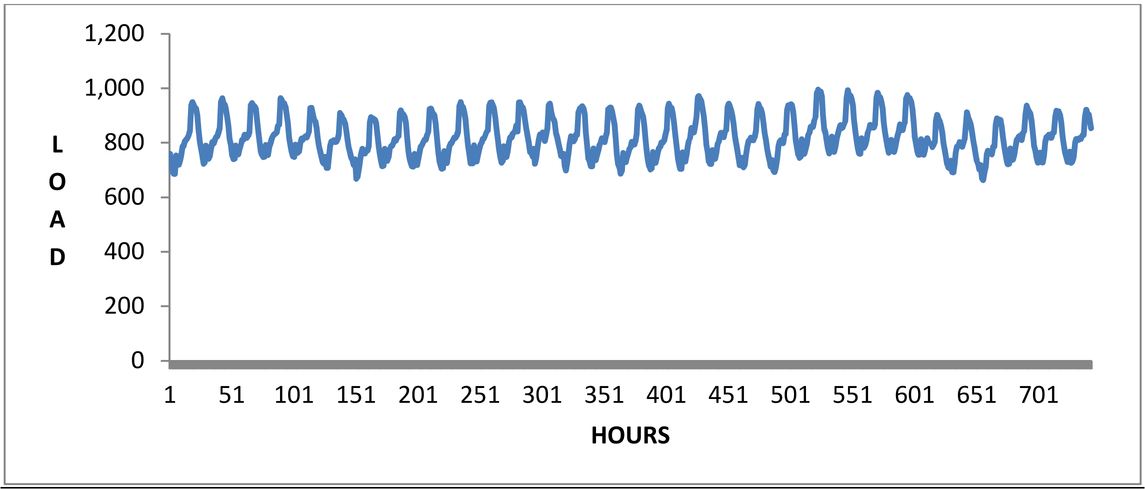

Figure 4.3 Load Variation Curve for 760 MW

Distribution of load for first 10 hours at different buses of the system is shown in table 4.1.

Table 4.1 Load Distribution for different Hours

Hours	Total Load MW	Bus no.1 MW	Bus no.2 MW	Bus no.3 MW	Bus no.4 MW	Bus no.5 MW
1	760	80	240	40	160	240
2	722	76	228	38	152	228
3	694	73	219	37	146	219
4	686	72	217	36	145	217
5	686	72	217	36	144	217
6	754	79	238	40	159	238
7	743	78	235	39	156	235
8	719	76	227	38	151	227
9	735	77	232	39	155	232
10	756	80	239	40	159	239

Figure 4.4 represents the one month social welfare curve without wind which shows that it is following the same trend as per the monthly load variation.

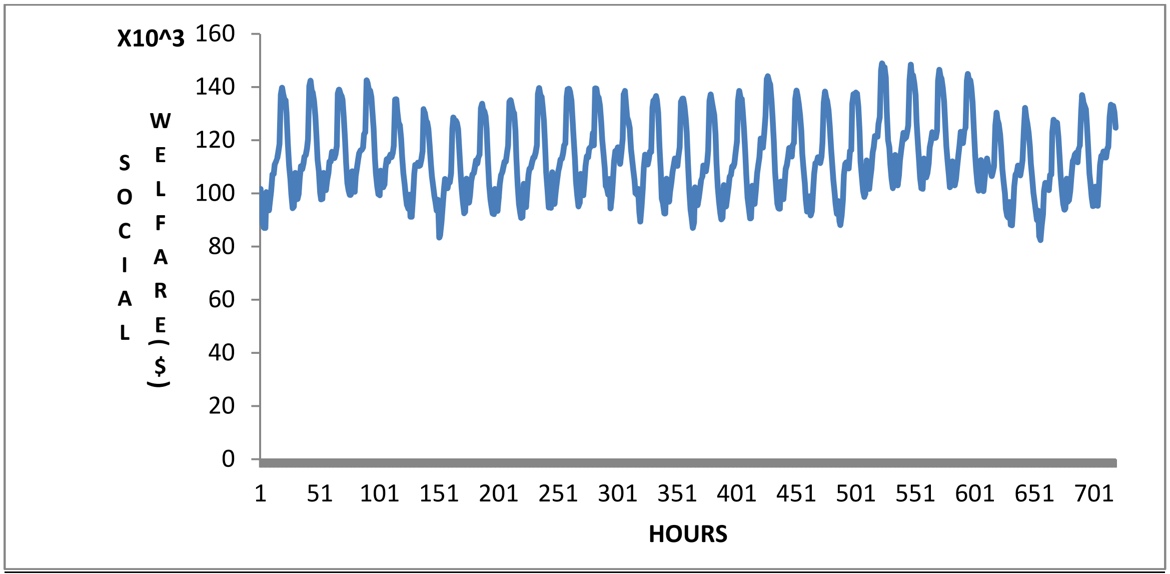

Figure 4.4Social Welfare Curve W/O Wind

Table 4.2 shows the results for social welfare without integration of a wind for two cases which are with and without investment in new line. The simulation results show that Social welfare decreases every year for the month of January due to increase in gas and coal prices. Social welfare also decreases due to increase in load from 760 MW up to 850 MW for the time duration of ten years. Results also show that with the investment in a new line between bus no.1 & 5 social welfare values almost remain same.

The integration of wind power increases the social welfare values compared to results without wind power and reduces cost of generation as shown in the results of Table 4.3. Even with integration of wind, the social welfare values are decreasing each year for the month of January due to increase in the gas, coal prices and load demand. With the investment in new line between bus no.1 & 5 social welfare values increase as compared to results without addition of new line. These social welfare values are even higher than those obtained without wind power integration.

The effect of renewable generation in the system can be considered as positive, improving the generation, transmission adequacy and system reliability.

Table 4.2 Social Welfare without Wind for Different Cases

Year	Without Investment SW (M$)	With Investment SW (M$)
	1 Month = January	1 Month = January
1	56.70	56.75
2	56.34	56.36
3	56.01	56.04
4	55.73	55.77
5	55.38	55.44
6	55.02	55.08
7	54.74	54.80
8	54.42	54.46
9	54.11	54.16

10	53.93	53.99

Table 4.3 Social Welfare with Wind for Different Cases

Year	Without Investment SW (M$)	With Investment SW (M$)
	1 Month =January	1 Month =January
1	61.95	61.98
2	61.72	61.78
3	61.38	61.39
4	61.11	61.16
5	60.84	60.87
6	60.51	60.58
7	60.23	60.29
8	59.98	60.04
9	59.71	59.74
10	59.38	59.46

In [41] Prime-dual interior Point method which applies Newton's method is used to obtain optimum power flow and for maximizing the social welfare. Table 4.4 shows the comparison of results of this work with results reported in [41] without wind.

Table 4.4 Comparison of results of this work with results in [41] W/O Wind

Time	Without Investment SW (M$)		With Investment SW (M$)	
Year	Results of This work	Results Reported in [41]	Results of This work	Results Reported in [41]
	1 Month = January	1 Month = January	1 Month = January	1 Month = January
1	56.70	50.63	56.75	50.65
2	56.34	50.40	56.36	50.43
3	56.01	50.15	56.04	50.20
4	55.73	49.90	55.77	49.90
5	55.38	49.62	55.44	49.66
6	55.02	49.20	55.08	49.23
7	54.74	48.95	54.80	48.95
8	54.42	48.72	54.46	48.73

9	54.11	48.36	54.16	48.36
10	53.93	48.0	53.99	48.06

It can be seen that social welfare values obtained without wind for the two cases using algorithm given in [41] are lower than those obtained with Differential Evolution algorithm used in this work.

Table 4.5represents the comparison of results of this work with results reported in [41] with wind.

Table 4.5 Comparison of results of this work with results in [41] with Wind

Time	Without Investment SW (M$)		With Investment SW (M$)	
Year	Results of This work	Results Reported in [41]	Results of This work	Results Reported in [41]
	1 Month = January	1 Month = January	1 Month = January	1 Month = January
1	61.95	56.80	61.98	56.83
2	61.72	56.59	61.78	56.62
3	61.38	56.38	61.39	56.40
4	61.11	56.10	61.16	56.11

5	60.84	55.84	60.87	55.84
6	60.51	55.67	60.58	55.69
7	60.23	55.42	60.29	55.44
8	59.98	55.12	60.04	55.13
9	59.71	54.83	59.74	54.84
10	59.38	54.52	59.46	54.55

It can be seen that social welfare values obtained with wind for two cases using Differential algorithm of this work are higher compared to those obtained using algorithm in [41].

4.2 IEEE 24 BUS SYSTEM

In order to verify the proposed method, multi-objective functions are tested using IEEE 24 bus system. Bus data is given in Appendix B. There are total 17 loads and 10 generators installed at different buses of the system. Total load of the system is 2850 MW and maximum generation is 3405 MW. Wind generator is installed at bus no.2 and 15.

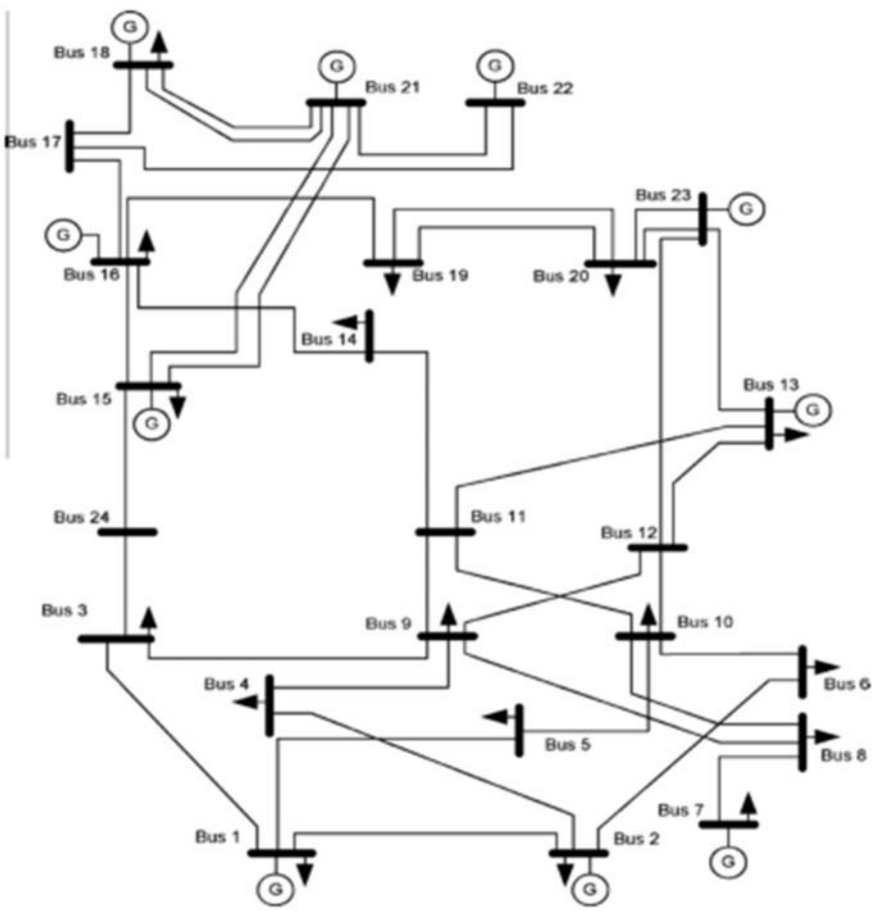

Figure 4.5 IEEE 24 Bus System

Figure 4.6 represents the monthly load variation curve of the system load.

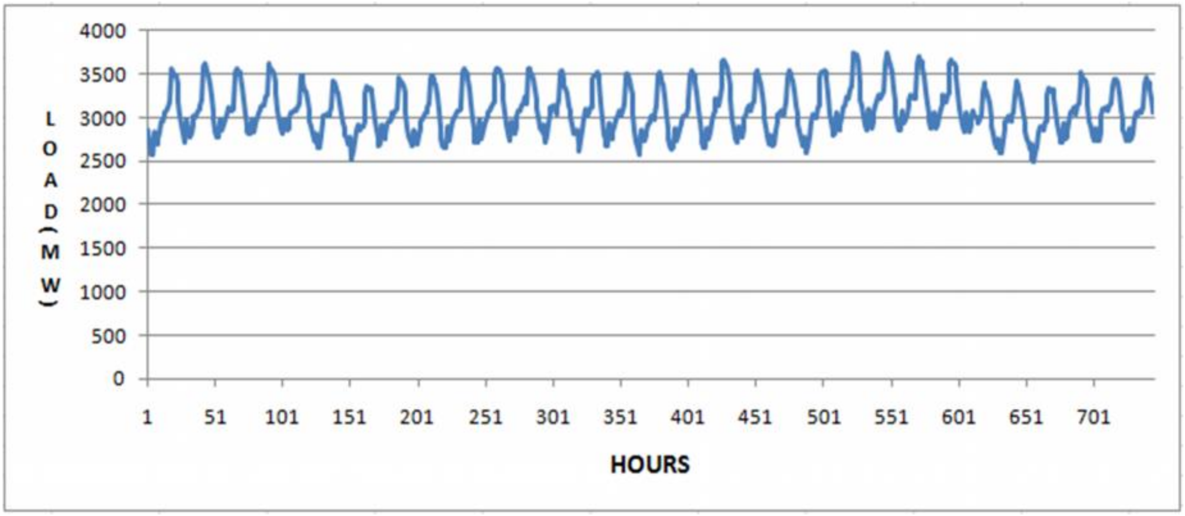

Figure 4.6 Load Variation Curve for 2850 MW

4.2.1 Optimal Placement of Transmission Line

Figure 4.7 is the representation of cost between multi-objective functions which are investment cost and curtailed wind energy. Optimum cost is obtained by adding objective functions values at a point where these are minimum. Wind power is installed at bus no.2 and 15.

Figure 4.8 is the representation of cost between multi-objective functions with inclusion of load curtailment. For this case power flow limits of transmission lines are multiplied by 0.5 to increase the stress on the lines. Values of both objective functions for different optimal solutions tend to increase with the inclusion of load curtailment. If value of one objective function increases then other decreases and vice versa. The optimal solution is the point where by adding the values of two objective functions a minimum total cost is obtained. Based on this total lowest cost, optimum location of transmission line in the network is found.

For first configuration optimum location of transmission line is found between bus no. 1 &5 meaning that in case of any future expansion in the network adding a line between bus no. 1 & 5 will cost less than optimum lowest cost of M$ 13.4. For second configuration optimum location of the line is between bus no.12 & 13 such that total installation cost will be less than the optimum total cost of M$ 27.

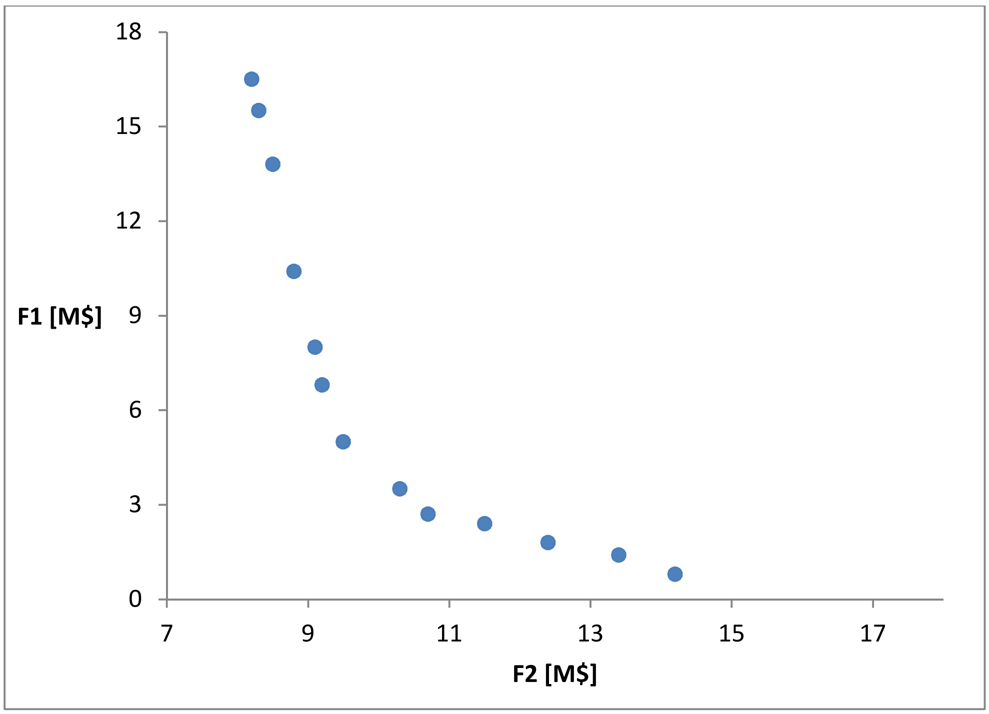

Figure 4.7 Multi-objective Functions Curve Without Load Curtailment

F1 [M$] = 2.7

F2 [M$] = 10.7

TOTAL = M$13.4

Location of Optimal Investment : 1-5

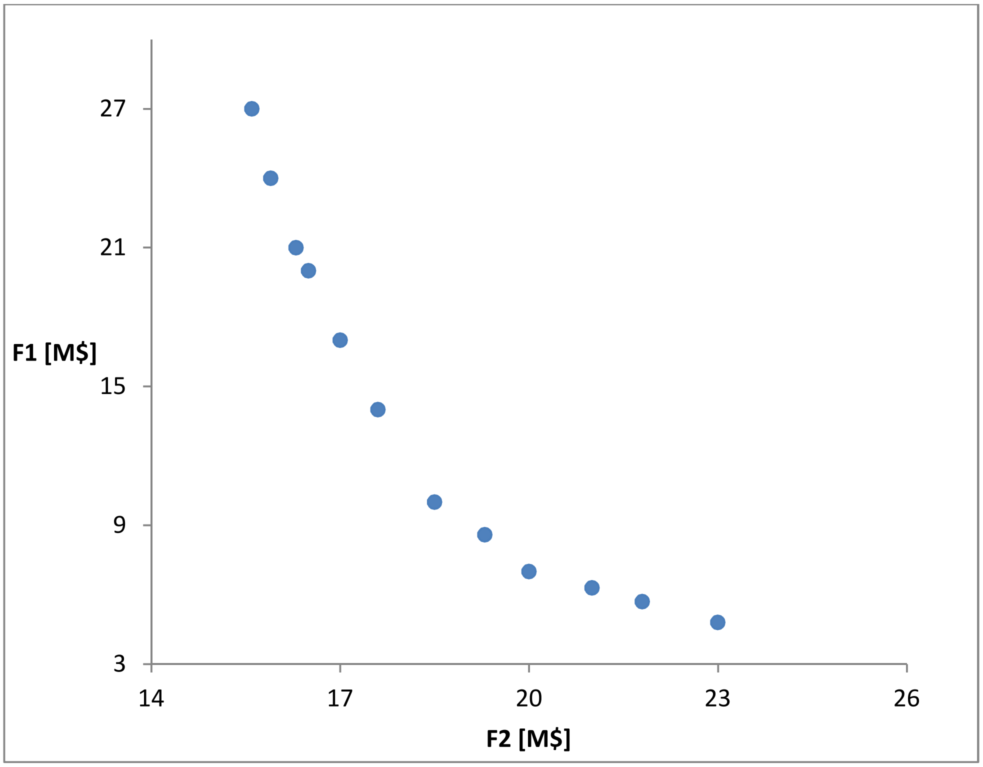

Figure 4.8 Multi-objective Functions Curve With Load Curtailment

F1 [M$] = 7.0

F2 [M$] = 20.0

TOTAL = M$ 27.0

Location of Optimal Investment : 12-13

In [42] a different approach called non-dominated sorting Genetic Algorithm is used to solve multi-objective functions. Table 4.6 shows the comparison of results for both configurations between this work and work proposed in [42].

Table 4.6 Comparison of Results of this work with in [42] for Optimal Placement

	Without Load Curtailment		With Load Curtailment	
Variables	Results Obtained in this Work	Results of Method in [42]	Results Obtained in this Work	Results of Method in [42]
Total Cost	13.4 M$	17.52 M$	27.0 M$	33.5 M$
Optimal Location of T.L	1-5	1-2	12-13	6-10

It can be seen that optimum cost using Differential Evolution Algorithm is lower than Genetic algorithm given in [42] for both configurations which are with and without load curtailment. It can be concluded that Differential Evolution is a more effective and efficient algorithm compared to Genetic algorithm.

4.2.2 Decision Making Based on Preference

Decision making procedure is applied to the obtained non-dominated solutions by considering different decision maker preferences. To achieve the desired results fuzzy satisfying approach is applied as given in equation 4.2. μ_i represents the membership function of the objective function i. f_i^{max} and f_i^{min} represent maximum and minimum value of objective function i among non-dominated solutions respectively. The value of the membership function is between zero and one. If μ_i is selected as one decision maker is fully satisfied with the results in terms of objective function i otherwise decision maker is not fully satisfied with the value of objective function i.

According to the results given in table 4.6, the number of lines to be added for $\mu_1 = 0.7$ and $\mu_2 = 1$ are more than others due to the reason that decision maker is not fully satisfied in terms of investment cost. For $\mu_1 = 1$ and $\mu_2 = 0.7$ decision maker is fully satisfied in terms of objective function 1 which is investment cost however more CWE is allowed. The objective functions values for final solutions are given in Figure 4.9. The objective function values are changing based on the chosen decision. CWE is minimum in case decision 2 is selected. On the other hand, more CWE is allowed to obtain less investment cost for decision 3.

$$\mu_{fi} = \begin{cases} 0 & f_i\left(X_j\right) > f_i^{max} \\ \frac{f_i^{max} - f_i\left(X_j\right)}{f_i^{max} - f_i^{min}} & f_i^{min} \leq f_i\left(X_j\right) \leq f_i^{max} \\ 1 & f_i\left(X_j\right) < f_i^{min} \end{cases} \quad (4.2)$$

The objective function values after final optimum solution for three different decisions are given in Figure 4.9.

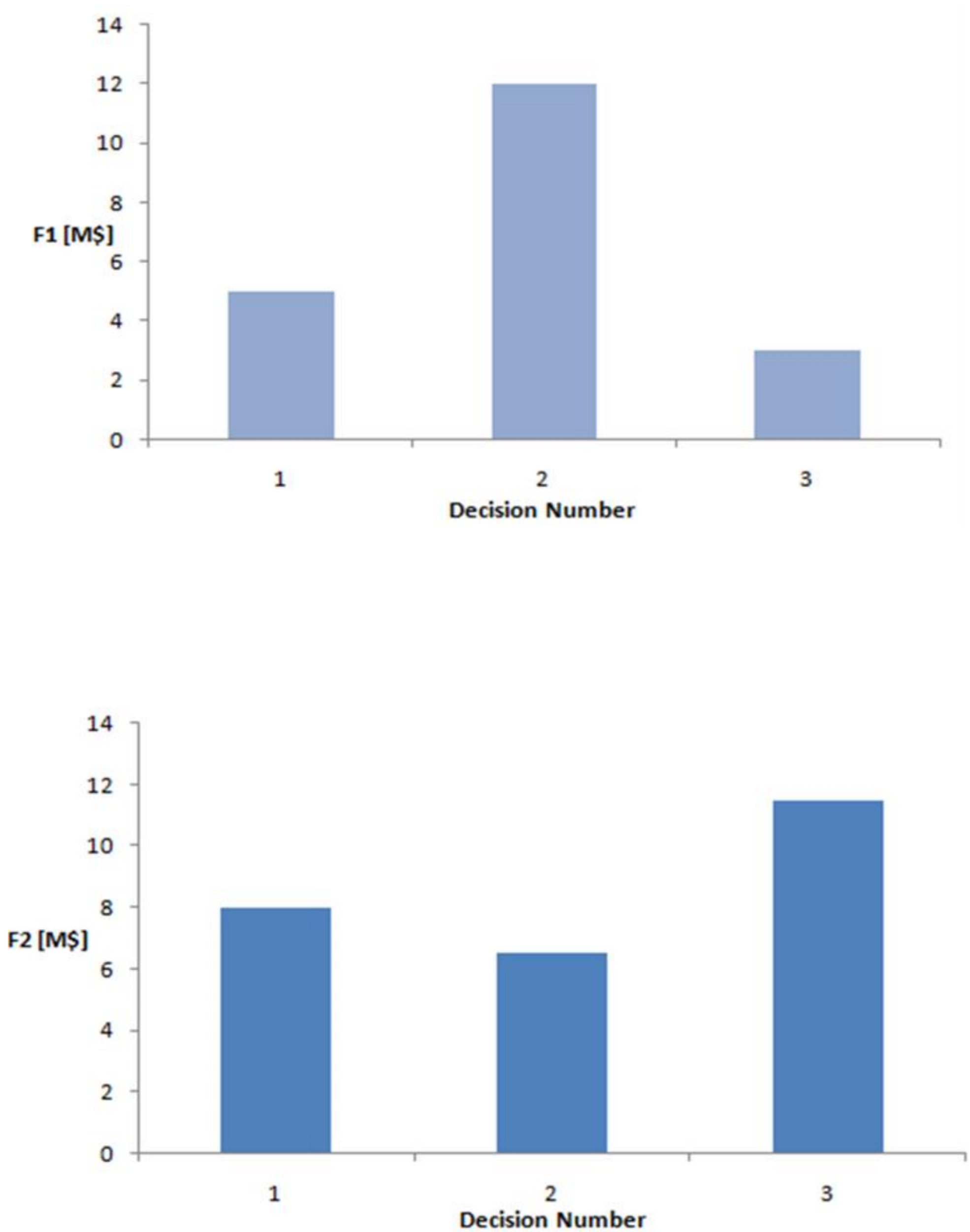

Figure 4.9 Objective Function Values

Table 4.7 represents the results obtained for optimal placement of line priority wise based on the line length. These results are also based on decision maker preference which is to minimize both objective functions cost or to minimize any one of the two objective functions cost.

Table 4.7 Location of Optimal Placement Based on Decision Maker Preference

Decision Number	Value of u1 & u2	Location of Optimal Investment In terms of Priority
1	$\mu_1 = 1$ $\mu_2 = 1$	1-2 6-10 15-16 5-10 10-12
2	$\mu_1 = 0.7$ $\mu_2 = 1$	1-2 6-10 15-16 5-10 3-9 1-3 10-12
3	$\mu_1 = 1$ $\mu_2 = 0.7$	1-2 1-5 6-10 10-12

4.2.3 Effect of Uncertainty/Error in Wind Forecast

I. With 15% Random Error

Figure 4.10 shows the variation in wind generation for time duration of one month with 15% positive random error at each hour.

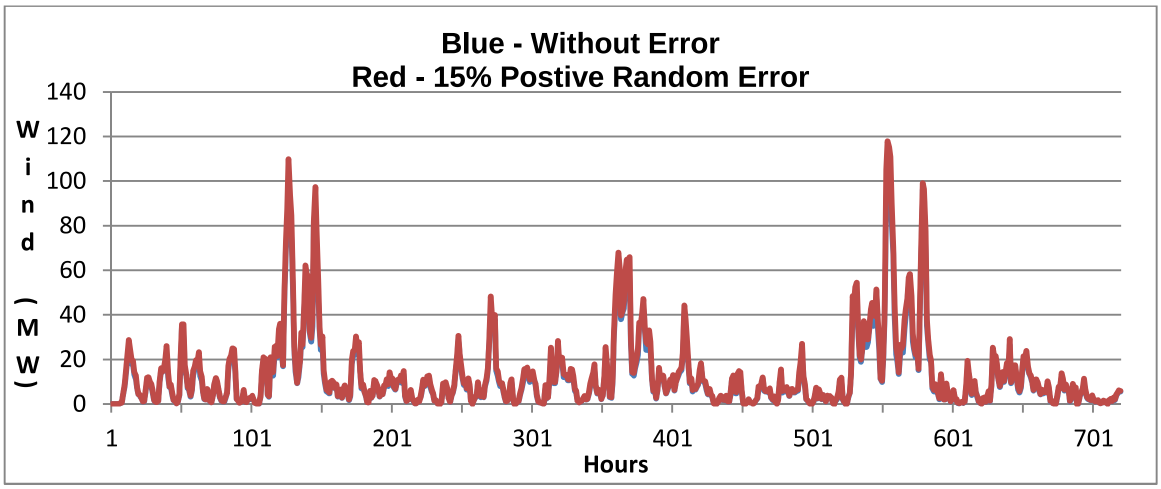

Figure 4.10 15% Positive Random Error in Wind Data

Figure 4.11 shows the variation in wind generation for time duration of one month with 15% negative random error at each hour.

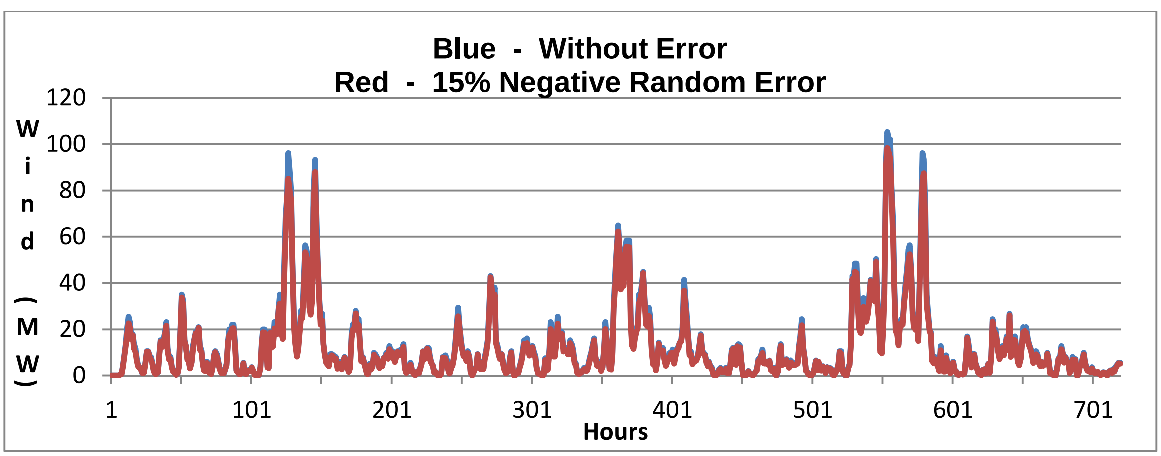

Figure 4.11 15% Negative Random Error in Wind Data

Figure 4.12 is the representation of the effect on objective function values due to 15% negative random error or uncertainty in wind forecast. Negative random error in wind speed shows that the value of wind speed at every hour can be -1 to-15% less than actual forecasted wind speed and cannot be lower than -15% at any time. Due to reduction in wind speed power generation from the wind turbine will be less than the estimated wind power generation. Therefore, to overcome the loss of wind power alternate resources of power generation shall be installed as a compensation which will result in the increase of cost. The cost will increase with the increase in percentage of negative error or uncertainty.

Figure 4.13 is the representation of the effect on objective function values due to 15% positive random error or uncertainty in wind forecast. 15% Positive random error in wind speed shows that the value of wind speed at every hour can be 1 to 15% more than actual forecasted wind speed and cannot exceed 15% at any time. Due to positive random error actual wind speed will be more than the forecasted wind speed for each hour which will cause more generation from wind turbine. Because of increase in wind power generation investment cost and compensation cost for alternate resources of power generation will decrease due to availability of excess power to meet the load demand. The greater the percentage of positive error or uncertainty greater will be the reduction in cost of objective function values.

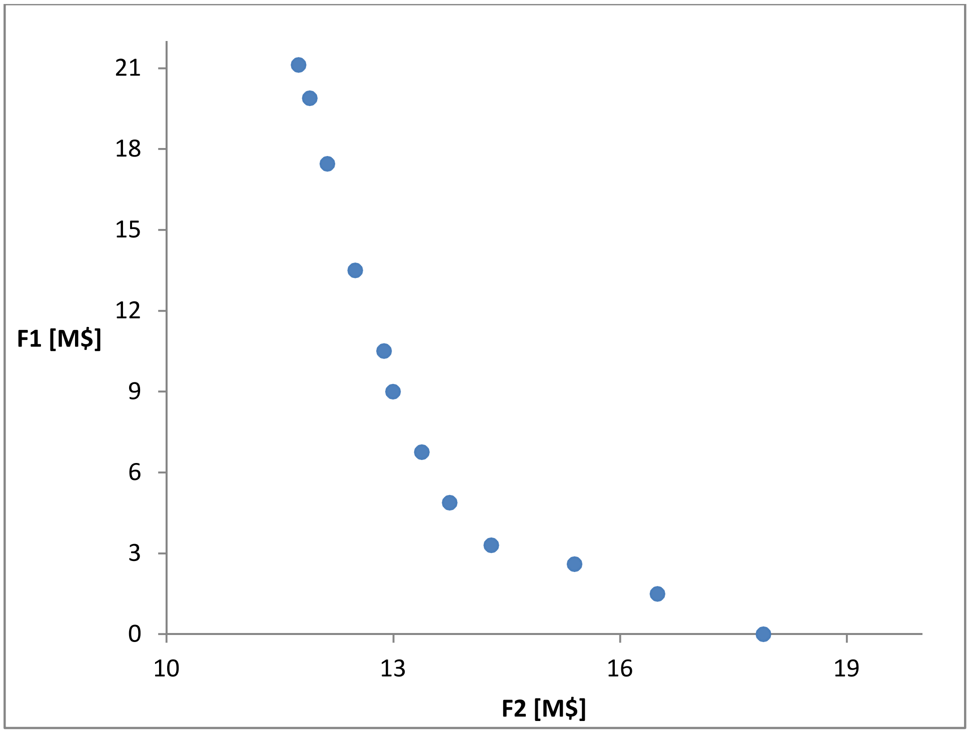

Figure 4.12 15% Negative Error in Wind Forecast

F1 [M$] = 3.30

F2 [M$] = 14.30

TOTAL = 17.60M$

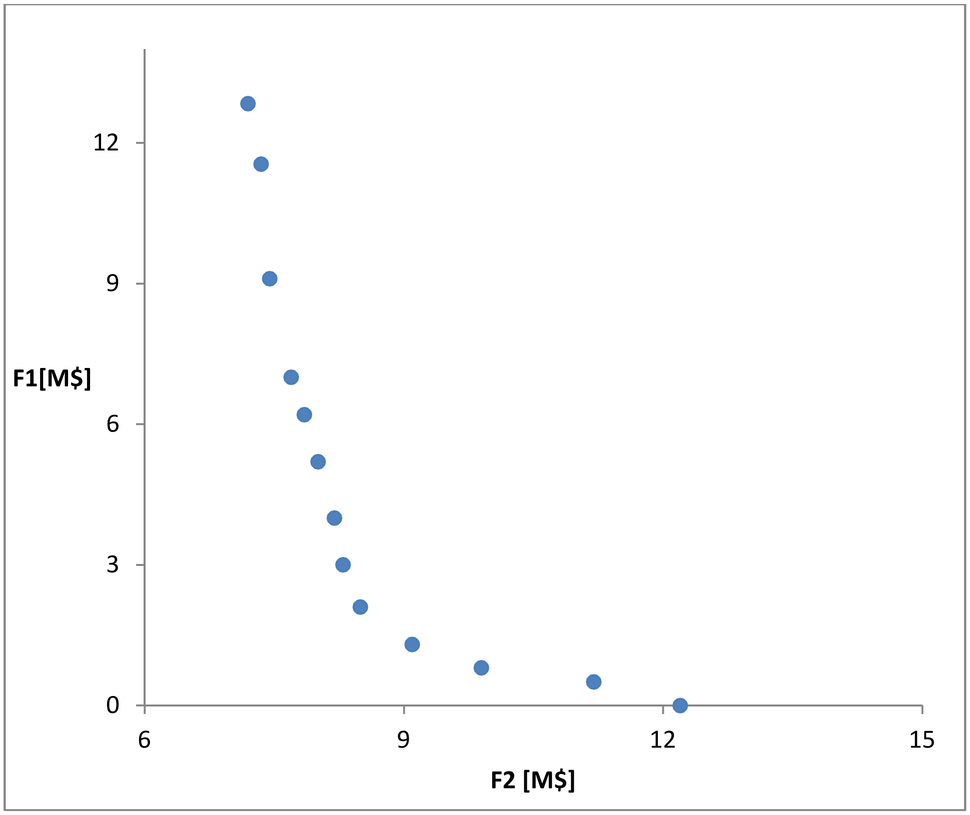

Figure 4.13 15% Positive Error in Wind Forecast

F1 [M$] = 1.3

F2 [M$] = 9.1

TOTAL = 10.4 M$

II. With 5% Random Error

Figure 4.14 represents the variation in wind generation for time duration of one month with 5% positive random error at each hour.

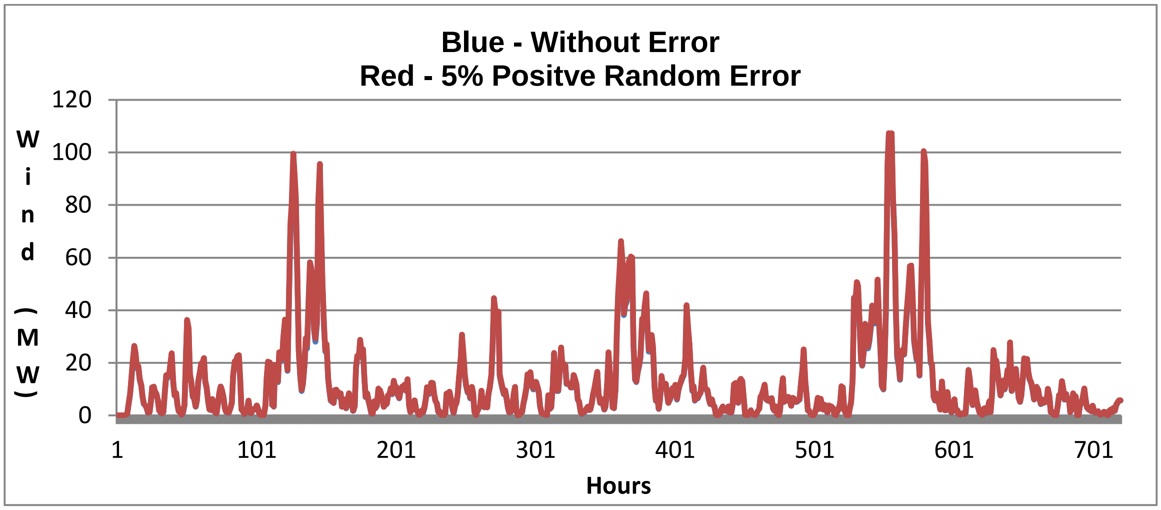

Figure 4.14 5% Positive Random Error in Wind Data

Figure 4.15 represents the variation in wind generation for time duration of one month with 5% negative random error at each hour.

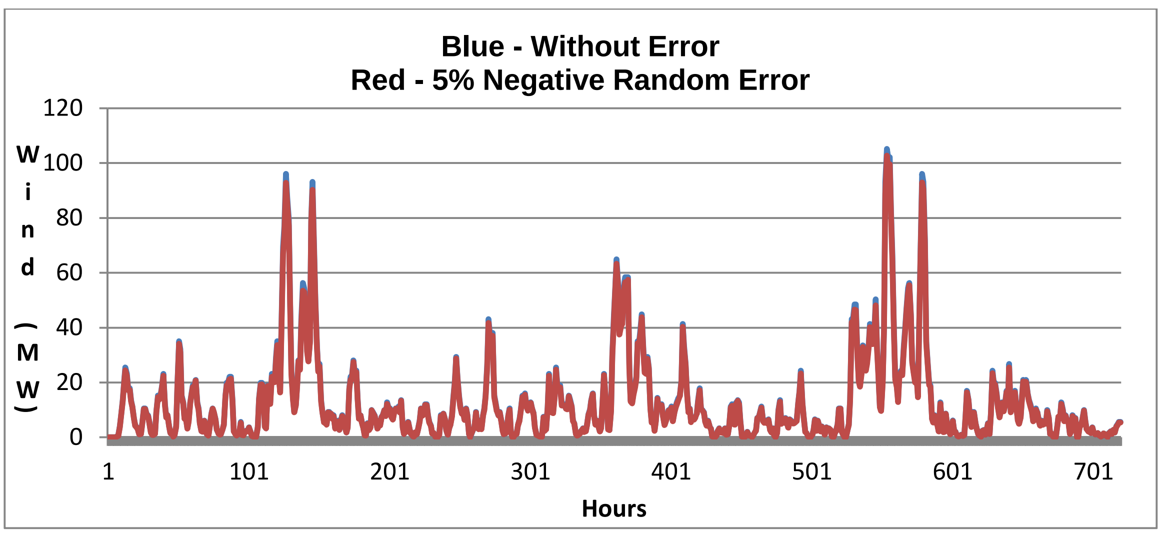

Figure 4.15 5% Negative Random Error in Wind Data

Figure 4.16 is the representation of the effect on objective function values due to 5% negative random error or uncertainty in wind forecast. Objective function values for 5% negative error are less than 15% negative error. This is due to the reason that values of wind speed for each hour in case of 5% negative error are more compared to wind speed values for 15% negative error. Therefore, less reduction in wind speed means less reduction in wind power generation and ultimately investment cost and compensation cost will be less compared to cost in case of 15% negative error.

Figure 4.17 is the representation of the effect on objective function values due to 5% positive random error or uncertainty in wind forecast. Objective function values for 5% positive random error are more than 15% positive random error due to the reason that values of wind speed for each hour in case of 5% positive error is less compared to wind speed values for 15% positive error. Therefore, more reduction in wind speed means more reduction in wind power generation and ultimately investment cost and compensation cost will be more compared to cost in case of 15% positive error.

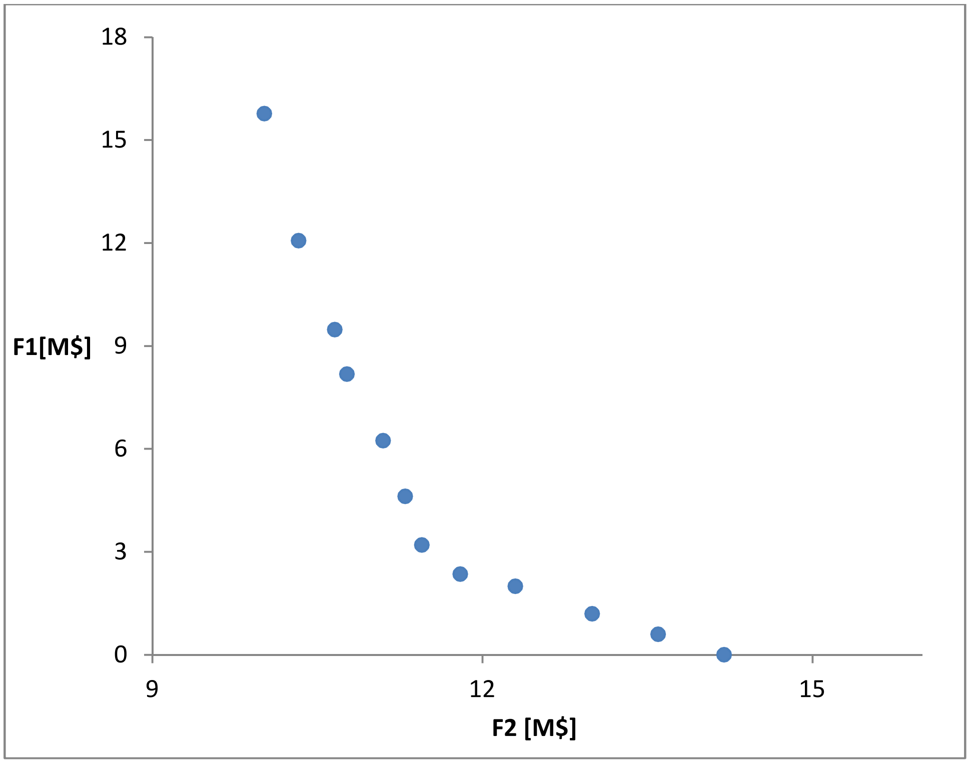

Figure 4.16 5% Negative Error in Wind Forecast

F1 [M$] = 2.35

F2 [M$] = 11.8

TOTAL = 14.2 M$

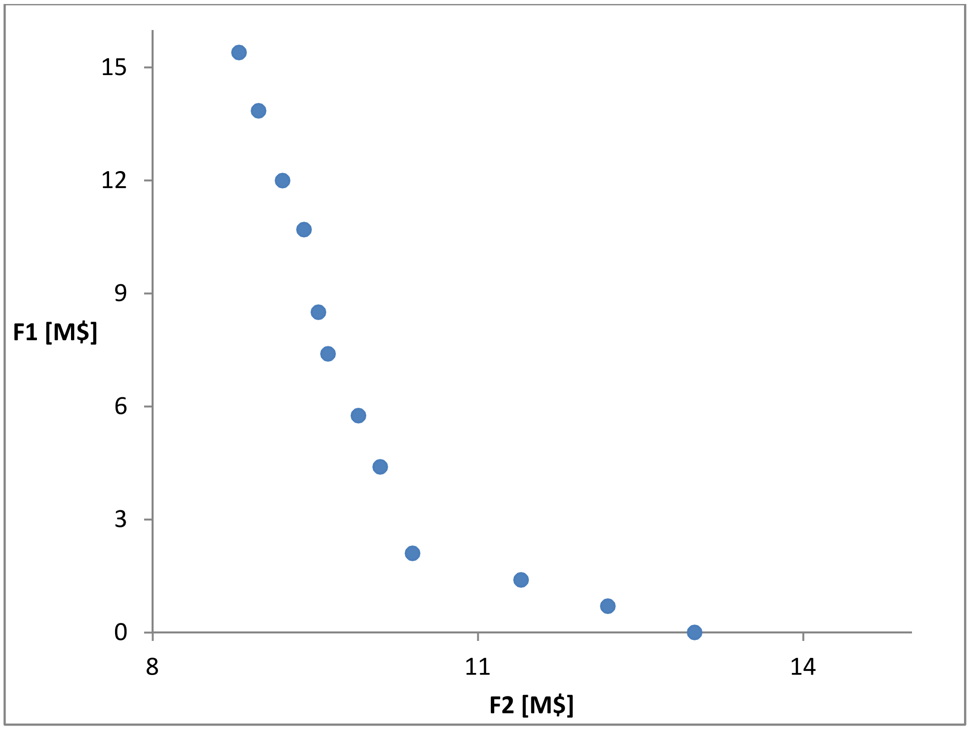

Figure 4.17 5% Positive Error in Wind Forecast

F1 [M$] = 2.1

F2 [M$] = 10.4

TOTAL =   12.5 M$

Table 4.8 Total Cost Comparison in terms of Negative Wind Error

Variable	Without Error	5% Negative Error	15% Negative Error
Total Cost	13.4 M$	14.2 M$	17.6 M$

Table 4.8 shows the comparison of total cost for all cases. These are without negative error, with 5% negative random error and 15% negative random error. The total cost is lowest in case of without any error however, total cost increase with the increase in percentage of negative error due to unavailability of wind to meet the load demand. Therefore, alternate resources of power generation needs to be installed to meet the load demand which will increase the cost.

Table 4.9 Total Cost Comparison in terms of Positive Wind Error

Variable	Without Error	5% Positive Error	15% Positive Error
Total Cost	13.4M$	12.5 M$	10.4 M$

Table 4.9 shows the comparison of total cost for all cases. These are without positive error, with 5% positive random error and 15% positive random error. The total cost is highest in case of without any error however, total cost decrease with the increase in percentage of positive error because of excess availability of wind power to cater the load demand.

4.2.4 Effect of Uncertainty/Error in Load Forecast

I. With 5% Random Error

Figure 4.18 displays the load data at each hour of the month with 5% positive random error in the load demand.

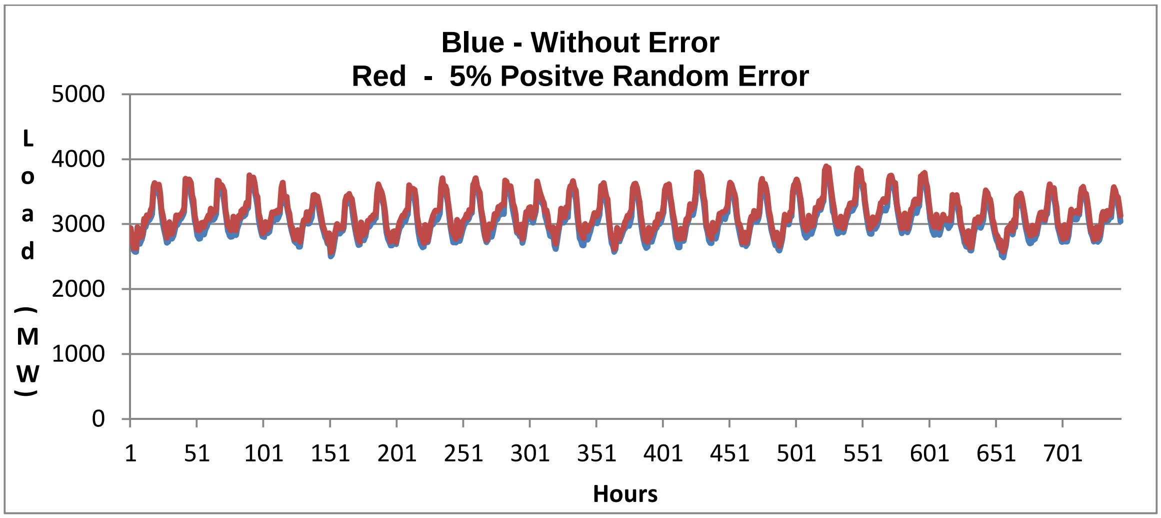

Figure 4.18 5% Positive Random Error in Load Data

Figure 4.19 displays the load data at each hour of the month with 5% negative random error in the load demand.

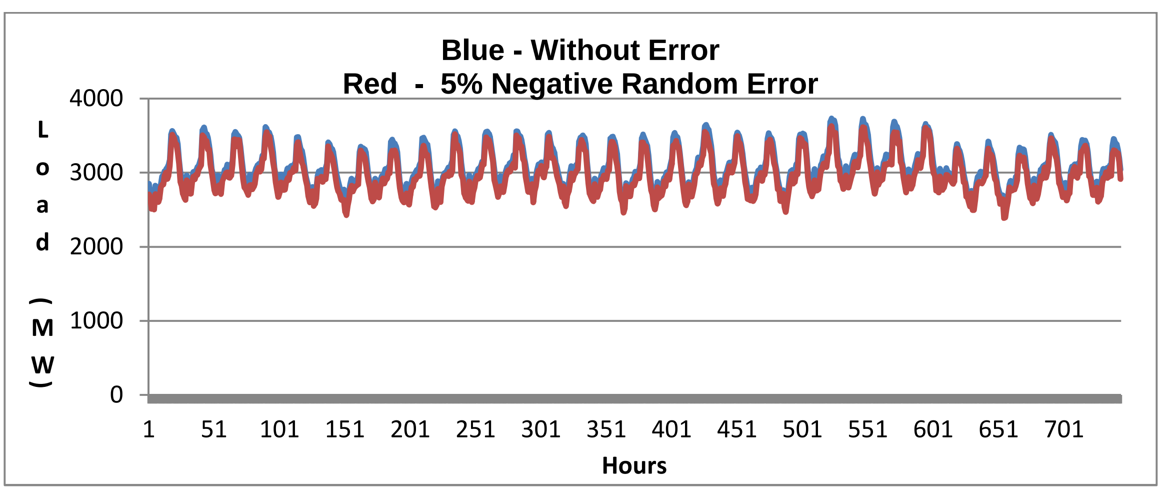

Figure 4.19 5% Negative Random Error in Load Data

Figure 4.20 is the representation of the effect on objective function values due to 5% negative random error or uncertainty in load forecast. Negative random error in load forecast shows that the actual load demand is less than forecasted load for each hour and it can vary between -1 to -5%. Due to reduction in load demand power generation required from the wind turbine will be less than the estimated power generation which will result in the decrease of investment cost. Cost will decrease with the increase in percentage of negative error or uncertainty.

Figure 4.21 is the representation of the effect on objective function values due to 5% positive random error or uncertainty in load forecast. Due to positive error actual load demand will be more than the forecasted load for each hour ranging from 1 to 5% which will require more power generation. Because of the increase in load demand investment cost and compensation cost will increase. Greater the percentage of positive error or uncertainty in load, greater will be the cost.

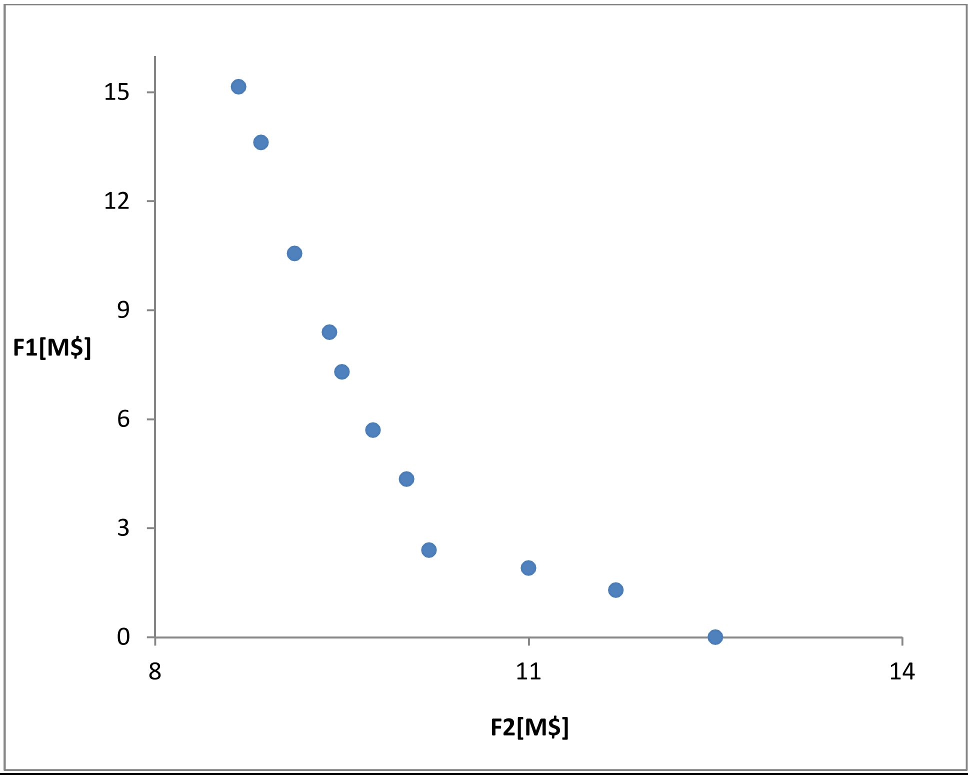

Figure 4.20 5% Negative Error in Load Forecast

F1 [M$] = 2.4

F2 [M$] = 10.2

TOTAL = 12.6 M$

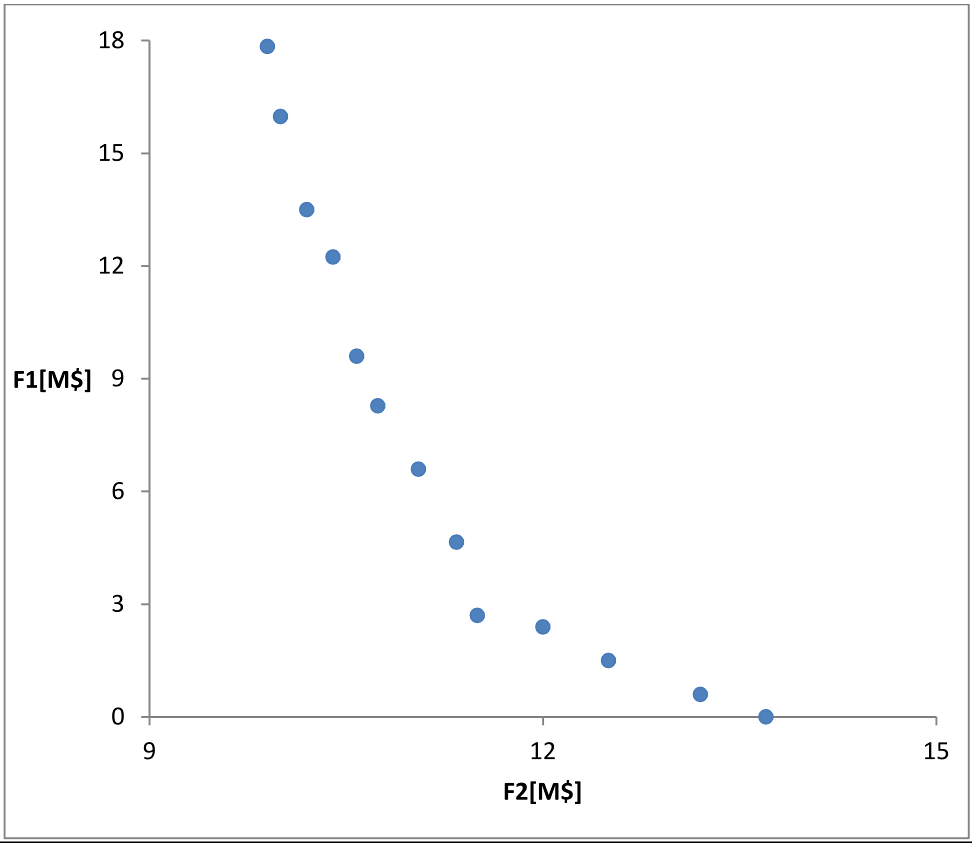

Figure 4.21 5% Positive Error in Load Forecast

F1 [M$] = 2.7

F2 [M$] = 11.5

TOTAL = 14.2 M$

II. With 15% Random Error

Figure 4.22 displays how the load data varies at each hour of the month with 15% positive random error in the load demand.

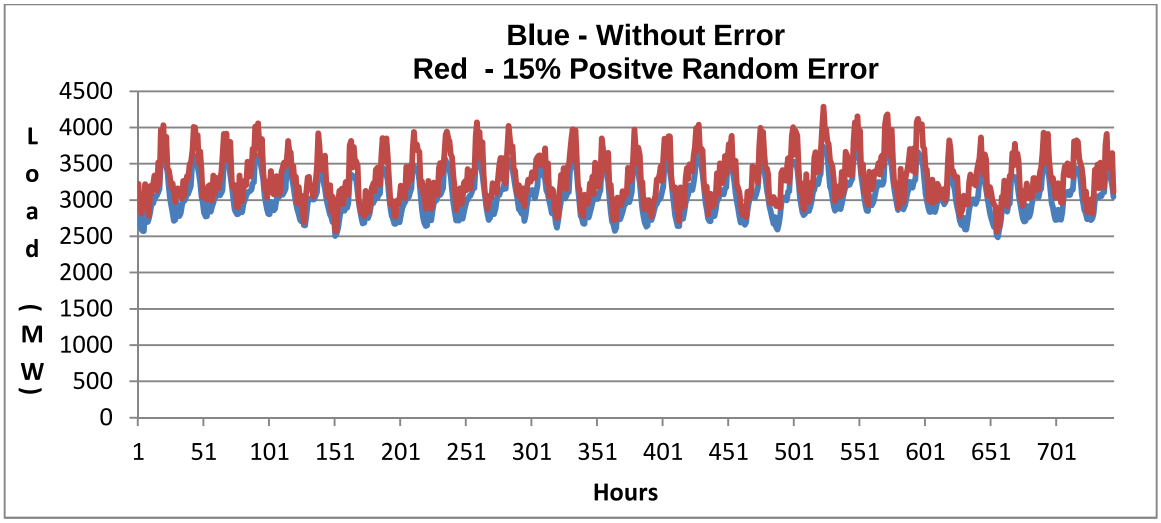

Figure 4.22 15% Positive Random Error in Load Data

Figure 4.23 displays how the load data varies at each hour of the month with 15% negative random error in the load demand

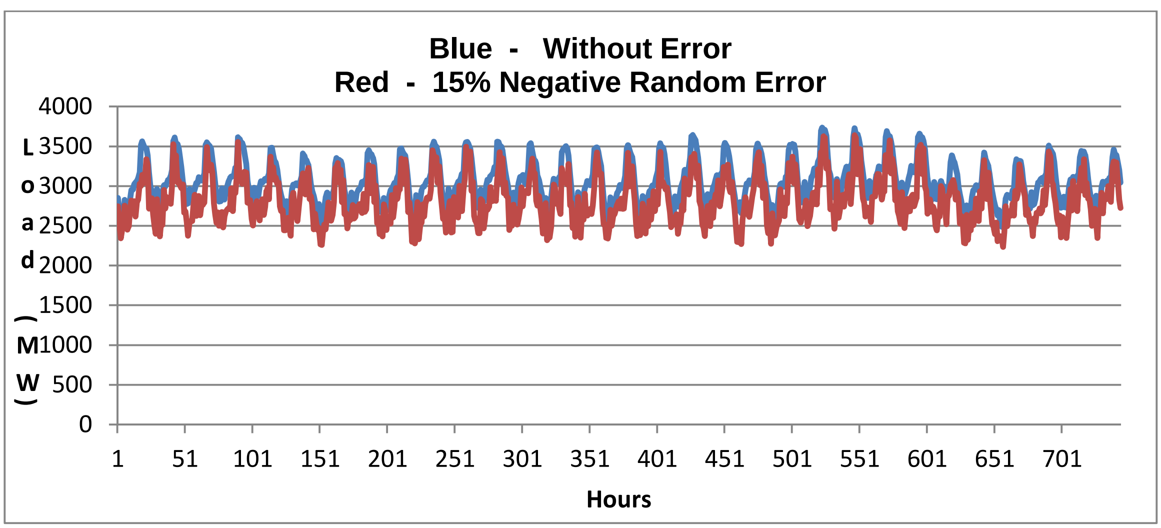

Figure 4.23 15% Negative Random Error in Load Data

Figure 4.24 is the representation of the effect on objective function values due to 15% negative random error or uncertainty in load forecast. The Objective function values for 15% negative error are less compared to 5% negative error due to the reason that load demand for each hour in case of 15% negative error is less compared to the load demand for 5% negative error. Hence, lesser the load means lesser power generation will be required to fulfill the demand which will result in the decrease of investment and compensation cost.

Figure 4.25 is the representation of the effect on objective function values due to 15% positive random error or uncertainty in load forecast. The Objective function values for 15% positive error are more than 5% positive error due to the reason that load demand for each hour in case of 15% positive error is more compared to the load demand for 5% positive error .Hence, increase in the load means that more power generation will be required which will ultimately result in the increase of cost.

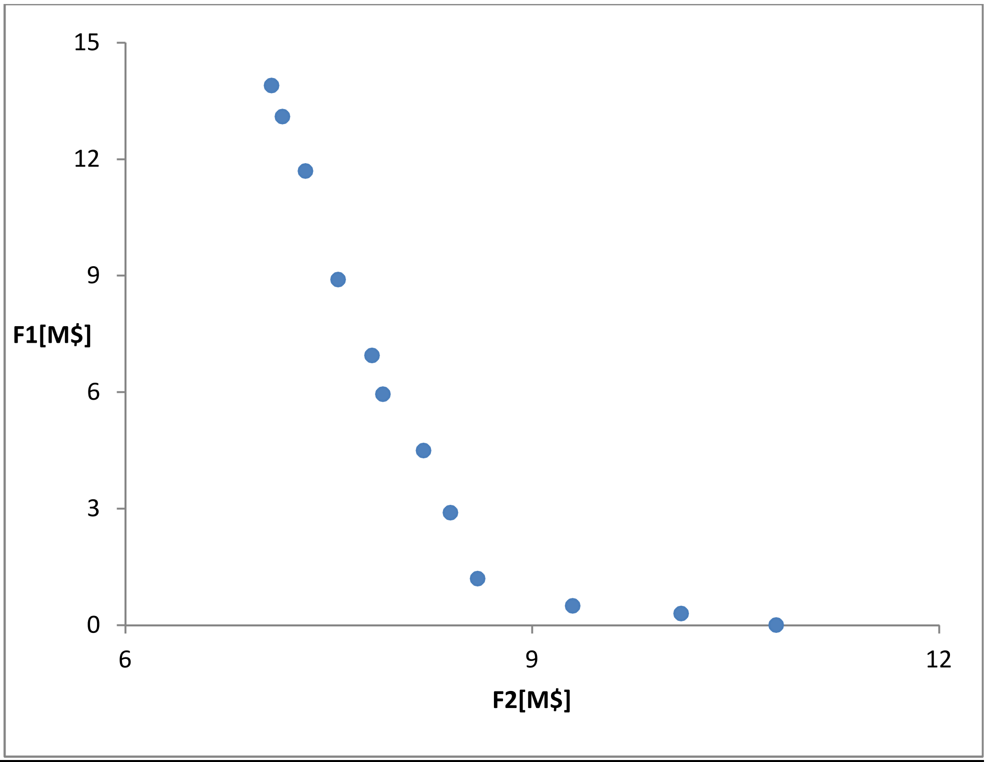

Figure 4.24 15% Negative Error in Load Forecast

F1 [M$] = 1.2

F2 [M$] = 8.6

TOTAL = 9.8 M$

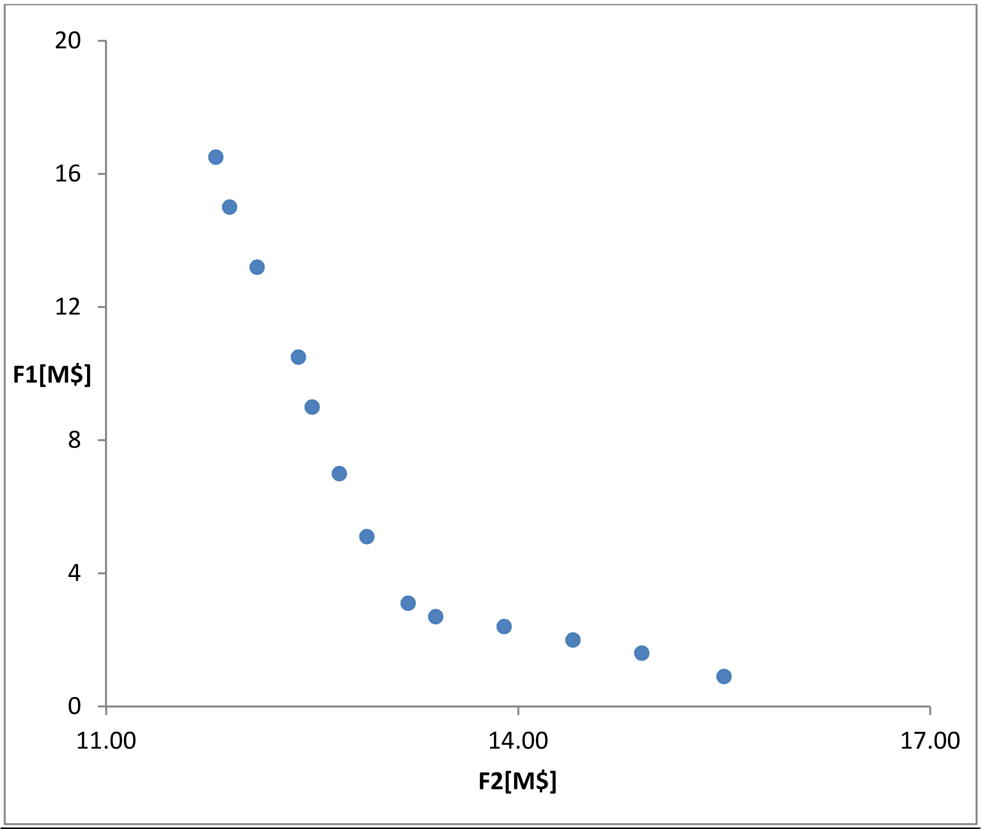

Figure 4.25 15% Positive Error in Load Forecast

F1 [M$] = 2.7

F2 [M$] = 13.4

TOTAL = 16.1 M$

Table 4.10 Total Cost Comparison in terms of Negative Load Error

Variable	Without Error	5% Negative Error	15% Negative Error
Total Cost	13.4M$	12.6 M$	9.8 M$

Table 4.10 shows the comparison of total cost for all 3 cases. These are without negative error , with 5% negative error and 15% negative error. The total cost is lowest in case of 15% uncertainty in load however, total cost increase with the decrease in percentage of negative error. Results show that more reduction in load demand will save more money as we don’t need to install alternate resources of power generation.

Table 4.11 Total Cost Comparison in terms of Positive Load Error

Variable	Without Error	5% Positive Error	15% Positive Error
Total Cost	13.4 M$	14.2 M$	16.1 M$

Table 4.11 shows the comparison of total cost for all 3 cases. These are without positive error, with 5% positive error and 15% positive error. The total cost is highest in case of 15% error however, total cost decrease with the decrease in percentage of positive error. Greater load requires more power resources to meet the demand which will result in the increase of cost.

4.2.5 Effect of Joint Uncertainty in Load and Wind Speed Forecast

I. With 15% Random Error

Figure 4.26 displays the combined effect of negative random error in wind speed and load forecast on objective function values. Negative random error in wind speed causes the reduction in wind power generation which will make it difficult to meet the load demand. However, due to negative random error in load demand simultaneously, negative uncertainty in wind speed will not have a major impact. Negative uncertainty in load will result in the decrease in demand so even the reduction in wind power generation will not cost extra in the form of alternate power generation resources. Therefore, the total value of the optimum cost between two objective functions will be very close the value as in case of without any error.

Figure 4.27 represents the combined effect of positive random error in wind speed and load forecast on multi-objective functions. Wind power generation will increase due to positive uncertainty in wind speed. However, due to positive random error in load forecast simultaneously, this extra power generation produced due to wind uncertainty will just be sufficient to meet the increase in load demand. As no alterante power resources will be installed to meet the increase in load demand therefore, total value of the cost between two objective functions will be very close to the amount as in case of without any error.

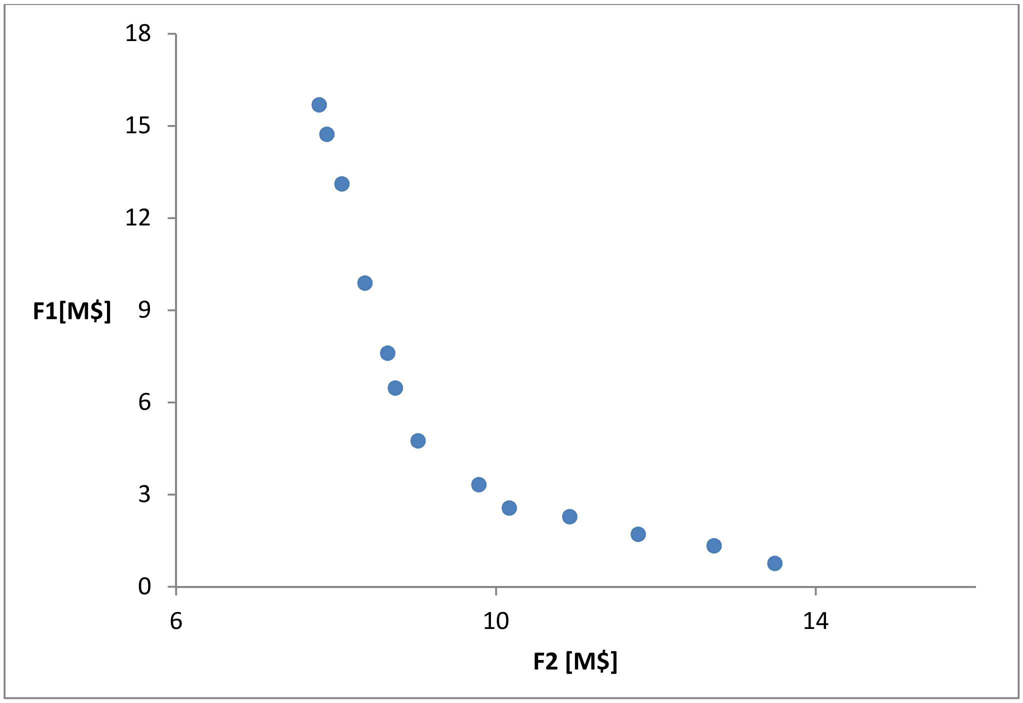

Figure 4.26 15% Negative Error in Load& Wind Speed Forecast

F1 [M$] = 2.5

F2 [M$] = 10.1

TOTAL = 12.6 M$

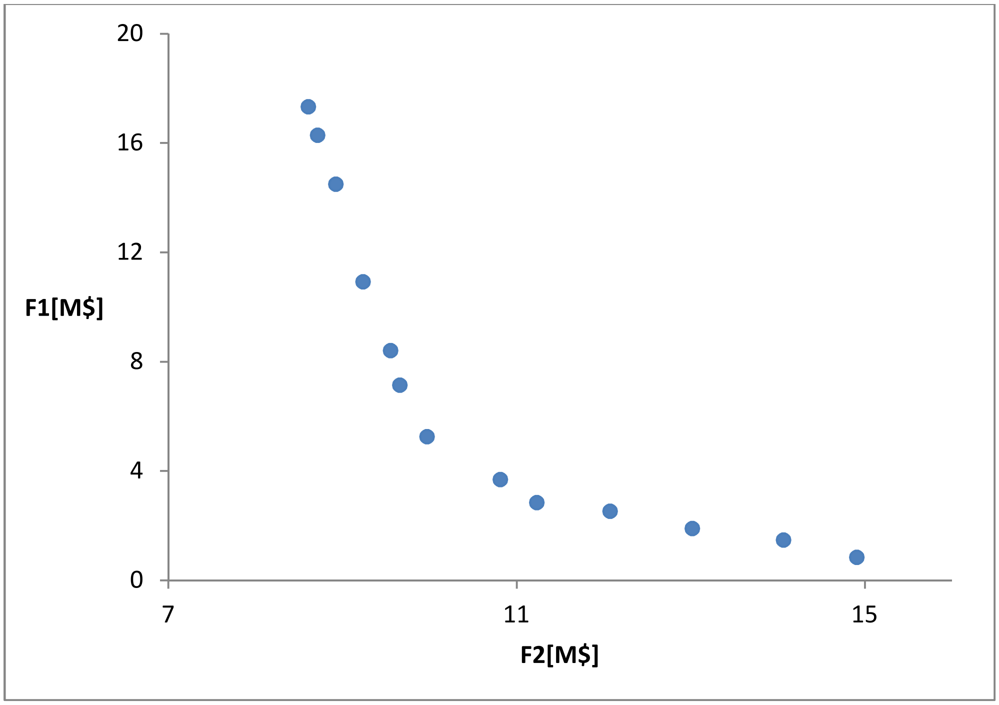

Figure 4.27 15% Positive Error in Load& Wind Speed Forecast

F1 [M$] = 2.8

F2 [M$] = 11.3

TOTAL = 14.1 M$

CHAPTER 5

CONCLUSION AND FUTURE WORK

Conclusion

The focus of this research work is to provide method or tool for transmission expansion planning with integration of renewable energy resources.Considering the complexity and uncertainty in development task, a method for calculation ofsingle and multi-objective functions is proposed to maximize social welfare and toreduce the investment cost .The single objective funciton considered is social welfare.Two multi-objective functions are: (1) Sum of Investment cost and load curtailment (2) Wind Curtailment .To calculate the objective function values Non-dominated sorted Differential Evolution algorithm combined with optimal power flow is utilized on IEEE 24 bus system.Later ENS is added in objective function to obtain optimal location of trasnmission lines in the network.Fuzzy satisfying approach is also applied to obtain best optimum resutls based on decision maker's preference.Moreover, effect of uncertainty in load and wind speed forecast is applied. Simualtion results show that how the different perectanges of random positive and negative error in load and wind speed forecast can effect the multi-objective function values.Effect of renewable generation can be considered as positive regarding to improved generation and transmission adequacy as well as system reliability.Developments in an electricity market and integration of renewable energy sources are driving force behind modificationsin transmission expansion planning and its operation.

Future Work

For future work, the effect of both uncertainty/error in wind and load forecast simultaneously for different cases can be verified on the system by applying different percentages of positive and negative error. Optimal location of wind and other power generation resources can be determined.

Planning should be effective which minimizes the cost and maximizes the social welfare.

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Appendix A

Data for Garver's 6 Bus System

Bus Data:

BUS #		Load Parameter		Generator Parameter			
		P(MW)	Q(MVAR)	Pmax (MW)	Pmin (MW)	Qmax (MW)	Qmin(MVAR)
1	Slack Bus	80	16	160	0	65	-10
2	Load Bus	240	48	100	0	0	0
3	Voltage Controlled	40	8	370	0	150	-10
4	Load Bus	160	32	-	-	-	-
5	Load Bus	240	48	-	-	-	-
6	Voltage Controlled	-	-	610	0	200	-10

Line Data:

Lines	R (Per Unit)	X (Per unit)	B (Per Unit)	Capacity		Line Length km
				MW	MVA	
1 – 2	0.04	0.4	0.04	100	120	25
1 – 4	0.06	0.6	0.06	80	100	40

1 – 5	0.02	0.2	0.02	100	120	15
2 - 3 X 2	0.02	0.2	0.02	100	120	25
2 – 4	0.04	0.4	0.04	100	120	38
2 - 6 X 2	0.03	0.3	0.03	100	120	50
3 - 5 X 3	0.02	0.2	0.02	100	120	45
4 - 6 X 3	0.03	0.3	0.03	100	120	15

Generator Cost and Demand Benefits:

Node	Generator			Demand	
	Fuel Source	aj (EUR/MW^2h)	bj (EUR/MWh)	cj (EUR/MW^2h)	dj (EUR/MWh)
1	Gas	0.0298	83.9	0	200
2	Wind	0	0	0	200
3	Coal	0.0081	58	0	200
4	-	-	-	0	200
5	-	-	-	0	200
6	Coal	0.0035	69.71	-	-

Appendix B

Data for IEEE 24 Bus System

Bus Data:

Bus no.	Load		Generation			
	MW	MVAR	MW	MVAR	Qmin	Qmax
1	108	22	172	0	-50	80
2	97	20.7	172	0	-50	80
3	180	37	0	0	0	0
4	74	15	0	0	0	0
5	71	14	0	0	0	0
6	136	28	0	0	0	0
7	125	25	240	0	0	180
8	171	35	0	0	0	0
9	175	36	0	0	0	0
10	195	40	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	265	54	285.3	0	0	240
14	194	39	0	35	-50	200
15	317	64	215	0	-50	110

16	100	20	155	0	-50	80
17	0	0	0	0	0	0
18	333	68	400	0	-50	200
19	181	37	0	0	0	0
20	128	26	0	0	0	0
21	0	0	400	0	-50	200
22	0	0	300	0	-50	80
23	0	0	660	0	-125	310
24	0	0	0	0	0	0

Line Data:

Line no.	From Bus	To Bus	Series Impedance pu		Half Line Charging Susceptance (pu)	Tap Setting	Line Limit	Line Length Km
			R	X				
1	1	2	0.0026	0.0139	0.23055	1	175	8
2	1	3	0.0546	0.2112	0.0285	1	175	55
3	1	5	0.0218	0.0845	0.01145	1	350	25
4	2	4	0.0328	0.1267	0.01715	1	175	35
5	2	6	0.0497	0.192	0.026	1	175	50
6	3	9	0.0308	0.119	0.0161	1	175	30
7	3	24	0.0023	0.0839	0	1	400	28
8	4	9	0.0268	0.1037	0.01405	1	175	24
9	5	10	0.0228	0.0833	0.01195	1	350	24

10	6	10	0.0139	0.0605	1.2295	1	175	20
11	7	8	0.0159	0.0614	0.0083	1	350	20
12	8	9	0.0427	0.1651	0.02385	1	175	45
13	8	10	0.0427	0.1651	0.02385	1	175	43
14	9	11	0.0023	0.0839	0	1	400	33
15	9	12	0.0023	0.0839	0	1	400	30
16	10	11	0.0023	0.0839	0	1	400	33
17	10	12	0.0023	0.0839	0	1	500	70
18	11	13	0.0061	0.0476	0.04995	1	500	60
19	11	14	0.0054	0.0418	0.04395	1	500	24
20	12	13	0.0061	0.0476	0.04995	1	500	15
21	12	23	0.0124	0.0966	0.1015	1	500	35
22	13	23	0.0111	0.0865	0.0909	1	500	40
23	14	16	0.005	0.0389	0.0409	1	500	25
24	15	16	0.0022	0.0173	0.0182	1	1000	20
25	15	21	0.0063	0.049	0.0515	1	500	15
26	15	21	0.0063	0.049	0.0515	1	500	70
27	15	24	0.0067	0.0519	0.0545	1	500	18
28	16	17	0.0033	0.0231	0.0245	1	500	18
29	16	19	0.003	0.0231	0.02425	1	500	25
30	17	18	0.0018	0.0144	0.01515	1	1000	25
31	17	22	0.0135	0.1035	0.1106	1	1000	22

32	18	21	0.0033	0.0259	0.02725	1	500	22
33	18	21	0.0033	0.0231	0.0245	1	500	15
34	19	20	0.0051	0.0396	0.04165	1	500	22
35	19	20	0.0051	0.0396	0.04165	1	500	22
36	20	23	0.0028	0.0216	0.02275	1	500	30
37	20	23	0.0028	0.0216	0.02275	1	500	26
38	21	22	0.0087	0.0678	0.0712	1	500	15

VITAE

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- Stabilization of Magnetic levitation System
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