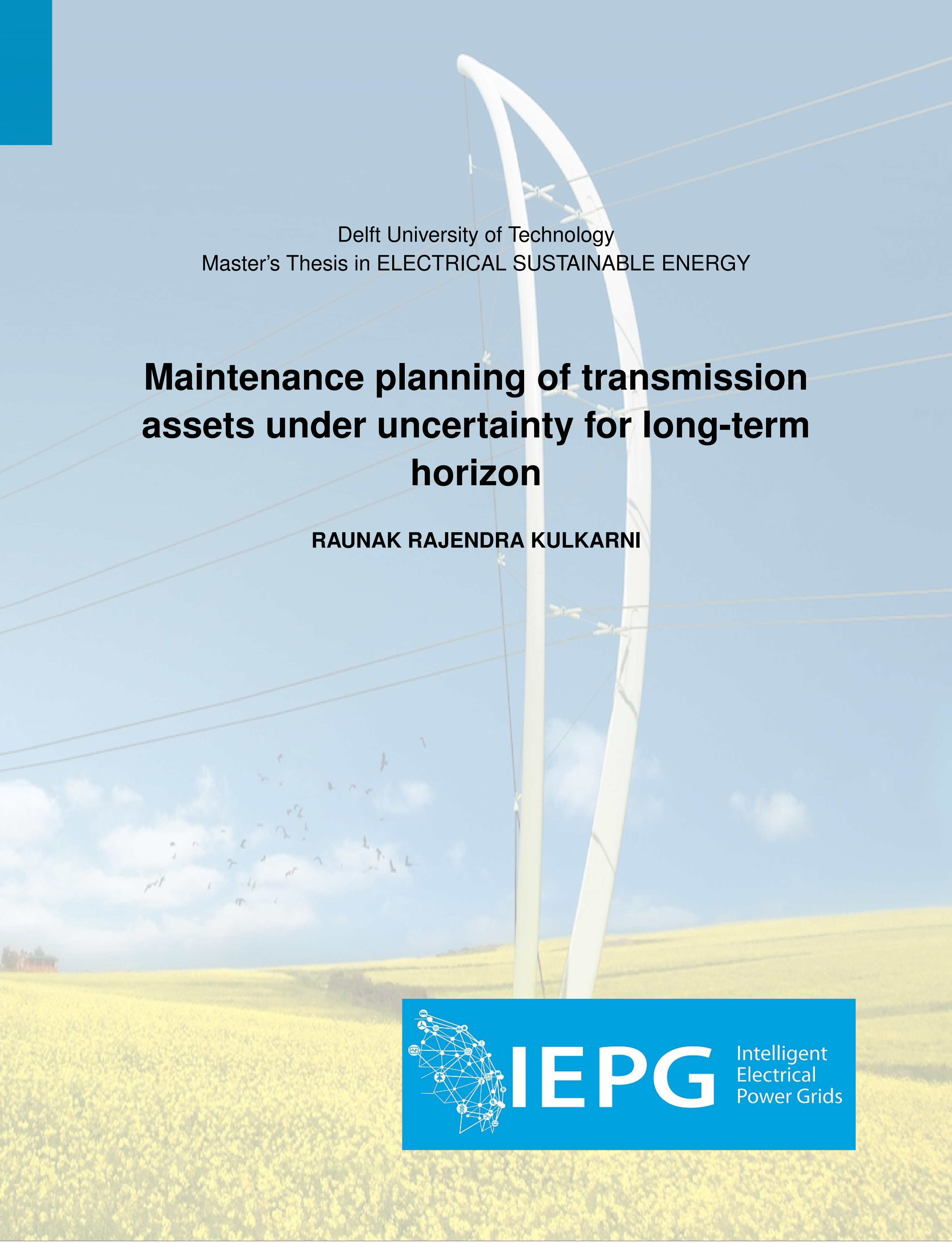

Delft University of Technology
Master's Thesis in ELECTRICAL SUSTAINABLE ENERGY

Maintenance planning of transmission assets under uncertainty for long-term horizon

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Title

Maintenance planning of transmission assets under uncertainty for long-term horizon

MSc presentation

22nd August 2017

Graduation Committee

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Abstract

Outage scheduling for maintenance in asset management of electrical transmission and distribution system plays an important role in power system reliability. For instance, failure probability of transmission line may change from time to time due to exogenous conditions. Impact of failure or service interruption can be described by using uncertainty condition while designing the long-term model for outage scheduling. Within a year horizon, a transmission system operator needs to schedule the maintenance outage of set of transmission lines due for maintenance. This is important because transmission line maintenance schedule ought to minimize the total maintenance cost and transmission provider's loss of revenue while satisfying the reliability and the network requirement. It is expected that in coming years, there will be substantial increase in renewable energy in-feed to the primary grid. Combined with increase in demand, high level of uncertainty from both renewable as well as demand can be predicted in the system. Definitely, transmission system operators (TSOs) have to tackle such increase in demand and generation while addressing security of supply (SoS); thereby transmission assets will play an important role since TSOs are not in favour of new investments. In order to maintain such reliable system with SoS, TSOs ought to have a proper and flexible maintenance scheme for their transmission assets. The scheduling scheme should be able to determine the exact transmission assets in the cluster of network which can be brought out of service for maintenance. The scheduling scheme should be accurate and fulfil the required constraints, both maintenance and network, while keeping the system reliable throughout the maintenance horizon. To solve such maintenance scheduling problem, benders decomposition technique is adapted incorporating uncertainties. Uncertainty plays a crucial role in formulation of the scheduling problem and has been given due consideration. Stochastic programming provides an adequate modelling framework in which problems of decision making under uncertainty are properly formulated. Optimization under uncertainty, spanning two-stage stochastic programming approach is used in this research study. For validation, small (RBTS 6-bus), medium (modified IEEE RTS-24 bus) and large (modified IEEE-118 bus) systems are studied, all in the GAMS environment.

Acknowledgement

First and foremost I would like to thank my family whose continued support encouraged me to work towards my dream fearlessly. This support kept me motivated throughout my academic period in the university. I would also like to thank my daily supervisor Prof. dr. Jose L.Rueda Torres for accepting me as his master student under his supervision and guiding me throughout my project work. I would also like to thank Prof. dr. Peter Palensky the chair of the Electrical sustainable energy department for guiding and providing valuable input during the whole phase of the project. Special thank is for Dr. Armando. Rodrigo Mor for accepting my request for being one of the thesis committee member. Last but not the least I would like to thank my Phd guide Mr. Swasti R. Khuntia from bottom of my heart for his tirelessly support and help during my full phase of the project. His experience, knowledge and positive attitude toward a master student like me made me more comfortable and less pressurized during the project work. At the very end, I would like to thank all my friends around the different part of world who made feel no different than home. All the memories that we had together will always remain cherished in the bottom of my heart. And the acknowledge wouldn't be complete without saying "Thank you God".

Raunak Rajendra Kulkarni

Delft, The Netherlands

22nd August 2017

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List of Symbols

The list describes several symbols that are used within the body of this document

γ_l	Susceptance at of transmission line l
θ_l	Voltage angle of transmission line l
c_{it}	Lost of revenue per MW at bus i in time t
C_{lt}	Transmission maintenance cost per-line in right of way of transmission line l at time t
d	Peak demand at every bus i
d_l	Duration of the maintenance for transmission line l
e_l	Earliest period to begin maintenance for transmission line l
$GAMS$	General Algebric Modelling System
i	Buses from (1 to i)
l	Transmission line from (1 to l)
l_l	Latest period to begin maintenance for transmission line l
p	Power generation by the generators
PGi_{bt}	Power delivered by generator at bus i at time t
PGi_{max}	Maximum power that can delivered by generator at bus i
PGi_{min}	Minimum power that can be delivered by generator at bus i
PL_{jmax}	Maximum power flow through existing lines of j^{th} transmission line
PL_{jmin}	Minimum power flow through existing lines of j^{th} transmission line

r	Load intensity at the base
r_{it}	Real power interruption at bus i in time t
$RBTS$	Roy Billinton Test System
RTS	Reliability Test System
s	Maintenance variable
sf	Power flow at peak load
SOS	Security of Supply
t	Time period
TSO	Transmission System Operator
TWh	TeraWatt Hours
X_{lt}	Number of candidate line to be operated in right of way at time t of transmission line l
Z	Optimized cost

Chapter 1

Introduction

> Clean, renewable energy will act
> as a catalyst and a
> force-multiplier for the
> Sustainable Development Goals
>
> *United Nations*
> *Secretary-General*
> *17 January 2016*

According the latest report from International renewable energy agency (IRENA) (**Renewable energy highlight, 1 July 2017**), as in 2015, the total amount of electricity generated from renewables was 5512 TWh [3]. An increase in 3.5 percent of renewable energy generation was observed compared to 2014 [3]. Recent innovations in renewable energy sources and their large scale integration in the power systems have a significant impact on the topology of the power system. Typically, the power system is summarized as generation, transmission and distribution system working together to provide the required energy demand to the different sectors of the society. The expansion of power system in 21^{st} century is exponentially growing which is leading to an increase in transmission level capacity of a power system. The demand side, on the other hand, is also increasing as people are largely shifting from conventional practices in sense of domestic usage or driving gasoline car to more electrical/hybrid transportation and usage of clean energy. To maintain the demand side supply and the generation side, a reliable transmission system should be incorporated and maintained to improve the society and have a balance power supply through out the system. In addition to power balance, the transmission system operators (TSO's) should also cope with the continued increase in penetration of renewable energy in the power sector, the emergence of storage, electric car and the long-anticipated components replacement wave.

1.1 Background Issue

In today's world, advent of new greener energy generation technologies and expansion of power system has critical effects on the existing grid network that is required to maintain and deliver reliable as well as efficient power supply to the integrated society. Or in other words, Security of Supply (SoS) is of primary concern, as it was and will be in future. Such development of power system has resulted in designing more complex network. Not only such complex network but also external scenario developed around the power system have become more uncertain and unreliable to fathom. Moreover, these uncertain scenarios develop large amount of stress on the power system, more specifically on the transmission system. The transmission system should be the pinnacle of reliability as it connects the two vital dots, that is, the generation side and the demand side. The large stress on the transmission system is not only because of the increase in power distribution but also due to the assets and their management in the power system. In this context, it is important to shed light on one important topic, i.e., ***netzstresstest***[1]. Currently, Transmission System Operators (TSOs) like TenneT Netherlands[2] are exploring ways to counter the impact of netzstresstest.

With the increasing pressure and stress on the transmission assets it has become important to study the reliability of the power systems. This need has given way to a new understanding of asset management [2]. Improving power system reliability has pushed the TSOs to find the optimal management for the present system while minimizing maintenance losses (both physical and economical) for the existing assets over their fundamental time span. To understand the existence of asset management, power system reliability researchers divide the power system time horizons into three main processes and/or activities in which crucial decision is undertaken for obtaining the optimal result. The three-main processes and/or activities are as follows [2]:

- Grid/system development (Long-term development)

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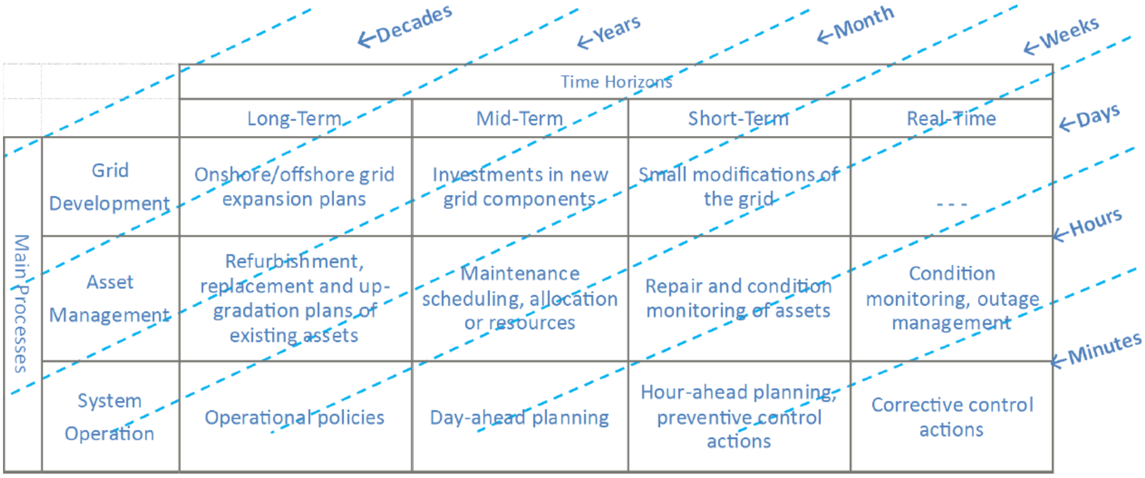
[1]: It is a German word to test the limit or net stress of the current transmission system due to increase of renewable penetration and other distributed energy sources into the primary grid.

[2]: Tennet TSO B.V. is TSO of Netherlands

- Asset management (Mid-term development)
- System operation (Short-term development)

In literature, there is no perfect definition of asset management since several researchers propose a definition according to their application. For electric utilities, CIGRE joint task force JTF23.18 [4] defines asset management as ***"The asset management of transmission and distribution business operating in an electricity market involves the network business to maximize long term profit, whilst delivering high service value to customer, with acceptable and manageable risk"***. In the electric power system domain, the transmission and distribution assets are capital-intensive assets which push the TSOs to effectively and efficiently use the resource at their disposal. Leaning towards the overall development of the power system, asset managers are being encouraged to move towards more optimal management of resources as well as perform different development in system which would result in optimization of the current infrastructure cost for different component with respect to their life span and durability. Development in the power system for maintaining reliability as to obtain optimal result and lower loss of revenue, three main development activities for the decision-making process are taken into consideration. Activities in these three-main processes are generally categorized according to their period of their work and time-span for their implantation on the site or field. It is clear that different sub-activities are performed under the three process which can be observed in figure 1.1. Figure 1.1 shows different time horizons with their respective time scale and the various processes, namely, grid development, asset management and system operation. The illustration in the figure 1.1 depicts that some of the sub-activities such as maintenance scheduling under mid-term time horizon are performed on time scale of years while system operation in mid-term decision making is performed on time scale of 1-5 years while system operation in mid-term development are performed under months. The figure 1.1 clearly illustrate that some activities can vary in their time horizon not only based on the task which is supposed to be performed but also the time scale. For instance regarding mid-term scheduling, we can discern that allocation of the resources for maintenance work of any asset in the power system network may alter from months to years or even decade. This shows the importance of time and asset management for the power system, as it plays an important role in decision making process undertaken for optimal result.

Maintenance in asset management of electrical transmission system plays an important role in power system reliability. Asset management consists mainly of two tasks, namely outage scheduling and maintenance budgeting. The task of outage scheduling under asset management plays an import-



		Time Horizons			
		Long-Term	Mid-Term	Short-Term	Real-Time
Main Processes	Grid Development	Onshore/offshore grid expansion plans	Investments in new grid components	Small modifications of the grid	- - -
	Asset Management	Refurbishment, replacement and up-gradation plans of existing assets	Maintenance scheduling, allocation or resources	Repair and condition monitoring of assets	Condition monitoring, outage management
	System Operation	Operational policies	Day-ahead planning	Hour-ahead planning, preventive control actions	Corrective control actions

Figure 1.1: Action taken during different time-horizon[1].

ant role in determining the specific asset in the transmission system which should be taken out for maintenance while satisfying all the system constraints. Asset management also plays an important role in transmission line maintenance scheduling. Making a decision on the extreme point or the peak concerning the assets in the power system will allow the TSOs to overcome or tackle the bottleneck in terms of resource, budget and time allocation during the most critical time span. One of the important objectives of maintenance policy is maintenance budgeting. Maintenance budgeting allows the TSOs to pay close attention on the budget and workforce in order to make the resource allocation more smooth and less complex [5]. But in this thesis we have not covered the aspect of maintenance budgeting but covered the topic of asset management. Asset management was introduced by TSOs in early 90's to reduce the expenditure on the transmission network maintenance and service. It also aimed to provide a reliable network. The primary aim of the asset management was to reduce the fund expenditure on the transmission line network maintenance and service, but also provide a reliable network during fault or breakdown condition. During the period of maintenance, the funds required for the service and maintenance should as low as possible. Proper asset management helps transmission system operators to gain more profits and improve reliability of the system.

Progress in the field of transmission line capacity for high voltage as well as for low voltage basically started around 1960's [6]. The progress ideology without much decoration was to transfer power between source and demand at high voltage level. The reason behind the ideology was to reduce the transmission line losses associated with low voltage power transfer. Increasing the infrastructure associated with the transmission line network resulted in increase in impact of external effects on the network. This external impact mainly includes the weather factors like rain, snow, etc. and unavailability of infrastructure to erect the large transmission lines. Moreover, system reliability was also considered a crucial problem in transferring high voltage as demand side of the network should be ready to adapt and well consume the required power supplied.

From industry to domestic sectors, the end user power consumption has been increasing enormously. The concept associated with the end user power consumption led to demand side management. The end user in recent times are approaching towards more clean and environmental friendly consumption of energy. Due to such adaptation their has been enormous increase in consumption electrical energy. Therefore, large demand on consumer side led to increase in generation capacity of the different electrical utility companies. The infrastructure associated with the transmission line network should be such that it adapts to the increase in power transfer from the generation side to the demand side of the network. Moreover, the transmission line network should be reliable in providing constant uninterrupted power supply from the source to the different end user. To maintain security of supply (SoS), TSOs should have a proper transmission system maintenance plan which includes scheduling and maintenance of transmission assets considering all the constraints in the network. The scheduling scheme to be incorporated by the TSOs for the transmission system should be able to determine the exact transmission assets, for instance transmission lines, in the cluster of the network which can be taken out of service for maintenance while maintaining the reliability of the system for the total time span of maintenance. Different maintenance schemes are followed by different TSOs so as to fulfill their specific condition and limitation while designing proper maintenance schedule for the transmission system. At the end of the day, the model selected for the maintenance schedule should be utmost accurate with little or no error and should be able to fulfill all the desired network constraint and reliability at all point of time in the network.

In future, it can be expected that the period of high renewable in-feed will push the TSOs to rely more on flexible response and corrective control. Both on-shore/off-shore wind farms as well as solar energy plants are the major players in the high renewable in-feed to the power system. Such high renewable in-feed will create a factor of uncertainty in planning and maintenance of the power system. The factor of uncertainty can be defined as the cumulative decision variable associated with different scenario as to observe the response of the power system when subjected to exogenous variables. Thus, it is necessary to take appropriate steps to make the decision making process more reliable and robust. Further, the future reliability assessment method have to consider probabilistic methodology. Due to consideration of probabilistic methodology the flexible assessment can be made regarding the volatility of the renewable energy production. A similar example can be seen from TenneT, the Dutch TSO who have already completed the a cable project called NorNed [7]. This cable project connect Norway and Netherlands by a High Voltage Direct Current submarine cable. The primary aim of the cable project is to supply high in-feed renewable energy from Norway top Netherlands. This interconnection plays a very important role in future reliability assessment and distributional renewable in-feed between two countries

1.2 Literature Study

It is well known now that the power system is growing rapidly with involvement of high in-feed renewable energy to the grid and maintenance of the assets are one of the important factor to be considered while considering the reliability of the power system. Advancement in power system serves as the backbone for all round development of infrastructure of the society. Every aspect of the society whether be it housing, transportation, health-care and information technology, all of this aspects are interlinked with infrastructure of the electrical power system. Therefore, it can be deduced that evolution of the electrical power system led to evolution the society which indeed led to more safe and healthy lifestyle for people of the society. In the last decade, significant penetration of renewable energy in form of wind and solar in the primary grid is noticeable. One example of such noticeable work was done by the German TSO, TenneT, in which they constructed a 135 kilometre of DC grid connected transmission line from an offshore wind power plant with capacity of 916 megawatts [8]. Therefore, due to such increase in infrastructure and development in renewable sector technology, we observe increase in penetration of energy in to the grid, which results in the increase in transmission capacity of the existing power system network. Moreover, the increase in the capacity led to increase in maintenance of transmission system as to provide security of supply (SoS). Therefore, effective and timely maintenance of transmission assets is important. Most importantly, transmission line maintenance scheduling results in reliable operation of the power system as well as stable and constant power supply to the distribution network from the generation sectors. As the capacity of the power transfer is increasing, one can say that transmission lines are the most important asset in the transmission system and maintenance scheduling of transmission line plays an important role in all the power system[9]. The aim of asset management is to enhance the life span of the system with incorporation of efficient business plan and approaches. Work done in asset management has showcased it as one of the most vital constituent for a reliable power system. For instance, in the GARPUR project[5], carried out a survey on different assets considered under asset management by different European TSOs. The results from survey in figure 1.2 shows different component considered under asset management by different TSOs. From the figure 1.2, it can be inferred that transmission lines are one of the major player included under asset management by the European TSOs. Asset management results in key decision making process in order to maximize the profit for the TSOs. Since transmission line outplays all other assets considered by TSOs, this research work undertook transmission line outage scheduling and come up with an efficient maintenance schedule for the TSOs..

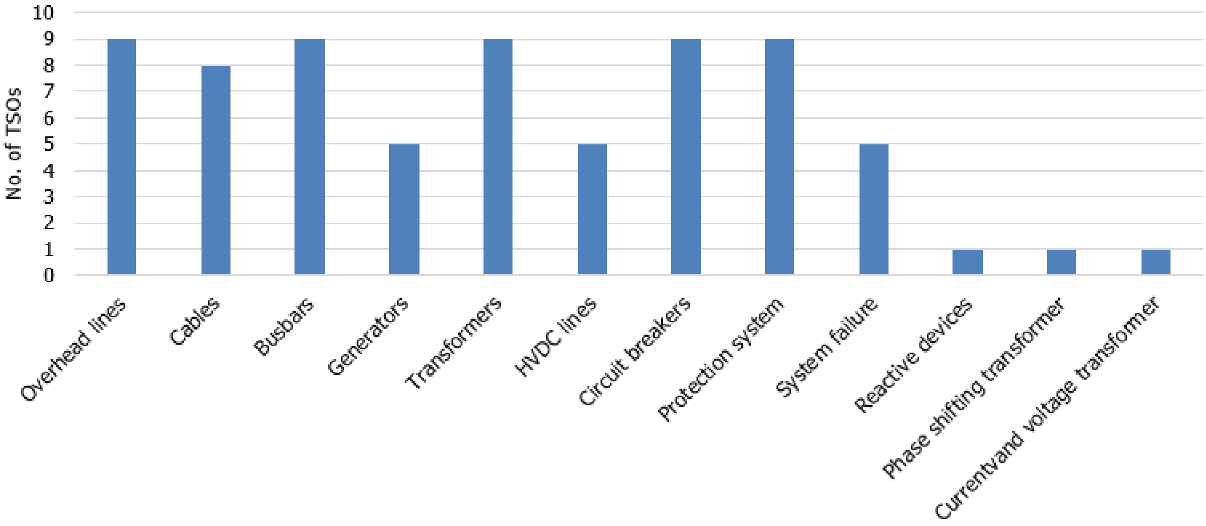


Figure 1.2: Number of transmission system operators considering different component under asset management [2].

Literature study suggests that asset management plays an important component in transformation of the power system industry. Analysis and research on the asset management suggest a compelling work about different asset management classification in terms of maintenance methods and research work. The study also suggests that majority of maintenance work is focused on generator maintenance scheduling. This maintenance work does not take into consideration the transmission system network constraints. For a complete overview and update biblical survey, refs. [10][2]can be referred to. During the early ages of power system development, transmission system was not given important as the generation sector. But after the expansion in power system in following years it was observed that the transmission system played crucial role in maintaining the power system more stable and reliable at point of calamities and fault. As generating facilities size were increasing a model was introduced for automated scheduling of maintenance of generating facility in [11]. This led to the foundation for future research work related to the generating facilities which can be seen in [12]. Decomposition approach was introduced to solve very large linear optimization problem. The most famous benders decomposition algorithm was first used in [13] to obtain solution for the maintenance schedule decision variable. Taking into consideration the transmission constraint of power system the maintenance scheduling of generating unit was first introduced in [14] which used the stochastic programming approach. Application of benders decomposition in deep understanding for power plant scheduling was first observed in [15]. Integrated generation and transmission maintenance scheduling with network constraint and deterministic approach for generation and transmission maintenance scheduling network constraint were first introduced in [9] and[16]. Introduction to long-term generation and maintenance scheduling with network fuel constraint using benders decomposition approach was proposed in [17]. A probabilistic approach for the generator maintenance scheduling was proposed in [18]. Later, short-term transmission line maintenance played an important role in providing scheduling of transmission line in short-term basis which provided maximum revenue for the producer while keeping the constraint intact in a deregulated network which was presented in paper [19]. A mixed integer approach for scheduling in generating unit provided in [20]. Development in long-term transmission line scheduling which explicitly considered the market environment by using the bi-level approach as seen in [21]. Credibility theory for short-term for transmission line maintenance scheduling introduced new approaches and requires understanding the comprehensive assessment for fuzziness and randomness in solving the scheduling problem in[22]. Introduction to the transmission switching in centralized transmission line maintenance scheduling was provided in [23]. Time-horizon related to planning and asset management was clearly mentioned in [1]. In figure 1.1 we can observe the overview of activities concerning the power system to the time horizon associated with each activity. It can be observed from the figure 1.1 that some of the activities in the main processes overlap different time zone. This significantly convey a message that some activities concerning the power system development process may take different period depending upon the type of activity is performed..

In such, maintenance scheduling practice the cost of operation and the loss of revenue plays a very important role in the profitable returns for the transmission system operators. The main aim of the TSOs is to minimize the losses during such maintenance scheduling operation. At end of day cost invested on development and the returns obtained should result in profit for the transmission provider as well as distribution provider. Such maintenance scheduling is performed by the TSOs as to detect the error and fault at the minimal level and to prevent any unwanted calamity during the work job is being performed. Fault can be due to natural cause but also can be due to the fault occurring at some distribution entity. Such fault and error result in loss of revenue for the utility company. But if the utility performs proper maintenance scheduling regularly their losses can be lower and they won't have to invest more on component change and replacement gears.

Transmission line maintenance scheduling is used to determine the outage for the specific transmission lines in power system as to keep the losses associated with funds and asset to minimum while maintaining the reliability of the system. The scheduling played an important role in fulfilling all the network constraint associate with the transmission system operators as well as perform the scheduling in specific time frame[24]. But it should be observed that performing an outage maintenance for the transmission system results in removal of a specific transmission line at a specific time which in directly result in loss of load and voltage imbalance which results in large transmission losses for the specific transmission line in the network. This loss of load result in loss of revenue for the transmission system operators but the objective of the schedule should be performing the outage schedule a specific time during which the loss of revenue for the transmission system operators is as minimum as possible

Outage scheduling for specific time frame without considering the exogenous and endogenous factor will make the schedule more vulnerable to uncertain scenario and may result in more loss of revenue for the transmission system operator. To understand and interpret the uncertainty associated with the outage scheduling, stochastic programming is used as an efficient tool to optimize under uncertainty. The programming is used to find the optimal solution in problem concerning uncertain data. Uncertainty plays an important role in formulating the algorithm, which result in use of the benders decomposition approach to solve the two-stage stochastic programming. In two-stage stochastic programming, uncertainty constraints are taken in terms of different scenario. Two-stage stochastic programming is the decision based approach wherein initial decision is taken into consideration and the optimal solution is calculated after the sub-problem is solved [25]. If the obtained solution is not optimal then the Benders cuts are added to the initial master problem and the loop is repeated until optimal solution is not obtained.

In a case of the transmission line scheduling maintenance, the optimal solution is the lowest loss of revenue observed by the transmission utility when a specific transmission line is brought down under maintenance. The result should be able to decide the specific transmission line to be taken out for outage while satisfying all the required constraint as well as keeping the system reliable at all point of time.

1.3 Objective & Research Question

The objective of this research work is to perform maintenance planning in the form of outage scheduling of the transmission assets under uncertainty. As discussed in the previous sections, this research work considers transmission line from the many transmission assets. The objective problem consists of an optimization problem with decision variable for selection of the transmission line subjected to different constraint as to keep the system reliable at all point of time. The problem formulation is achieved using benders decomposition technique after formation of a multi-stage optimization problem. The optimization problem is solved in General Algebraic Modelling System $GAMS$. $GAMS$ is a high-level modelling system for mathematical programming and optimization. It consists of a language compiler and stable of integrated high performance solver. The software allows the user to build large complex modelling application for analytic basis. $GAMS$-based script is used to model the transmission network which includes generators, demands and transmission line respectively. The defined model in $GAMS$ have their constraints defined and solved using mixed integer linear programming solver. The $GAMS$ model provides an optimized result to the model defined while subjected to all the constraints in the model. This optimized result provides the lowest possible optimized cost for the model as well as the selected outage in the network. The model in $GAMS$ is defined in such a way that the whole network is subjected to constraints which maintain the stability and the reliability of the network at all time.

The following research questions are answered at the end of the work:

- How do you aim to minimize the loss of revenue experienced by the TSOs during maintenance planning of transmission assets?
- What can be the suitable optimization approach to solve the preventive maintenance problem of a specific asset at specific period of time?
- What is the effect of demand uncertainty on maintenance planning of transmission assets?

1.4 Research Approach

The present research complies of result of research carried out with in general algebraic modelling system $GAMS$ environment for outage scheduling for transmission line under uncertainty, for the transmission system in context of asset management.

To provide the research approach in more synthetic way with sufficient technical data and analysis, we have ordered the document from the basic theoretical understanding of the software to the final case study associated with results.

Outage scheduling problem is a multi-stage optimization problem that provides schedules for the transmission line that are ought to be taken out for maintenance while the system remains stable and the transmission system operators have the lowest loss of revenue as possible. This research work focuses on managing the constraint while uncertainty has been taken into consideration. The primary goal is to satisfy the operating constraint for the all the plausible scenario. The basic maintenance equation is defined as the summation of the two important parameters namely the transmission line maintenance cost and cost of lost load. All the constraints later are designed to fulfil the maintenance equation and decision variable associated with the maintenance equation provides with outage schedule and the optimized cost of maintenance. A standardized test case is taken in to consideration to provide benchmark result which can used for future reference of work by different researcher in the same field.

All the equations and constraints corresponding to the model for defining the outage schedule are modelled in general algebraic modelling system $GAMS$ environment. Limits on the constraints and the decision variable concerning the uncertainties all are modelled and defined in general algebraic modelling system $GAMS$. The result obtained as an Excel sheet from the $GAMS$ environment.

The research work aims to provide the optimized scheduling model which would lower the loss of revenue for the transmission system operators while taking in to consideration the uncertainties and limits in the power system.

The overall time-line with work flow can be seen in figure 1.3. The research approach comprised of the different study process starting from literature survey to test case analysis. All work flow carried out is mentioned and described in the following report.

1.5 Outline

The outline of this thesis is as follows:

- Following this introductory chapter which discuss the background and the literature survey associated with the topic, ***Chapter 2*** talks about

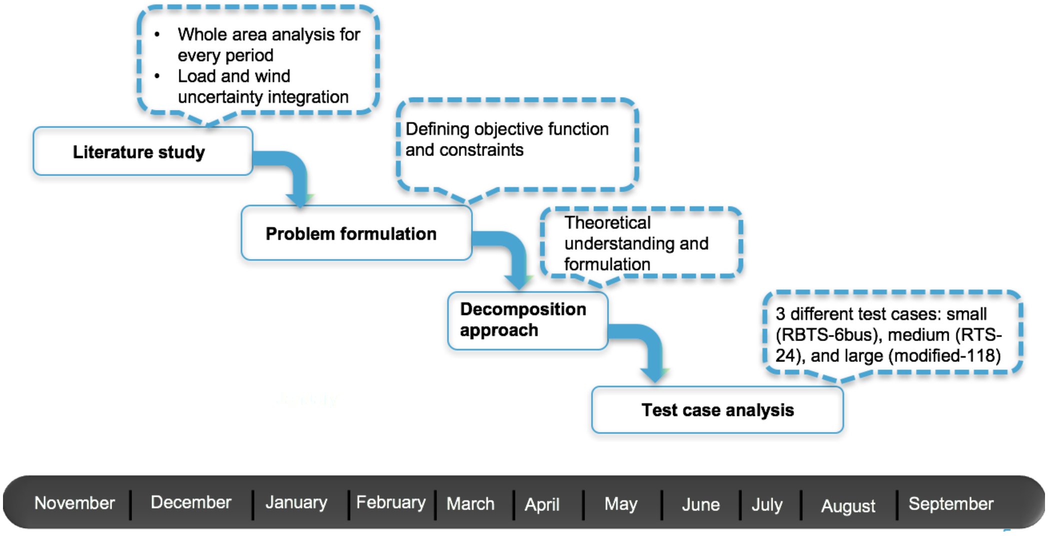


Figure 1.3: Timeline and work flow

decision making under uncertainty and its importance in maintenance scheduling of transmission line. It also discusses the type of uncertainties that comes in to play while outage scheduling is to be performed on transmission line network.

- Then, ***Chapter 3*** describes the bender decomposition algorithm in a theoretical manner. The algorithm, rule and the procedure involving the benders decomposition is explained in the chapter. An example comprising of mixed integer linear problem is solved and the general algebraic modelling system ($GAMS$) script for the solved program is given in the Appendix.

- ***Chapter 4*** talks about the problem definition concerning the maintenance schedule model. All the constraints used in modelling the maintenance scheduling in general algebraic modelling system ($GAMS$) environment are explained in this chapter in detail.

- Then, ***chapter 5*** provides the first case study comprising of three bus system. Modelling of the three-bus system is done using all the deterministic data available and the result is shown.

- ***Chapter 6*** talks about the small test case system i.e. the RBTS 6-bus system. All the constraint discussed in chapter 4 are modelled and outage schedule is displayed and result is discussed.

- ***Chapter 7*** talks about the second case study which is performed on a benchmark reliability testy case i.e. IEEE RTS-24 bus system. All the constraints discussed in the chapter4 are modelled and the outage schedule is displayed in result.

- ***Chapter 8*** talks about the large test case system i.e. the IEEE 118-bus system. All the constraint discussed in chapter 4 are modelled and outage schedule is displayed and result is discussed.
- ***Chapter 9*** concludes the research work from informative results, studied on three different systems of different size and scale. Recommendations for future work are included in this chapter too.

Chapter 2

Uncertainty

The infrastructure associated with electrical power system should sustain and remain stable for operation for many decades. This infrastructure should be able to withstand external factor such as weather change, energy demand, pollution, natural calamities and material deformation. Such external factors are exogenous variable [5]. These variables are uncertain and TSOs don't have any control over such variables. Other external factors associated with the electrical power system such as load shedding, generation dispatching and availability of human resources are called endogenous variables. The endogenous variables are also considered as uncertain parameter but these variables can be modelled using certain assumption and approach for different analysis purposes. One of the endogenous variable describes in the $GARPUR$ project is generation dispatching. Power generation dispatching is modelled in way to improve the transient stability of the power system using different modelling methodology [26]. In the electrical power system, the generation facilities have an effective operation for 30 to 50 years, whereas transmission facilities must operate for more than the generation facilities. As the transmission facilities should work more than the generation facilities, the transmission system operators should tackle most of the endogenous variable and provide decision making approach in analyzing and modelling the transmission line network. Therefore, constant outage maintenance and expansion in the transmission facilities are the long-term exercise leading to the decision that influences the long-term operation of the transmission facility[25]. The overall outage maintenance results in reduction of annual investment cost and lower the loss of revenue for the TSOs.

Decision making for a specific asset of transmission line network requires modelling of the total system. Modelling of the total system takes in account all the elements corresponding to the power system network. Models are designed to make decision on the outage schedule are necessary for long-term basis which include many variables, constraints and large number of different operating conditions[25]. In the model, there are binary variable which represent the selection of the discrete parameter and continue variable represent operating decision.

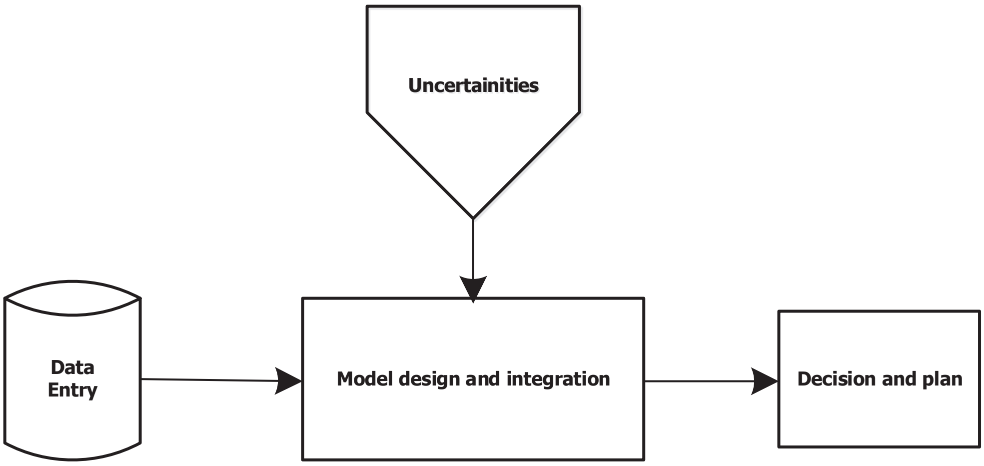


Figure 2.1: Action taken during different time-horizon.

Figure 2.1 shows the long-term decision making for the outage schedule along with the associated uncertainty. Following uncertainty is involved in modelling the outage scheduling for the maintenance .

- Change of load in future consumed by the demand located in the whole power system.
- Change of generation due to integration of non-conventional sources of energy such as wind energy and solar energy through out the power system.
- Change of operating cost of different production technologies in the power system.

However, more often than not, such input data concerning the change in load or generation is described through probability distribution function. There are two specific ways in formulating the decision making problem. Firstly, substitution of uncertain data by corresponding value which result in formulation of the optimization problem but the drawback of such approach is the obtained result is not the best outcome. Secondly, approximating the probability distribution of input data by collection of plausible set of input data. Therefore, decision need to be made with such lack of information result in use of stochastic programming model for decision under uncertainty.

2.1 Decision making under uncertainty

Operating, maintaining and scheduling of a bulk interconnected electrical power system are complex activities. These activities have to be performed with utmost precision with inclusion of uncertain nature of the of the complex power system. Many issues regarding the reliability and economy have to be addressed and right decision should be taken in order for stable and reliable power system. Mostly the decision making concerning the economic compensation is emphasized but reliability also plays an important role in decision making process. Overall concern regarding proper decision regarding the economic while considering the reliability under uncertainty plays a very vital role in the complex power system.

Generally the decision making variable is place in two categories:

- Allocation of resource which indirectly refer to control and distribution of available resources.
- Maintenance of existing component for replacement or repair.

Integration of renewable energy sources in to the complex power system has resulted in uneven distribution of generation. This distributed generation cannot have a deterministic value due to it variable nature. Similarly, the demand side of the power system is also subjected to uneven load distribution. Both of the above case are considered as scenario based uncertain conditions. Different scenarios are being formulated for different uncertain sets and this robust approach towards demand uncertainty is formulated. Such optimization models takes into consideration uncertainty as a deterministic set of possible scenario range of possible uncertain parameters.

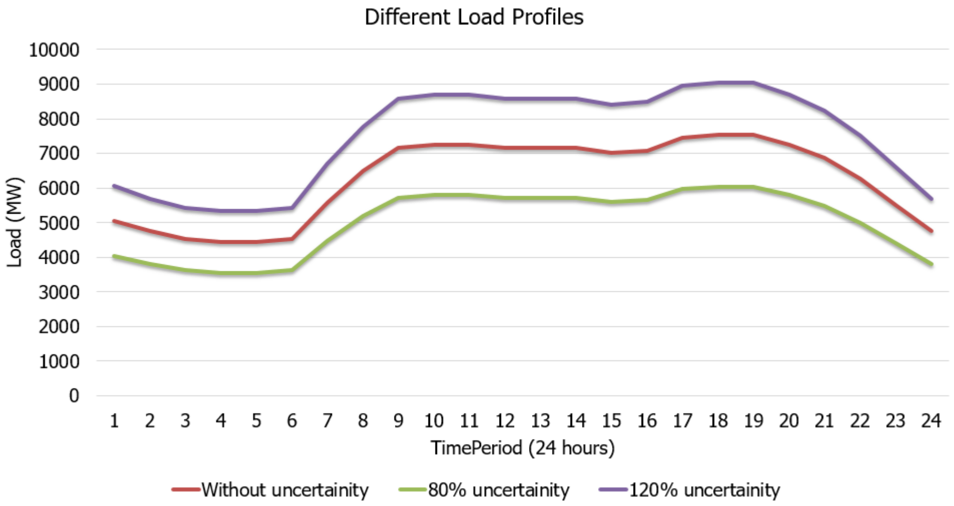


Figure 2.2: Load distribution over the period 24-h with different uncertainty sets

2.2 Demand uncertainty in asset management problem

Demand is one of the major uncertainties introduced to the power system network. To study its impact in asset management decision-making processes, it is proposed to generate yearly or hourly load time series as per the problem requirement. Demand uncertainty refers to uncertainty with respect to load profile on the demand side. A load profile on the demand side is never standard nor the same for a specific time period. In such cases, a thorough understanding of uncertainty in terms of modelling gives a better perspective of load profile. Literature study reveals that demand uncertainty is modelled using two principal approaches, one being probability distribution method and the other being deterministic approach. A study on probabilistic approach for generator maintenance scheduling was proposed in [18].

In this thesis, we have considered deterministic approach for the demand uncertainty. The advantage of deterministic modelling is that the model's outcome is certain as the input is fixed. The modelling is easy to understand and debug. A standard load profile from IEEE data sheet is taken into consideration The system data is taken form the report of IEEE reliability test system [27]. The load data formulated takes in account weekly peak load in percent of annual peak, daily peak load in percent of weekly peak, hourly load in percent of daily peak and percentage of system load on each bus. All the load data at each bus is multiplied to the peak load of the system, which in this case of IEEE reliability test system of 24-bus system is 3150 MW. All the weekly, daily, hourly, peak load of system and percent of system load on each bus is multiplied to obtain the load value at each bus at each hour.

The aim of this study is to include demand uncertainty for outage scheduling problem. For the demand data, we introduce different factors of uncertainty as per the deterministic approach. It is achieved by multiplying a specific percentage value to the load profile. For instance, in this study, two different factors of uncertainty is introduced to the demand data. Form the figure 2.2 we can observe that the blue line on the graph is the load profile with 120% uncertainty and the green line on the graph is the load profile with 80% uncertainty. The load profile is subjected to change due to percent change in load. A more detailed study as well as application to outage scheduling for different test-cases is presented later in this report in chapters 7 and 8. The change in load profile creates deterministic demand uncertainty load profile which is subjected to the required problem formulation. In figure 2.2 we can observe 24-hour load distribution for different deterministic uncertainty sets. In figure 2.2 we can observe the change in load profile when the original load profile is multiples with the percent uncertainty factor.

Wind power uncertainty is also one of the major uncertainties to the power system. Proper decision making in wind power forecast using deterministic approach will provide a constructive generation profile. This generation profile will load uncertainty will provide an optimal result for different asset management problem. This work is not covered in the thesis but it can be achieved.

Chapter 3

Benders Decomposition

Benders decomposition was first introduced by J. F. Benders for solving a large-scale mixed scale programming problem. This mixed integer programming problem may include linear, non-linear, continuous or integer problem. The benders decomposition methodology is also considered in solving complicating variable problem in a distributed manner for the cost of integration approach [25]. Moreover, the benders decomposition is profoundly adapted in solving complicated integer programming problem. Optimized result from the complicated integer problem with an advantage of reduced time for convergence are the primary goals of implementing bender decomposition algorithm.

The general format of the complicated integer problem adapted in bender decomposition is shown below :

$$Maximize \quad z = c(x) + d(y) \tag{3.1}$$

$$S.t Ax \geq b$$

$$E(x) + F(y) \geq h$$

$$x \geq 0, \quad y \epsilon Y$$

where E and F are coefficient matrix of x and y ;

x and y are vectors of continuous variable;

Y is set of integers.

3.1 Benders decomposition methodology

The equations in the complicated integer programming problem takes into account the condition that the objectives and the constraint in the equations are linear. These equations are also called as benders equations in general.

$$\begin{gathered}
Maximize \quad z = c(x) + d(y) \qquad (3.2) \\
S.tAx \geq b \\
E(x) + F(y) \geq h \\
x \geq 0, y\epsilon Y
\end{gathered}$$

The benders equations observed in equation 3.2 with their respective constraints are together called integer problems. The main problem excluding the constraints is called objective problem. This objective problem is usually subjected to minimization or maximization as per the requirement of the problem. The overall problem with the objective and the constraints is decomposed into two parts to solve the benders decomposition:

- Master problem
- Sub-problem

The master problem is considered in the first half of the decomposition problem which is subjected to the master constraints in the problem, whereas, the sub-problem is considered to be the second half of the decomposition approach which is subjected to sub-problem constraint but also feasibility as well as optimality of the optimal solution is checked to observe the convergence of the benders decomposition algorithm.

Overall basic understanding of the decomposition problem is explained below:

- **Master Problem**

  A feasible value of x^* is taken in to consideration by only considering the constraint subjected to objective equation which can be seen in equation 3.2.

  $$\begin{gathered}
  Maximize \quad \bar{z} = c(x) + \alpha(x) \qquad (3.3) \\
  S.tAx \geq b
  \end{gathered}$$

The master problem is formulated in equation 3.3 and it can be observed that the y^* variable is omitted as it corresponds to the sub-problem and $\alpha(x)$ is added to the master problem equation as it considered the piece-wise function of the optimality sub-problem which proved the optimal value as the function of master problem. $\bar{z}$ is the lower bound value of the solution and is updated for every iteration performed by optimality sub-problem.

- **Feasibility Sub-problem**

  Feasibility check generally checks whether feasible value x^* provides a feasible solution to the equation 3.2. The check is observed in terms of violation index of the master problem's solution. If the condition developed for violation is observed then the feasibility cut is added to master problem. This process repeats until feasible solution is achieved by the master problem.

  To eliminate the violation and obtain feasible solution, the feasibility cut equation is added to the master problem.

  $$v + \lambda E(x^* - x) \leq 0 \tag{3.4}$$

  Where λ is the Lagrangian multiplier vector for inequality constraint.

- **Optimality Sub-problem**

  If a feasible solution with no violation of the feasible value x^* is available then we can now define feasible value y^* as seen in equation 3.5. The value w is the value of$\alpha(x)$ at x^*.

  $$w = Min \quad d(y) \tag{3.5}$$

  Similarly to the feasibility sub-problem approach, If the obtained solution from equation 3.5 is not optimal then an optimal cut is generated and this optimal cut is added to the master problem for further analysis.

  $$w + \pi E(x^* - x) \leq \alpha \tag{3.6}$$

  From equation 3.6 it can be observed that, π is the Lagrangian multiplier vector in the inequality constraint. Therefore, this approach is called optimal sub-problem check because it check the optimality of the objective problem with respect other constraints and displays the optimal result with help of optimal cut which are being applied to the master problem.

3.1.1 Benders Decomposition rule

Optimal solution obtained from the optimal sub-problem is subjected to follow some specific set of bender rules. Some of those basic rules are mentioned below:

- Optimal solution $\bar{z}^*$ and x^* from the master problem and optimal solution from y^* from the sub=problem are too obtained.
- Small tolerance value of ϵ is taken in to consideration to control the convergence.
- Upper bound of the optimal solution as well as lower bound of the optimal value of the objective problem is calculated.
- Difference between upper bound and lower bound of the optimal problem is calculated.
- Final optimal solution is considered as optimal solution when ϵ value is greater than the difference of upper bound and lower bound value previously calculated.

3.2 Benders decomposition algorithm

A typical procedure of the benders decomposition algorithm is illustrated as follows:

1. **Initialization**

   Limit is set on number of iteration to be carried out and initially the Iteration value v is set to 1. Firstly, the master problem is solved and the optimal value of x^* is taken in to consideration to solve the sub-problem.

2. **Sub-problem solution**

   Solution obtained from the master problem is checked whether it's feasible or not. If the solution is not feasible then the feasibility cut from equation 3.4 is added to the master problem. The solution of the sub-problem also provide with the dual variable values $(\lambda_1^v, ..., \lambda_n^v)$ associated with the sub-problem.

3. **Convergence checking**

Benders rules are used to check the optimal value of the obtained solution. If optimal solution obtained is lower than declared value of ϵ, then the optimal solution is considered as the final result or else the algorithm continues to the next step. If the solution is not optimal then the optimal cut equation is added to the master problem and the simulation is again carried out.

4. **Master problem solution**

   For the next consecutive iteration, the iteration counter is updated, $v, \leftarrow v{+}1$. The master problem is solved with the optimal cut added to the master problem. Once the solution is obtained then the algorithm continues to step 2.

The overall algorithm of benders decomposition involving its feasibility and optimality is shown in figure 3.1.

3.3 Computational Example

For the computational example a generic mixed integer linear program is taken in to consideration. The following computational example has one objective equation which is supposed to provide with optimized answer subjected to two constraint equation.

$$\begin{aligned} Minimize \quad & z = 2x_1 + 6x_2 + 2y_1 + 3y_2 \\ S.T:. \quad & -x_1 + 2x_2 + 3y_1 + y_2 \geq 5 \\ & x_1 - 3x_2 + 2y_1 + 2y_2 \geq 4 \\ & x_1, x_2 \geq 0 \\ & y \epsilon Y \end{aligned} \tag{3.7}$$

The above problem 3.7 has a a similar format as of in equations 3.1. Therefore the following term A and B can be formulated as follows:

$$A = \begin{bmatrix} 3 & -1 \\ 2 & 2 \end{bmatrix};$$

$$B = \begin{bmatrix} -1 & 2 \\ 1 & -3 \end{bmatrix};$$

$$C = \begin{bmatrix} 2 & 3 \end{bmatrix};$$

$$D = \begin{bmatrix} 2 & 6 \end{bmatrix};$$

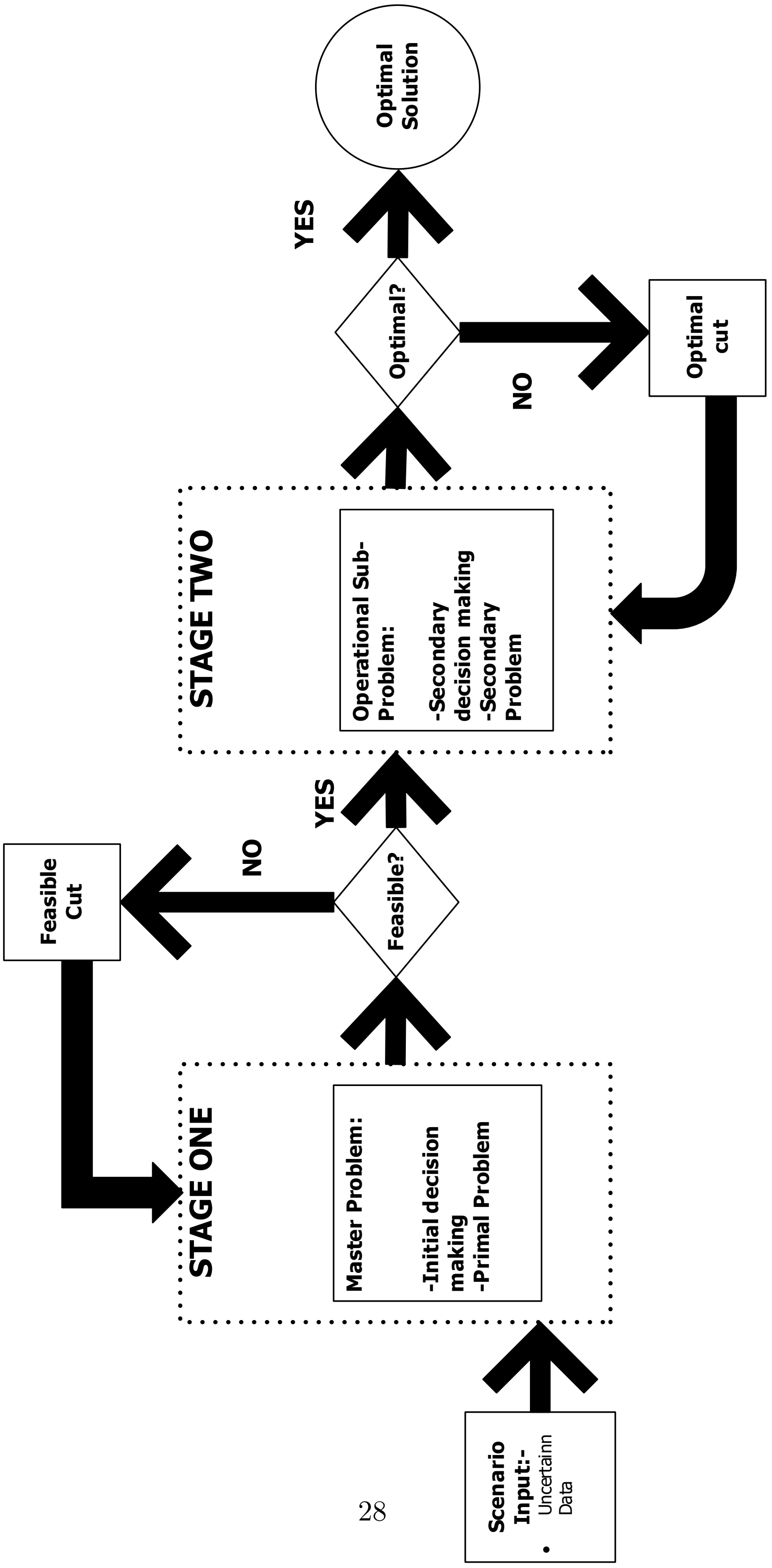


Figure 3.1: Typical benders decomposition methodology.

The process methodology to formulate and run the above problem in GAMS.

- Data file is created with all the matrix A,B, C and D. The parameter corresponding to the right hand side of the constraint are introduced and different set are created.
- Algorithm file is created separately and the data filled is called in the algorithm file by using $\$include$ command in GAMS.
- In master problem the variable and the equation are modelled and the master problem is solved using the minimizing command in GAMS.
- In sub-problem the modelling is done similar to the master problem only the lower limit associated with the variable x and the benders cut formulation is taken into consideration. Looping is performed to obtained maximum lower bound answer associated with problem and the tolerance is also checked.
- If the tolerance is with in the limit then the iteration is stopped and the final optimal result is displayed.

The above problem 3.7 is solved using two GAMS file. The optimal answer obtained from solving the problem is found to be $z = 9$.

3.4 Theoretical example

The following theoretical example is a standard theoretical example of mixed integer linear programming. The following theoretical example has one objective equation which is supposed to provide optimized answer when subjected to two constraint equation.

$$Maximize \quad z = 3x_1 + 2y_1 \tag{3.8}$$

$$S.T : .x_1 + y_1 \leq 6$$

$$5x_1 + 2y_1 \leq 20$$

$$x_1, y_1 \geq 0$$

Initially, solving the mixed integer linear problem by partitioning the linear variable in to two sets. First variable that should take integer value and the second variable that should take continues value. For the following example we consider different notation so as to specify the x who take continues value and y for integer value.

Therefore, we start the solving of the master problem by taking the following into solving;

$$Maximize \quad z = 3x_1 \tag{3.9}$$

$$S.T : .x_1 \leq 6 - y_1$$

$$5x_1 \leq 20 - 2y_1$$

$$x_1 \geq 0$$

In equation 3.9 we have written the problem in terms of x assuming that x_1 is unknown. From the above problem formulation if we say that we know the value of y, we can say that the equation 3.9 becomes $(3x_1 + constant)$ and therefore, we can right now ignore a constant in linear programming.

Now, writing the dual of the equation 3.9 as follows;

$$Minimize \quad w \begin{bmatrix} 6 - u_1 \\ 20 - u - 1 \end{bmatrix} \quad \begin{bmatrix} u_1 & u_2 \end{bmatrix}; \tag{3.10}$$

$$u_1 + 5u_2 \geq 3$$

$$u_1, u_2 \geq 0$$

Since we don't know the solution to the equation 3.10 as we don't know the value of y, we take into consideration the feasible solution to the dual be $(3, 0)$.

Therefore, we can say that $3(6 - y_1)$ is the value of the objective function corresponding to the feasible solution to minimization problem. As it is a feasible solution to the minimization problem it sis an upper bound to the optimal solution to the equation 3.10. In minimization problem the objective function value of a feasible solution is greater than or equal to that of the optimal problem.

Thus, $3(6 - y_1)$ is the upper bound to w.

By the duality theorem we know that the objective function of the every feasible solution tot he dual is greater than or equal tot he objective function value of every value's every feasible solution to the primal. Thus if the objective function refereed in equation3.8 becomes $z \leq 3(6 - y_1)$.

Therefore, rewriting the problem by referring to equation 3.7 as;

$$Maximize \quad z \leq 2y_1 + 3(3(6 - y_1))$$

Solving for y_1,

$$Therefore, \quad z \leq 18 - y_1$$

Thus the optimal solution the above equation for $(y_1 = 0)$ is $z = 18$.

Now, we substitute the known value of y_1 to the dual formulation in equation 3.9.

Therefore,

$$Minimize\ w = 6u_1 + 20u_2 \tag{3.11}$$

$$u_1 + 5u_2 \geq 3$$

$$u_1, u_2 \geq 0$$

Solving equation 3.11 which is referred as single constraint linear programming problem, we get the optimal solution of $u_1 = 0$ and $u_2 = 3/5$ to be $w = 12$. The solution on the primal side is higher than the solution on the dual side. the solution on the primal side should come down as at some point the objective function value of the primal side and dual side have to match.

Now, as we know that $u_2 = 3/5$ the objective function in equation 3.10 becomes $3/5(20 - 2y_1)$.

Therefore, introducing new upper bound constraint for minimization of z.

$$Minimize \quad z \tag{3.12}$$

$$z \leq 18 - y_1$$

$$z \leq 3/5(20 - 2y_1) + 2y_1$$

$$z, y_1 \geq 0, integer$$

Simplifying the constraints to solve for the value of z.

Therefore,

$$z \leq 18 - y_1$$

$$z \leq 12 + 4/5(y_1)$$

Obtaining the optimal value of y_1 using tabular method.

Therefore, we can say that $y_1 = 3 \quad or \quad 4$ is the optimal to the z.

But, we firstly consider $y_1 = 3$ because when we substitute $y_1 = 3$ in equation 3.9 we calculate the value of z to be 72/5 which is greater than 14. This simply means that the primal is giving solution 14 and the dual is giving solution 72/5 which satisfy the duality theorem. The only reason both the value are not same is because we have considered the variable y_1 to be integers.

Table 3.1: Optimal value of y_1

y_1	z
0	12
1	12
2	13
3	14
4	14
5	13

Now, substituting the value of y_1 to the master problem in equation 3.9 and obtaining the value of $x_1 = 14/5$.

Therefor, the value of z is equal to 72/5.

But, we also have another value of y_1 to be equal to 4 ans similairy finding the value of x_1 and z. the value of $x_1 = 2$ and the value of $z = 14$.

From both the solution we chose the first solution with $y_1 = 3$ and $z = 72/5$ because as its a maximization problem we have to consider the maximum optimal solution to the objective function.

Chapter 4

Problem Definition

In today's world, due to the expansion and the advancement in the power system it is observed that the topological structure of the power system is becoming more and more complex. The expansion has also resulted in increase in number of assets in the power system. As the number of assets are increasing, the reliability analysis of the assets will play an important role in maintaining the system more reliable. Due to all such analysis involving the different assets from various sector of the power system the reliability of the power system is going top increase.

In the thesis, objective of the proposed approach is to perform maintenance planning of transmission asset under uncertainty for a long-term horizon. The approach will provide an optimal schedule for a specified transmission line in the power system network with an aim of reducing the total maintenance cost involving the loss of revenue for TSOs as well as by keeping the reliability of the power system at its prime. The transmission asset considered in this thesis is the transmission line. The result of the analysis is to be able to formulate an optimal outage schedule of the transmission line of the designed network for the lowest loss of revenue for the TSOs. The objective function in the problem formulation has two variables that should be addressed to provide optimal maintenance schedule with lowest possible maintenance cost. As the optimization problem consist of two variables, decomposition approach is to be implied to solve the optimization problem with more accurate and precise result. The decomposition approach used for problem is the benders decomposition algorithm. The benders decomposition algorithm was proposed by J. F. Bender [28]. The proposed technique is widely used in solving large mixed integer problem with multiple constraint subjected to objective function. The result from the decomposition technique has proven to be more accurate. The problem formulation of the maintenance planning of the transmission assets under uncertainty consists of large constraint which take in to consideration time bound, network balance and uncertainty terms. All these term in problem formulation makes the formulation more complex, and thus solving the problem with normal linear programming approach make its less accurate and time consuming.

Figure 4.1 shows the basic flowchart of the benders decomposition approach to be used in the problem formulation. As from the flowchart, it can be observed that benders decomposition approach solves the mixed integer linear programming problem in to two parts. The first part being the master problem and second part being the sub problem. Every part of the problem is subjected to the modelled constraint. The result from the algorithm will provide the optimal solution in term of lowest possible maintenance cost and the best possible schedule of the transmission planning for the specified network.

4.1 Duality

The concept of duality plays a very important role in solving the benders decomposition technique. In principle, the concept of duality implies that every linear programming problem has dual whose objective function i.e. (for example, maximization changes to minimization). But if the primal problem has a finite optimal solution its dual after changing the objective function, there exists a finite optimal solution. Another example to explain primal and dual is that if the primal has an unfeasible solution then the dual also should have an unfeasible or unbounded solution.

The primal problem can be expressed as following notation:

$$\begin{gathered} Maximize \quad z = c^T.x \\ S.t Ax \leq b \\ x \leq 0 \end{gathered} \tag{4.1}$$

where c and x is n-vector;

b is m vector;

A is m x n matrix.

The following dual of the above equation is formulated as:

$$Maximize \quad z = b^T.x \tag{4.2}$$

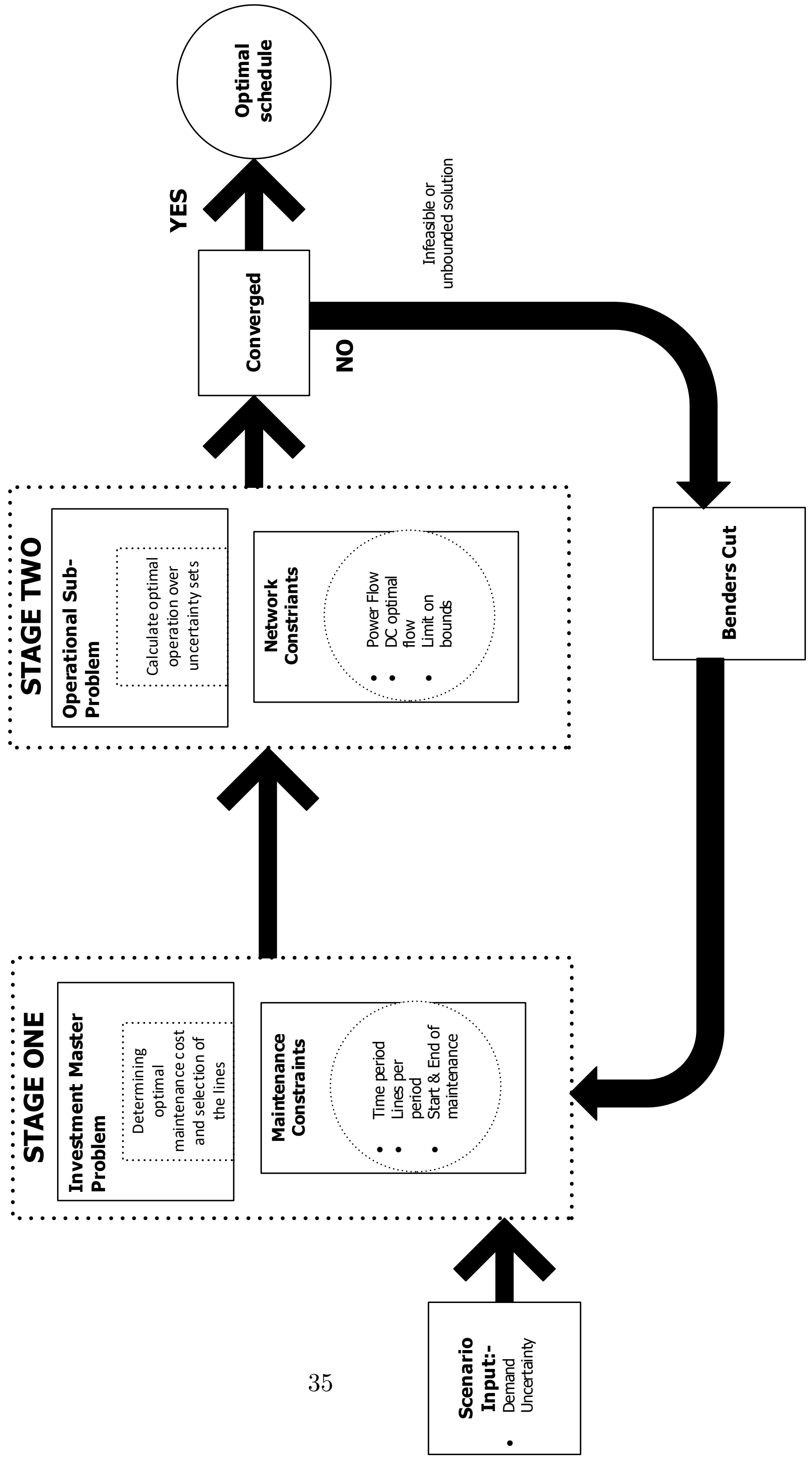


Figure 4.1: Benders decomposition flowchart.

$$S.tAx \geq b$$

$$x \geq 0$$

In the above notation for primal problem, we can observe that the constraints indicated for the objective function acts as feasible region constraints for the minimizing objective function. The feasible region constraints imply that optimal solution to the objection function should lie between that region.

The basic transformation of primal to dual is done to reduce the number of constraints associated with primal objective function. The transformation from primal to dual also reduces the complexity of the objective function. As the number of constraints reduce, the number of inequalities are increased which helps in solving the objective function. Increase in inequalities reduces the complexity of the linear programming problem

4.2 Problem Formulation

The objective of the proposed approach is to perform maintenance planning of transmission asset under uncertainty for long-term horizon. The transmission line is the transmission asset considered in the part of problem formulation. Outage schedule of the transmission line while the system satisfies all the constraints formulated in the model is the transmission planning objective of the problem formulation.

Some of the widely-accepted cost based analysis research work is explained in the following paragraph. Cost based analysis for the transmission network is one complex analysis because lot of factors are involved in modelling the transmission network and indication every single component in the analysis results in increase in the complexity of the modelling and analysis. According to the following six paper[19][29][30][31][32][33][9] the complexity of the transmission network maintenance cost is very complex and hard to determine the precise cost. Some major research has been done on the marginal cost analysis.The cost determination also includes the marginal cost which indicate the marginal increase the cost when in 1 KW of increase or decrease of transferred power is observed [29]. Opportunity cost, operating cost and existing system cost are also considered in the maintenance cost while deciding for a short-term analysis. Wheeling transaction is also one the profound concept which determines the total transmission network evaluation in term of cost. Wheeling transaction in broad sense means transaction of power to other entity by utility that neither generates nor intend to use the power beyond its nature demand. The methodology used in wheeling transaction consists of MW-Mile method [31]. In MW-Mile methodology the length of the transmission line is multiplied by the transmitted power and the overall transaction is calculated. The main drawback of the MW-Mile methodology was lumping observed between operating cost and existing system cost.

The advanced approach in this thesis for transmission line outage schedule take in account the whole transmission network, transmission charges, network constraint and reliability. All the problem formulation is done according to the benders decomposition methodology.

Now, the main objective of the problem formulation for the transmission line outage schedule at minimized cost and lower loss of revenue for the TSOs while satisfying the system reliability is formulated [30] as follows:

$$Min \quad Z \quad \sum_{t}(\sum_{l} C_{lt}(X_{lt}) + \sum_{i}(c_{it}r_{it}) \tag{4.3}$$

The above objective function of the problem formulation has two terms. The first term determines the total maintenance cost of the selected transmission line maintenance for outage schedule and the second determines the total loss of revenue by the TSOs due to loss of load when the transmission line is subjected to an outage schedule. The overall equation provides an optimized maintenance cost for the selected transmission line in the network and an outage schedule for the selected transmission line for the schedule.

The objective function specified in the equation 4.3 is subjected to different constraint as per the requirement of the network and the TSO's. The constraints are to be defined to get the most efficient solution for the maintenance problem. In the thesis two main types of the constraints are defined. Maintenance constraints and the network constraints the two type of constraint defined for the objective function problem.

4.2.1 Maintenance constraint

The maintenance constraint takes in to account the number of candidate line in right of way and the maximum number of line allowed in right of way. While deciding the candidate line, the candidate should be available before the earliest period e_k and after the latest period i.e $l_k + d_k$. The maintenance constraint can be stated as[9]:

$$X_{lt} = 1, \quad \text{for} \quad t \leq e_k or \quad t \geq l_k + d_k \tag{4.4}$$

$$X_{lt} = 0, \quad \text{for} \quad s_k \leq t \leq s_k + dk$$

$$X_{lt}\epsilon \quad (0,1), \quad \text{for} \quad e_k \leq t \leq l_k$$

The above set of constraints provides the information to which transmission line is to be selected for outage from the given time window in order to obtain the minimized maintenance cost.

4.2.2 Network Constraint

The system constraint takes in account the voltage, power and the reliability aspect of the transmission network. The system constraints for every scenario are as follows [30] :

$$sf + p + r = d \tag{4.5}$$

Equation 4.5 is the power balance equation. This equation result in generation and demand balance at each node.

$$f_k - \gamma_k(\theta_k - \theta n) = 0 \tag{4.6}$$

Equation 4.6 is the power flow through existing line in the power system.

$$-PL_{jmax} \leq f_k \leq -PL_{jmin} \tag{4.7}$$

$$P_{Gi_{min}} \leq P_{Gi_{bt}} \leq P_{Gi_{max}} \tag{4.8}$$

All the above equation contribute towards network constraints for optimal scheduling of transmission line.

All the network in the analysis are considered to be dc model without losses. All the considering consist of voltage magnitudes are considered approximately constant in the system and that voltage angle differences are small enough between two connected nodes. This allows us to formulate power equation using linear expression.

Chapter 5

Case Study: 3-bus system

In order to test the scheduling method, a 3-bus network was used in this thesis. An example of a simple 3-bus system is shown in figure 5.1. A single deterministic time period has been considered for this specific case study. The transmission line has a capacity of 0.5 units. The data of the generators is provided in table 5.1. Table 5.2 provides with transmission line data. Table 5.2 also provides the cost of maintenance for each transmission line. Table 5.3 provides with the information of load data and cost of load shedding during maintenance.

Table 5.1: Generator data

Generator	Node	Max Power per units	Output
G1	N1	2.5	1
G2	N2	2.5	2
G3	N3	3.0	3

Table 5.2: Transmission line data

Transmission line	From node	To node	Max capacity	Cost(dollar/line)
1	1	2	0.5	200
2	1	3	0.5	300
3	1	2	0.5	100

Table 5.3: Demand data

Demand	Node	Demand
D1	N1	1
D2	N2	2
D3	N3	1

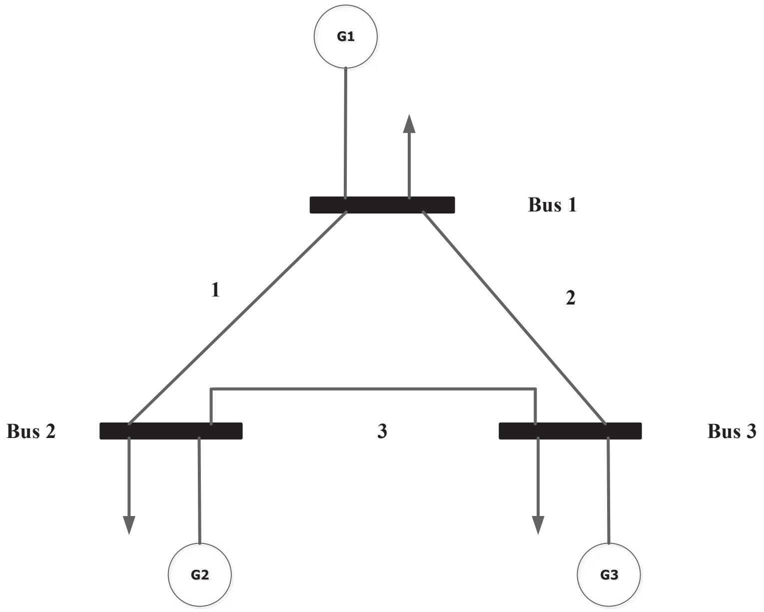


Figure 5.1: 3-bus system.

The proposed model in problem definition is applied to 3-bus test from [34] as shown in figure 5.1. The system include 3 buses, 3 generators , 3 demands and 3 lines.

A Data

- Generator data is given in table 5.1. We consider the maximum and minimum limits of the each generator in the network. We also define the deterministic value associated with the generator in the table of the generator.
- Transmission line data is given in the table 5.2. We have considered the upper limit of the transmission line in order for better performance of the model.Susceptance is also shown table of transmission line data.
- Demand data is given in the table 5.3. We also consider the deterministic data associated with demand which can be seen in the table of demand data.

The presented case study is solved in GAMS 23.5 using *CPLEX* solver. *CPLEX* solver is used for benders decomposition algorithm implementation in the model.

B Result & discussion

The result obtained are depicted in figure 5.2 and table 5.4. The figure shows the selecting of transmission line for the outage maintenance and the table shows the optimal cost required for maintenance outage.

From the result one can observe that selection of transmission line 1 and 2 at the deterministic time period will provide the lowest possible maintenance cost as compared to any other combination during the line outage and also satisfies all the constraints.

The *GAMS* code for the 3-bus case study is presented in **Appendix-I** for reference purpose.

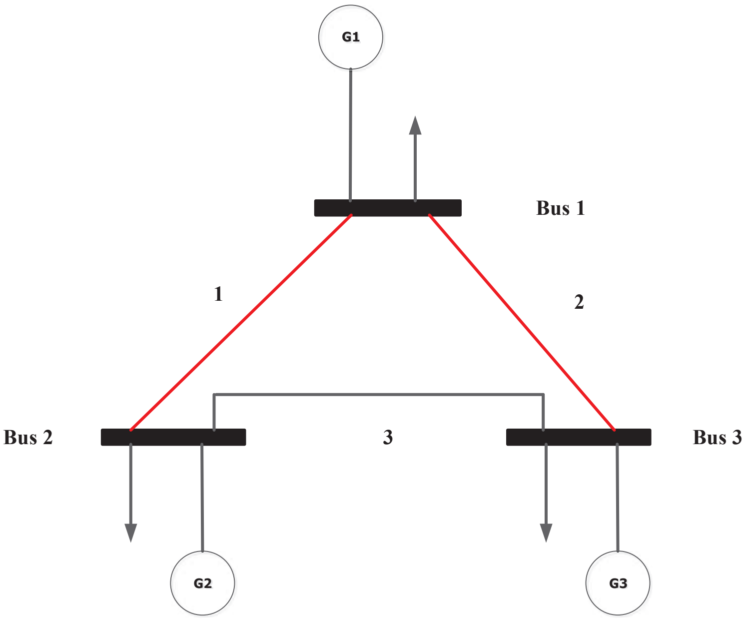


Figure 5.2: 3-bus system result.

Table 5.4: 3-bus Result

Lines	Optimal Cost
1 & 2	300

Chapter 6

Case Study: IEEE RBTS 6-bus system

In order to test the scheduling method a IEEE RBTS 6-bus network was used in this thesis. The 6-bus system is shown in figure 6.1 . Table 6.1 provides with transmission line data. Table 6.2 provided with the load data in terms of percentage for 26-week period. The annual peak load for the test case is 3150 MW. Table 6.3 give the upper limit and lower limit on every generator in the network.

The proposed model in problem definition is applied to IEEE RBTS 6-bus test from [34] as shown in figure 6.1. The system include 6 buses, 2 generators, 5 demands and 9 transmission lines.

Table 6.1: Transmission line data for IEEE RBTS 6-bus system

Transmission line	From node	To node	Max capacity
1	1	2	193
2	1	3	208
3	1	5	208
4	2	4	208
5	2	6	208
6	3	9	208
7	3	24	510
8	4	9	208
9	5	10	208

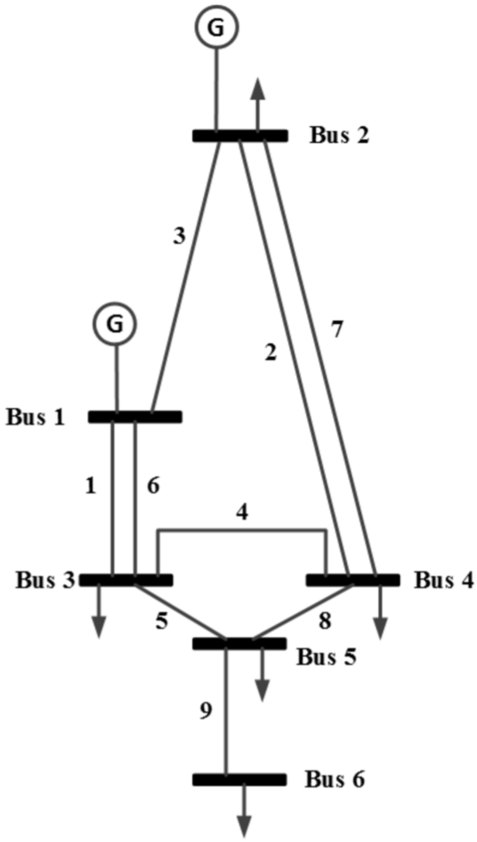


Figure 6.1: IEEE RBTS 6-bus system

A Data

- From table 6.1, the upper limit of the transmission line is considered o improve the performance order for better performance of the model.

The presented case study is solved in GAMS 23.5 using CPLEX solver. CPLEX solver is used for benders decomposition algorithm implementation in the model.

B Result & discussion

- The result in figure 6.2 displays the outage schedule.
- The obtained schedule is plotted between transmission line and time (hours).

Table 6.2: Weekly peak load in percentage of annual peak for IEEE RBTS 6-bus system

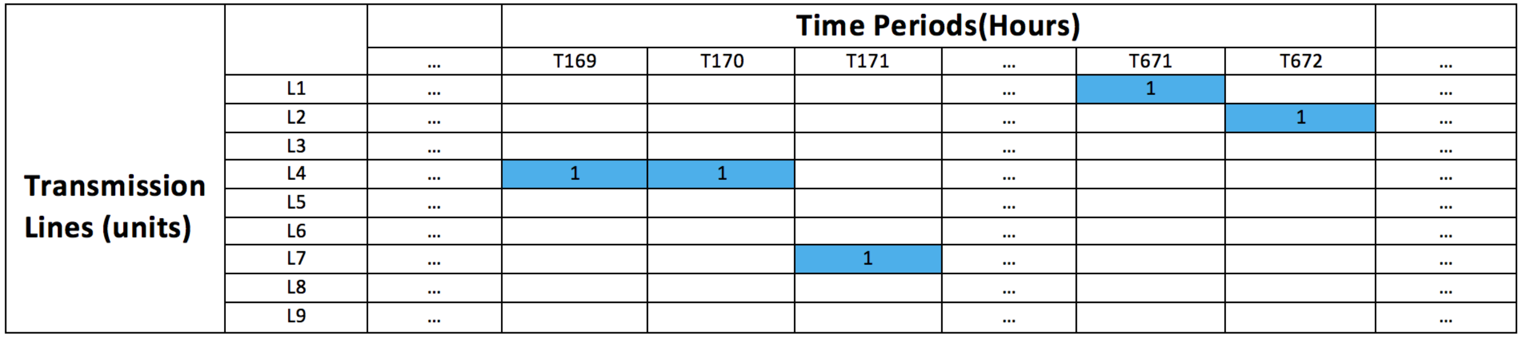
Week	Peak Load
1	86.2
2	90
3	87.8
4	83.4
5	88

Table 6.3: Generating unit data for IEEE RBTS 6-bus system

Gen no.	P^{max}	P^{min}
1	200	60
2	200	60

- The schedule displays the selected transmission line for a specific time.
- The constraint defined for the specific schedule allows only one transmission line to be taken out for outage maintenance for each period.
- The defined constraint can be changed according the the requirement of the TSOs as well as the time period can be altered as per requirement of the TSOs.
- The schedule displayed in figure 6.2 has fulfilled all the required constraint defined in problem formulation and optimal schedule been displayed.

.



Transmission Lines (units)			Time Periods(Hours)						
		...	T169	T170	T171	...	T671	T672	...
	L1	...				...	1		...
	L2	...				...		1	...
	L3	...				...			...
	L4	...	1	1		...			...
	L5	...				...			...
	L6	...				...			...
	L7	...			1	...			...
	L8	...				...			...
	L9	...				...			...

Figure 6.2: IEEE 6-bus system outage schedule for 5 week analysis.

Chapter 7

Case Study: IEEE RTS 24-bus system

In order to test the scheduling method a IEEE RTS 24-bus network was used in this thesis. The 24-bus system is shown in figure 7.1 . Table 7.1 provides with transmission line data. Table 7.2 provided with the load data in terms of percentage for 26-week period. The annual peak load for the test case is 3150 MW. Table 7.3 give the upper limit and lower limit on every generator in the network.

The proposed model in problem definition is applied to IEEE RTS 24-bus test from [34] as shown in figure 7.1. The system include 24 buses, 32 generators, 17 demands and 33 lines.

A Data

- In table 7.1 of transmission line data, we have considered the upper limit of the transmission line in order for better performance of the model.

The presented case study is solved in GAMS 23.5 using *CPLEX* solver. *CPLEX* solver is used for benders decomposition algorithm implementation in the model.

Table 7.1: Transmission line data for IEEE RTS 24-bus system

Transmission line	From node	To node	Max capacity
1	1	2	193
2	1	3	208
3	1	5	208
4	2	4	208
5	2	6	208
6	3	9	208
7	3	24	510
8	4	9	208
9	5	10	208
10	6	10	193
11	7	8	208
12	8	9	208
13	8	10	208
14	9	11	510
15	9	12	510
16	10	11	510
17	10	12	510
18	11	13	600
19	11	14	600
20	12	13	600
21	12	23	600
22	13	23	600
23	14	16	600
24	15	16	600
25	15	21	600
26	15	24	600
27	16	17	600
28	16	19	600
29	17	22	600
30	18	21	600
31	19	20	600
32	20	23	600
33	21	22	600

Table 7.2: Weekly peak load in percentage of annual peak for IEEE RTS 24-bus system

Week	Peak Load
1	86.2
2	90
3	87.8
4	83.4
5	88
6	84.1
7	83.2
8	80.6
9	74
10	73.7
11	71.5
12	72.7
13	70.4
14	75
15	72.1
16	80
17	75.4
18	83.7
19	87
20	88
21	85.6
22	81.1
23	90
24	88.7
25	89.6
26	86.1

Table 7.3: Generating unit data for IEEE RTS 24-bus system

Gen no.	P^{max}	P^{min}
1	12	2.40
2	12	2.40
3	12	2.40
4	12	2.40
5	12	2.40
6	20	4.0
7	20	4.0
8	20	4.0
9	20	4.0
10	20	4.0
11	76	15.20
12	76	15.20
13	76	15.20
14	100	25.00
15	100	25.00
16	100	25.00
17	100	25.00
18	100	25.00
19	100	25.00
20	155	54.25
21	155	54.25
22	155	54.25
23	155	54.25
24	197	68.95
25	197	68.95
26	197	68.95
27	197	68.95
28	197	68.95
29	197	68.95
30	350	140.95
31	400	100
32	400	100

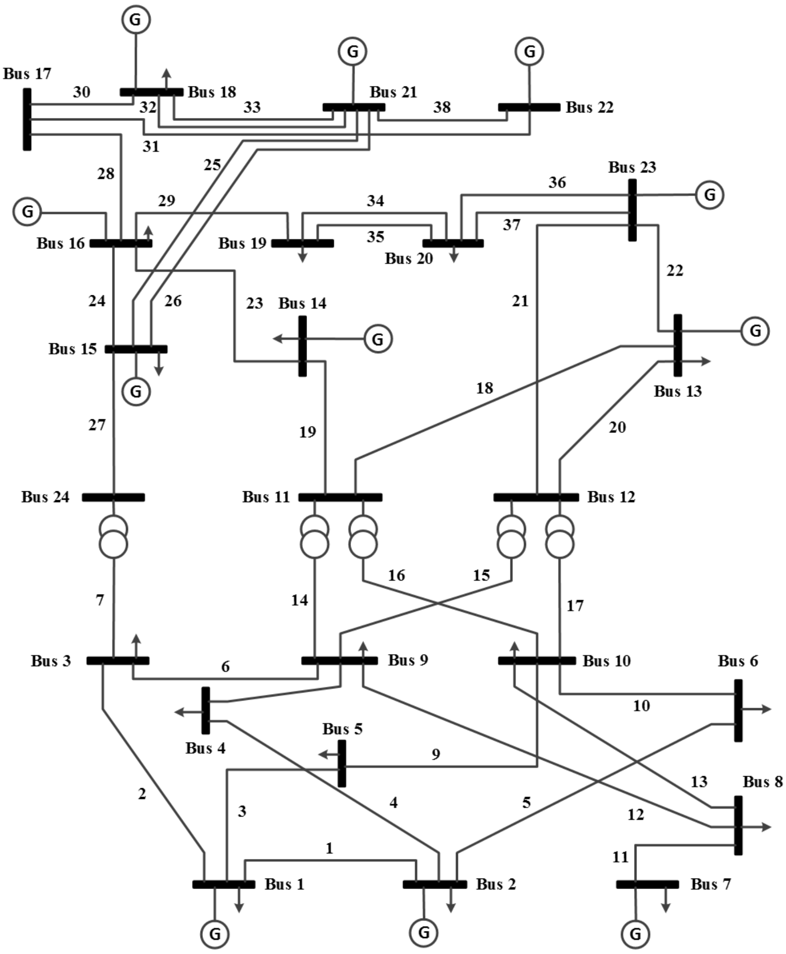


Figure 7.1: IEEE RTS 24-bus system.

B Result & discussion without uncertainty

- The result in figure 7.2 displays the outage schedule without uncertainty.
- The obtained schedule is plotted between transmission line and time (hours).
- The schedule displays the selected transmission line for a specific time.
- The constraint defined for the specific schedule allows only one transmission line to be taken out for outage maintenance for each period.
- The defined constraint can be changed according to the requirement of the TSOs as well as the time period can be altered as per requirement

of the TSOs.

- The schedule displayed in figure 7.2 has fulfilled all the required constraint defined in problem formulation and optimal schedule been displayed.

.

C Result & discussion with uncertainty

- The result in figure 7.3 displays the outage schedule with uncertainty.
- The obtained schedule is plotted between transmission line and time (hours).
- The schedule displays the selected transmission line for a specific time.
- The constraint defined for the specific schedule allows only one transmission line to be taken out for outage maintenance for each period.
- The defined constraint can be changed according to the requirement of the TSOs as well as the time period can be altered as per requirement of the TSOs.
- The schedule displayed in figure 7.3 has fulfilled all the required constraint defined in problem formulation and optimal schedule been displayed.
- A deterministic uncertainty of 20 percentage was considered for the analysis and the schedule was displayed in figure 7.3.
- The schedule displayed under uncertainty has different schedule than that of without uncertainty.

.

Transmission Lines (units)			Time Periods(Hours)						
		...	T168	T169	T170	...	T671	T672	...
	L1	...				...			...
	L2	...				...			...
	L3	...				...			...
	L4	...				...			...
	L5	...				...			...
	L6	...				...			...
	L7	...				...			...
	L8	...				...			...
	L9	...				...			...
	L10	...				...			...
	L11	...				...			...
	L12	...				...			...
	L13	...				...			...
	L14	...				...			...
	L15	...				...			...
	L16	...				...			...
	L17	...	1			...			...
	L18	...				...			...
	L19	...				...			...
	L20	...				...			...
	L21	...				...			...
	L22	...			1	...			...
	L23	...				...		1	...
	L24	...				...			...
	L25	...				...	1		...
	L26	...				...			...
	L27	...				...			...
	L28	...		1		...			...
	L29	...				...			...
	L30	...				...			...
	L31	...				...			...
	L32	...				...			...
	L33	...				...			

Figure 7.2: IEEE 24 bus system outage schedule for 5 week analysis.

			Time Periods(Hours)					
		...	T168	T169	T170	...	T671	T672	...
Transmission Lines (units)	L1	...				...			...
	L2	...				...			...
	L3	...				...			...
	L4	...				...			...
	L5	...				...			...
	L6	...				...			...
	L7	...				...	1		...
	L8	...				...			...
	L9	...				...			...
	L10	...				...			...
	L11	...				...			...
	L12	...				...			...
	L13	...				...			...
	L14	...				...			...
	L15	...				...			...
	L16	...				...			...
	L17	...				...			...
	L18	...				...			...
	L19	...				...			...
	L20	...			1	...			...
	L21	...				...			...
	L22	...				...			...
	L23	...				...			...
	L24	...				...		1	...
	L25	...				...			...
	L26	...				...			...
	L27	...				...			...
	L28	...	1			...			...
	L29	...				...			...
	L30	...				...			...
	L31	...				...			...
	L32	...		1		...			...
	L33	...				...			...

Figure 7.3: IEEE 24 bus system outage schedule for 5 week analysis with load uncertainty.

Chapter 8

Case Study: IEEE 118-bus system

In order to test the scheduling method a IEEE 118-bus network was used in this thesis. The main aim of selecting this specific 118-bus system is in order to study models of different sizes and analyze the result. The 118-bus system is shown in figure 8.1. The annual peak load for the test case is 3150 MW. The generator data, transmission line data, demand data and bus data is been attached in appendix II.

The proposed model in problem definition is applied to IEEE 118-bus test from [34] as shown in figure 8.1. The system include 118buses, 19 generators, 118 demands and 185 lines.

The presented case of 118-bus system is divided in to three sections. The algorithm for the outage schedule has been adopted for one of the section highlighted in red. The highlighted section has 52 transmission line, 31 demands , 5 generating units and 32 buses.

The presented case study only takes in account only one section of the network as the whole network simulation requires high-end computer processor with high-end RAM memory to complete the simulation.

The presented case study is solved in GAMS 23.5 using *CPLEX* solver. *CPLEX* solver is used for benders decomposition algorithm implementation in the model.

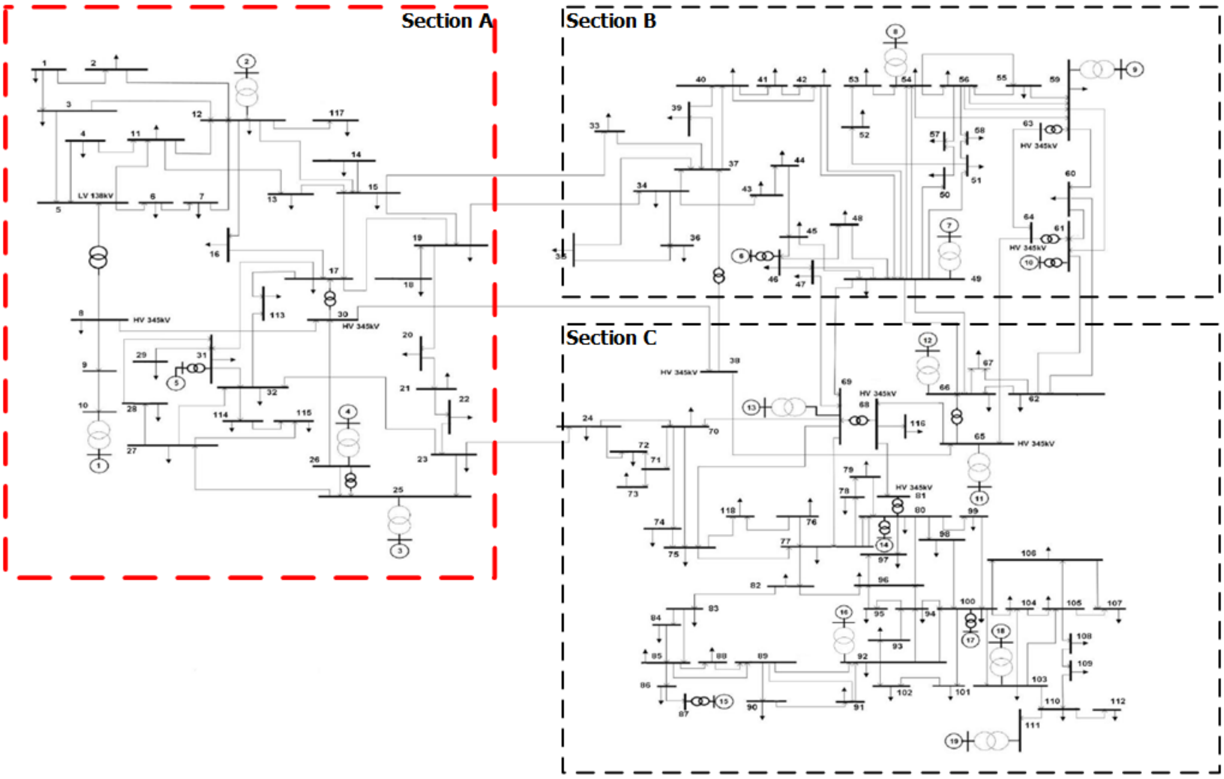


Figure 8.1: IEEE 118-bus system.

A Result & discussion without uncertainty

- The result in figure 8.2 displays the outage schedule without uncertainty.
- The obtained schedule is plotted between transmission line and time (hours).
- The schedule displays the selected transmission line for a specific time.
- The constraint defined for the specific schedule allows only one transmission line to be taken out for outage maintenance for each period.
- The defined constraint can be changed according to the requirement of the TSOs as well as the time period can be altered as per requirement of the TSOs.
- The schedule displayed in figure 8.2 has fulfilled all the required constraint defined in problem formulation and optimal schedule been displayed.

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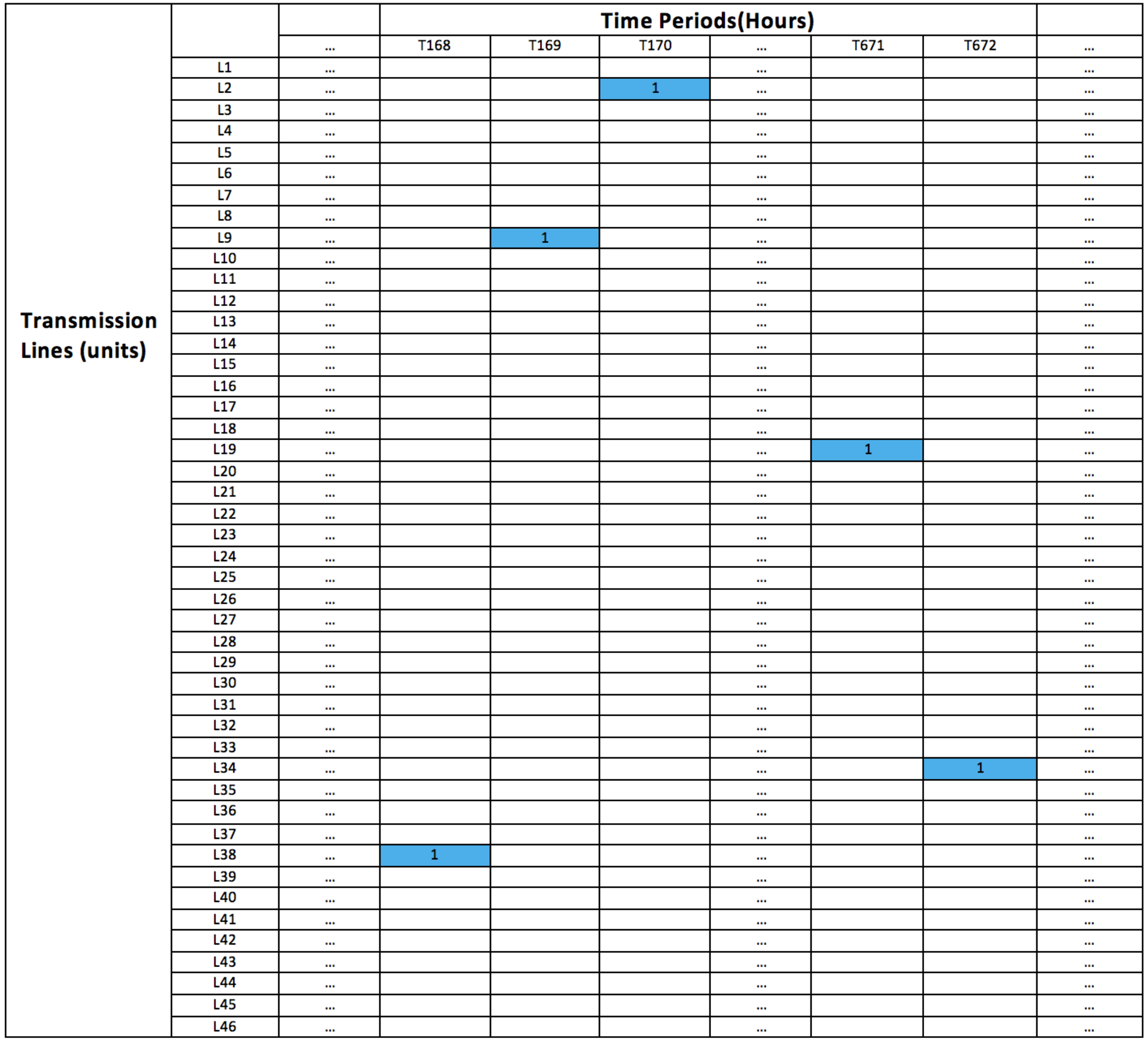

			Time Periods(Hours)						
		...	T168	T169	T170	...	T671	T672	...
Transmission Lines (units)	L1	...				...			...
	L2	...			1	...			...
	L3	...				...			...
	L4	...				...			...
	L5	...				...			...
	L6	...				...			...
	L7	...				...			...
	L8	...				...			...
	L9	...		1		...			...
	L10	...				...			...
	L11	...				...			...
	L12	...				...			...
	L13	...				...			...
	L14	...				...			...
	L15	...				...			...
	L16	...				...			...
	L17	...				...			...
	L18	...				...			...
	L19	...				...	1		...
	L20	...				...			...
	L21	...				...			...
	L22	...				...			...
	L23	...				...			...
	L24	...				...			...
	L25	...				...			...
	L26	...				...			...
	L27	...				...			...
	L28	...				...			...
	L29	...				...			...
	L30	...				...			...
	L31	...				...			...
	L32	...				...			...
	L33	...				...			...
	L34	...				...		1	...
	L35	...				...			...
	L36	...				...			...
	L37	...				...			...
	L38	...	1			...			...
	L39	...				...			...
	L40	...				...			...
	L41	...				...			...
	L42	...				...			...
	L43	...				...			...
	L44	...				...			...
	L45	...				...			...
	L46	...				...			...

Figure 8.2: IEEE 118 bus system outage schedule for 5 week analysis.

B Result & discussion with uncertainty

- The result in figure 8.3 displays the outage schedule with uncertainty.
- The obtained schedule is plotted between transmission line and time (hours).

- The schedule displays the selected transmission line for a specific time.
- The constraint defined for the specific schedule allows only one transmission line to be taken out for outage maintenance for each period.
- The defined constraint can be changed according to the requirement of the TSOs as well as the time period can be altered as per requirement of the TSOs.
- The schedule displayed in figure 8.3 has fulfilled all the required constraint defined in problem formulation and optimal schedule been displayed.
- A deterministic uncertainty of 20 percentage was considered for the analysis and the schedule was displayed in figure 8.3.
- The schedule displayed under uncertainty has different schedule than that of without uncertainty.

.

Transmission Lines (units)			**Time Periods(Hours)**						
		...	T168	T169	T170	...	T671	T672	...
	L1	...				...			...
	L2	...				...			...
	L3	...				...			...
	L4	...				...			...
	L5	...				...			...
	L6	...				...			...
	L7	...				...			...
	L8	...				...			...
	L9	...				...			...
	L10	...				...			...
	L11	...				...			...
	L12	...				...		1	...
	L13	...				...	1		...
	L14	...				...			...
	L15	...				...			...
	L16	...				...			...
	L17	...				...			...
	L18	...				...			...
	L19	...				...			...
	L20	...				...			...
	L21	...				...			...
	L22	...				...			...
	L23	...				...			...
	L24	...				...			...
	L25	...				...			...
	L26	...				...			...
	L27	...				...			...
	L28	...				...			...
	L29	...				...			...
	L30	...				...			...
	L31	...				...			...
	L32	...		1		...			...
	L33	...				...			...
	L34	...				...			...
	L35	...				...			...
	L36	...				...			...
	L37	...				...			...
	L38	...	1			...			...
	L39	...				...			...
	L40	...				...			...
	L41	...				...			...
	L42	...				...			...
	L43	...				...			...
	L44	...				...			...
	L45	...			1	...			...
	L46	...				...			...

Figure 8.3: IEEE 118 bus system outage schedule for 5 week analysis with load uncertainty.

Chapter 9

Conclusion & Future work

This chapter concludes the research work carried out on outage scheduling for different test cases under uncertainty. The research questions that were the motivation towards this research work are answered in this chapter too. In addition, recommendation for future work is also presented at the end of this chapter.

9.1 Conclusion

It is important to brief the main outcomes of this research work at the first instance, and is presented below:

- Problem formulation involving the maintenance constraints as well as the network constraints were modelled as to develop an optimal maintenance outage schedule for the TSOs.
- Modelling of the network in the GAMS environment was simplified for easy understanding of the constantly evolving complex power system network. As the modelling is done in GAMS, the software remains the benchmark software by many TSOs for maintenance scheduling.
- Adaptability of the GAMS code with respect to various network topology reduce the transfer time and adaptation time.
- New constraints for maintenance scheduling was developed to satisfy the network requirement while keeping the system constantly reliable.
- The developed modelling algorithm can be used to provide outage schedule for the transmission asset for a required time period.

- Specific area in the whole power system can be also selected and the analysis can be performed to find the optimal schedule for the selected transmission asset.

- The developed modelling algorithm also takes into consideration the deterministic uncertainty with respect to the load change due to external factor effecting the power system.

- The developed modelling algorithm give a direct freedom for the scheduler to increase or decrease the number of line that can be carried out for maintenance at a specific period of time.

- The developed modelling algorithm has been tested on small, medium and large test case system which are accepted on IEEE standards.

- The developed modelling algorithm will work as a base work for another master student in order to optimize the algorithm and get optimal result.

9.2 Answer to Research Questions

The research questions formulated in the introduction chapter are answered below:

1. **How do you aim to minimize the loss of revenue experienced by the TSOs during maintenance planning of transmission assets?** The loss of revenue experienced by the TSOs during maintenance planning of transmission assets is due to loss of load and maintenance cost of the specific transmission assets. Loss of load results in zero or negative revenue for the TSOs and maintenance cost of the transmission asset result in more expenditure of the fund by the TSOs. The developed model takes into account both the factor responsible for the loss of revenue for the TSOs. The developed modelling algorithm is designed specifically for providing outage schedule for the required network of transmission lines. The developed modelling algorithm is modelled for optimization problem which take in account in providing the optimal minimal cost of the whole schedule. The obtained optimal minimized cost consists of all the transmission line that are included in the output schedule which result in a large number and it is hard to understand. But selection of transmission line form the schedule for a specific period can directly be selected because the schedule provides optimal schedule with respect to lowest loss of revenue for the TSOs.

2. **What can be the suitable optimization approach to solve the preventive maintenance problem of a specific asset at specific period of time?** The optimization approach used in the modelling of the problem formulation takes into account stochastic programming approach. The programming approach provide adequate modelling framework for decision making in preventive maintenance of specific asset in specific time-period. The developed modelling algorithm has two main aspects in problem formulation. First, the maintenance constraints and secondly, network constraints. The maintenance constraints are modelled in such a way that flexible period can be integrated in the model according to the requirement for a specific area and optimal schedule is presented. The optimal schedule will fulfill the requirement of the TSO involving the specific asset in specific area and specific time.

3. **What is the effect of demand uncertainty on maintenance planning of transmission assets?** Demand uncertainty plays an important role in determining the behaviour pattern of the maintenance planning of the transmission assets. The behaviour pattern refers to the change in outage schedule with the load on the demand side may change in the future due to some exogenous variables. Such exogenous variables should be modelled and analysis is to be performed to understand and evaluate the systems behaviour. Generally, in case of uncertainty, the modelling is done using probability distribution method but in this thesis deterministic approach is taken into consideration. Deterministic uncertainty is considered while developing the modelling algorithm. Deterministic uncertainty implies change in load profile are a deterministic value and observing changes in schedule. The developed model shown the result that uncertainty on the load side plays an important role and result in change in the outage schedule for the transmission asset. Tackling the uncertainty was a difficult job because the overall time required for the algorithm to converge increased to an extent that the university computer lack the storage of internal memory and the computer usually crashes. But by reducing the total period the algorithm ran smoothly and result were displayed. But to analysis and obtain result for long-term analysis period the computer provide by the university should be upgraded to run the algorithm.

9.3 Contribution

1. Developed a flexible outage schedule algorithm for TSOs considering demand uncertainty and validating for three different sized test-cases.
2. Developed deep understanding of the software GAMS and the unique coding which helped to model the outage schedule for transmission asset under uncertainty.
3. Results of the research work accepted in the prestigious PSCC'18 conference in Dublin, Ireland.

9.4 Future Work

The developed model in this thesis can be considered a base case model as few assumption and simplified constraint were used in designing the model. New maintenance constraint has been developed but they have be more perfected as they are still in their primary phases. Wind uncertainty is also an important point to be taken into consideration for the future work. Wind uncertainty will provide more realistic and enhanced schedule for the TSOs. Some point for the future work are provide below which would surly help in developing more optimized algorithm for optimal result.

1. Analysis and modelling of wind uncertainty in the problem formulation to obtain more optimum and reliable result.
2. Increase the number buses in the network and perform analysis for very large and realistic network topology.
3. Make the algorithm more efficient and fast by improving the hardware of the computer system or by using multiple GPUs and RAMs for fast convergence of the algorithm.

Chapter 10

Appendix

10.1 APPENDIX I

The intention of the appendix I is to help the researchers to implement the 3−bus model described in chapter 5. The result and analysis for the GAMS code mentioned in the appendix is presented in figure 5.2 and table 5.4 .

```
**********************************
**SETS DECLARATION
**********************************
Sets
g           /g1*g3/
b           /b1*b3/
k           /k1*k3/
d           /d1*d3/
t           /1/
ref(b)      /b1/
mapG(g,b)            /g1.b1,g2.b2,g3.b3/
mapD(d,b)            /d1.b1,d2.b2,d3.b3/
mapSL(k,b)           /k1.b1,k2.b1,k3.b2/
mapRL(k,b)           /k1.b2,k2.b3,k3.b3/
;


**********************************
**DATA TABLE
**********************************
Table kdata(k,*)
```

```
         IC      kmax    klimit  SUS
k1       200     0.5     0.5     0.2
k2       300     0.5     0.5     0.25
k3       100     0.5     0       0.4
;


**********************************
**SCALAR DATA
**********************************

Scalar Nk
/2/;

Scalar sigma
/250/;



**********************************
**PARAMETER DECLRATION
**********************************
Parameter
i(g)     /g1 1,g2 2,g3 3/
j(d)     /d1 1,d2 2,d3 1/
;

**********************************
**VARIABLE
**********************************
Variable
Z
PL(k)
Theta(b)
;

semicont variables N(k,t);

N.lo(k,t)= 0; N.up(k,t)=2;


**********************************
**EQUATIONS
**********************************
```

```
Equation
E11,E21,E2,E4,E5,E6,E7,E8,E3
;

E11..       Z=e=sum(t,sum(k,kdata(k,'IC')*(Nk-N(k,t)))
                 +sigma*(sum(b,r(b))));
E21..       sum(t,sum(k,N(k,t)))=l=4;

E2(b)..   (-sum(k\$mapSL(k,b),PL(k))+sum(k\$mapRL(k,b),PL(k)))+
           r(b)=e=sum(d\$mapD(d,b),j(d))-sum(g\$mapG(g,b),i(g));
E3(k)..    PL(k)=e=kdata(k,'SUS')*
          (sum(b\$mapSL(k,b),Theta(b))-sum(b\$mapRL(k,b),Theta(b)));
E4(k)..    2*(kdata(k,'klimit'))=g=-PL(k);
E5(k)..    PL(k)=l=2*(kdata(k,'klimit'));
E6(b)..    -3.14=l=Theta(b);
E7(b)..    Theta(b)=l=3.14;
E8(b)\$ref(b)..      Theta(b)=l=0;


*********************************
**SOLVERS
*********************************

model master /all/;
option MIP = CPLEX;
master.optfile=1;
solve master using mip minimizing Z ;
```

10.2 APPENDIX II

The intention of the appendix II is provide the information of the required data that has been used in modelling the modified 118-bus system in chapter 8. All the data mentioned below has been used in modelling and analyzing the 118-bus test system.

TABLE I
GENERATOR DATA

U	Bus No.	P_g (MW)	Q_g (MVar)	Marginal Cost ($/MWh)	P_{max} (MW)	P_{min} (MW)	Q_{max} (MVar)	Q_{min} (MVar)
1	10	450	-5	0.217	550	0	200	-147
2	12	85	91.27	1.052	185	0	120	-35
3	25	220	49.72	0.434	320	0	140	-47
4	26	314	9.89	0.308	414	0	1000	-1000
5	31	7	31.57	5.882	107	0	300	-300
6	46	19	-5.25	3.448	119	0	100	-100
7	49	204	115.63	0.467	304	0	210	-85
8	54	48	3.9	1.724	148	0	300	-300
9	59	155	76.83	0.606	255	0	180	-60
10	61	160	-40.39	0.588	260	0	300	-100
11	65	391	80.76	0.2493	491	0	200	-67
12	66	392	-1.95	0.2487	492	0	200	-67
13	69	513.48	-82.39	0.1897	805.2	0	300	-300
14	80	477	104.9	0.205	577	0	280	-165
15	87	4	11.02	7.142	104	0	1000	-100
16	92	607	0.49	10	1100	0	9	-3
17	100	252	108.87	0.381	352	0	155	-50
18	103	40	41.69	2	140	0	40	-15
19	111	36	-1.84	2.173	136	0	1000	-100

TABLE II
BUS DATA

Bus No.	Conductance (G) (mhos)	Susceptance (B) (mhos)	Base Voltage (kV)	Voltage-Max (pu)	Voltage-Min (pu)
1	0	0	138	1.06	0.94
2	0	0	138	1.06	0.94
3	0	0	138	1.06	0.94
4	0	0	138	1.06	0.94
5	0	-40	138	1.06	0.94
6	0	0	138	1.06	0.94
7	0	0	138	1.06	0.94
8	0	0	345	1.06	0.94
9	0	0	345	1.06	0.94
10	0	0	345	1.06	0.94
11	0	0	138	1.06	0.94
12	0	0	138	1.06	0.94

13	0	0	138	1.06	0.94
14	0	0	138	1.06	0.94
15	0	0	138	1.06	0.94
16	0	0	138	1.06	0.94
17	0	0	138	1.06	0.94
18	0	0	138	1.06	0.94
19	0	0	138	1.06	0.94
20	0	0	138	1.06	0.94
21	0	0	138	1.06	0.94
22	0	0	138	1.06	0.94
23	0	0	138	1.06	0.94
24	0	0	138	1.06	0.94
25	0	0	138	1.06	0.94
26	0	0	345	1.06	0.94
27	0	0	138	1.06	0.94
28	0	0	138	1.06	0.94
29	0	0	138	1.06	0.94
30	0	0	345	1.06	0.94
31	0	0	138	1.06	0.94
32	0	0	138	1.06	0.94
33	0	0	138	1.06	0.94
34	0	14	138	1.06	0.94
35	0	0	138	1.06	0.94
36	0	0	138	1.06	0.94
37	0	-25	138	1.06	0.94
38	0	0	345	1.06	0.94
39	0	0	138	1.06	0.94
40	0	0	138	1.06	0.94
41	0	0	138	1.06	0.94
42	0	0	138	1.06	0.94
43	0	0	138	1.06	0.94
44	0	10	138	1.06	0.94
45	0	10	138	1.06	0.94
46	0	10	138	1.06	0.94
47	0	0	138	1.06	0.94
48	0	15	138	1.06	0.94
49	0	0	138	1.06	0.94
50	0	0	138	1.06	0.94
51	0	0	138	1.06	0.94
52	0	0	138	1.06	0.94
53	0	0	138	1.06	0.94

54	0	0	138	1.06	0.94
55	0	0	138	1.06	0.94
56	0	0	138	1.06	0.94
57	0	0	138	1.06	0.94
58	0	0	138	1.06	0.94
59	0	0	138	1.06	0.94
60	0	0	138	1.06	0.94
61	0	0	138	1.06	0.94
62	0	0	138	1.06	0.94
63	0	0	345	1.06	0.94
64	0	0	345	1.06	0.94
65	0	0	345	1.06	0.94
66	0	0	138	1.06	0.94
67	0	0	138	1.06	0.94
68	0	0	345	1.06	0.94
69	0	0	138	1.06	0.94
70	0	0	138	1.06	0.94
71	0	0	138	1.06	0.94
72	0	0	138	1.06	0.94
73	0	0	138	1.06	0.94
74	0	12	138	1.06	0.94
75	0	0	138	1.06	0.94
76	0	0	138	1.06	0.94
77	0	0	138	1.06	0.94
78	0	0	138	1.06	0.94
79	0	20	138	1.06	0.94
80	0	0	138	1.06	0.94
81	0	0	345	1.06	0.94
82	0	20	138	1.06	0.94
83	0	10	138	1.06	0.94
84	0	0	138	1.06	0.94
85	0	0	138	1.06	0.94
86	0	0	138	1.06	0.94
87	0	0	161	1.06	0.94
88	0	0	138	1.06	0.94
89	0	0	138	1.06	0.94
90	0	0	138	1.06	0.94
91	0	0	138	1.06	0.94
92	0	0	138	1.06	0.94
93	0	0	138	1.06	0.94
94	0	0	138	1.06	0.94

95	0	0	138	1.06	0.94
96	0	0	138	1.06	0.94
97	0	0	138	1.06	0.94
98	0	0	138	1.06	0.94
99	0	0	138	1.06	0.94
100	0	0	138	1.06	0.94
101	0	0	138	1.06	0.94
102	0	0	138	1.06	0.94
103	0	0	138	1.06	0.94
104	0	0	138	1.06	0.94
105	0	20	138	1.06	0.94
106	0	0	138	1.06	0.94
107	0	6	138	1.06	0.94
108	0	0	138	1.06	0.94
109	0	0	138	1.06	0.94
110	0	6	138	1.06	0.94
111	0	0	138	1.06	0.94
112	0	0	138	1.06	0.94
113	0	0	138	1.06	0.94
114	0	0	138	1.06	0.94
115	0	0	138	1.06	0.94
116	0	0	138	1.06	0.94
117	0	0	138	1.06	0.94
118	0	0	138	1.06	0.94

TABLE III
TRANSMISSION LINE DATA

Line No.	**From Bus**	**To Bus**	**R (pu)**	**X (pu)**	**B (pu)**	**Rate A (MVA)**	**Rate B (MVA)**	**Rate C (MVA)**
1	1	2	0.0303	0.0999	0.0254	220	230	250
2	1	3	0.0129	0.0424	0.01082	220	230	250
3	2	12	0.0187	0.0616	0.01572	220	230	250
4	3	5	0.0241	0.108	0.0284	220	230	250
5	3	12	0.0484	0.16	0.0406	220	230	250
6	4	5	0.0017	0.00798	0.0021	440	460	500
7	4	11	0.0209	0.0688	0.01748	220	230	250
8	5	6	0.0119	0.054	0.01426	220	230	250
9	5	11	0.0203	0.0682	0.01738	220	230	250
10	6	7	0.0045	0.0208	0.0055	220	230	250
11	7	12	0.0086	0.034	0.00874	220	230	250
12	8	9	0.0024	0.0305	1.1620	1100	1150	1250

13	8	5	0	0.0267	0	880	920	1000
14	8	30	0.0043	0.0504	0.514	220	230	250
15	9	10	0.0025	0.0322	1.230	1100	1150	1250
16	11	12	0.0059	0.0196	0.00502	220	230	250
17	11	13	0.0222	0.0731	0.01876	220	230	250
18	12	15	0.0215	0.0707	0.01816	220	230	250
19	12	17	0.0212	0.0834	0.0214	220	230	250
20	12	117	0.0329	0.14	0.0358	220	230	250
21	13	15	0.0744	0.2444	0.06268	220	230	250
22	14	15	0.0595	0.195	0.0502	220	230	250
23	15	17	0.0132	0.0437	0.0444	440	460	500
24	15	19	0.012	0.0394	0.0101	220	230	250
25	15	33	0.038	0.1244	0.03194	220	230	250
26	16	17	0.0454	0.1801	0.0466	220	230	250
27	17	19	0.0123	0.0505	0.01298	220	230	250
28	17	31	0.0474	0.1563	0.0399	220	230	250
29	17	113	0.0091	0.0301	0.00768	220	230	250
30	18	19	0.0111	0.0493	0.01142	220	230	250
31	19	20	0.0252	0.117	0.0298	220	230	250
32	19	34	0.0752	0.247	0.0632	220	230	250
33	20	21	0.0183	0.0849	0.0216	220	230	250
34	21	22	0.0209	0.097	0.0246	220	230	250
35	22	23	0.0342	0.159	0.0404	220	230	250
36	23	24	0.0135	0.0492	0.0498	220	230	250
37	23	25	0.0156	0.080	0.0864	440	460	500
38	23	32	0.0317	0.1153	0.1173	220	230	250
39	24	70	0.0022	0.4115	0.10198	220	230	250
40	24	72	0.0488	0.196	0.0488	220	230	250
41	25	27	0.0318	0.163	0.1764	440	460	500
42	26	25	0	0.0382	0	220	230	250
43	26	30	0.0079	0.086	0.908	660	690	750
44	27	28	0.0191	0.0855	0.0216	220	230	250
45	27	32	0.0229	0.0755	0.01926	220	230	250
46	27	115	0.0164	0.0741	0.01972	220	230	250
47	28	31	0.0237	0.0943	0.0238	220	230	250
48	29	31	0.0108	0.0331	0.0083	220	230	250
49	30	17	0	0.0388	0	660	690	750
50	30	38	0.0046	0.054	0.422	220	230	250
51	31	32	0.0298	0.0985	0.0251	220	230	250
52	32	113	0.0615	0.203	0.0518	220	230	250
53	32	114	0.0135	0.0612	0.01628	220	230	250

54	33	37	0.0415	0.142	0.0366	220	230	250
55	34	36	0.0087	0.0268	0.00568	220	230	250
56	34	37	0.0025	0.00940	0.00984	440	460	500
57	34	43	0.0413	0.1681	0.04226	220	230	250
58	35	36	0.0022	0.0102	0.00268	220	230	250
59	35	37	0.011	0.0497	0.01318	220	230	250
60	37	39	0.0321	0.106	0.0270	220	230	250
61	37	40	0.0593	0.168	0.0420	220	230	250
62	38	37	0	0.0375	0	660	690	750
63	38	65	0.009	0.0986	1.046	440	460	500
64	39	40	0.0184	0.0605	0.01552	220	230	250
65	40	41	0.0145	0.0487	0.01222	220	230	250
66	40	42	0.0555	0.183	0.0466	220	230	250
67	41	42	0.041	0.135	0.0344	220	230	250
68	42	49	0.0715	0.323	0.0860	220	230	250
69	42	49	0.0715	0.323	0.0860	220	230	250
70	43	44	0.0608	0.2454	0.06068	220	230	250
71	44	45	0.0224	0.0901	0.0224	220	230	250
72	45	46	0.04	0.1356	0.0332	220	230	250
73	45	49	0.0684	0.186	0.0444	220	230	250
74	46	47	0.038	0.127	0.0316	220	230	250
75	46	48	0.0601	0.189	0.0472	220	230	250
76	47	49	0.0191	0.0625	0.01604	220	230	250
77	47	69	0.0844	0.2778	0.07092	220	230	250
78	48	49	0.0179	0.0505	0.01258	220	230	250
79	49	50	0.0267	0.0752	0.01874	220	230	250
80	49	51	0.0486	0.137	0.0342	220	230	250
81	49	54	0.073	0.289	0.0738	220	230	250
82	49	54	0.0869	0.291	0.0730	220	230	250
83	49	66	0.018	0.0919	0.0248	440	460	500
84	49	66	0.018	0.0919	0.0248	440	460	500
85	49	69	0.0985	0.324	0.0828	220	230	250
86	50	57	0.0474	0.134	0.0332	220	230	250
87	51	52	0.0203	0.0588	0.01396	220	230	250
88	51	58	0.0255	0.0719	0.01788	220	230	250
89	52	53	0.0405	0.1635	0.04058	220	230	250
90	53	54	0.0263	0.122	0.0310	220	230	250
91	54	55	0.0169	0.0707	0.0202	220	230	250
92	54	56	0.0027	0.00955	0.00732	220	230	250
93	54	59	0.0503	0.2293	0.0598	220	230	250
94	55	56	0.0048	0.0151	0.00374	220	230	250

95	55	59	0.0473	0.2158	0.05646	220	230	250
96	56	57	0.0343	0.0966	0.0242	220	230	250
97	56	58	0.0343	0.0966	0.0242	220	230	250
98	56	59	0.0825	0.251	0.0569	220	230	250
99	56	59	0.0803	0.239	0.0536	220	230	250
100	59	60	0.0317	0.145	0.0376	220	230	250
101	59	61	0.0328	0.150	0.0388	220	230	250
102	60	61	0.00260	0.0135	0.01456	440	460	500
103	60	62	0.0123	0.0561	0.01468	220	230	250
104	61	62	0.0082	0.0376	0.00980	220	230	250
105	62	66	0.0482	0.218	0.0578	220	230	250
106	62	67	0.0258	0.117	0.031	220	230	250
107	63	59	0	0.0386	0	440	460	500
108	63	64	0.0017	0.0200	0.216	440	460	500
109	64	61	0	0.0268	0	220	230	250
110	64	65	0.0026	0.0302	0.380	440	460	500
111	65	66	0	0.0370	0	220	230	250
112	65	68	0.0013	0.016	0.638	220	230	250
113	66	67	0.0224	0.1015	0.02682	220	230	250
114	68	69	0	0.0370	0	440	460	500
115	68	81	0.0017	0.0202	0.808	220	230	250
116	68	116	0.0003	0.00405	0.164	440	460	500
117	69	70	0.03	0.127	0.122	440	460	500
118	69	75	0.0405	0.122	0.124	440	460	500
119	69	77	0.0309	0.101	0.1038	220	230	250
120	70	71	0.0088	0.0355	0.00878	220	230	250
121	70	74	0.0401	0.1323	0.03368	220	230	250
122	70	75	0.0428	0.141	0.0360	220	230	250
123	71	72	0.0446	0.180	0.04444	220	230	250
124	71	73	0.0086	0.0454	0.01178	220	230	250
125	74	75	0.0123	0.0406	0.01034	220	230	250
126	75	77	0.0601	0.1999	0.04978	220	230	250
127	75	118	0.0145	0.0481	0.01198	220	230	250
128	76	77	0.0444	0.148	0.0368	220	230	250
129	76	118	0.0164	0.0544	0.01356	220	230	250
130	77	78	0.0037	0.0124	0.01264	220	230	250
131	77	80	0.017	0.0485	0.0472	440	460	500
132	77	80	0.0294	0.105	0.0228	220	230	250
133	77	82	0.0298	0.0853	0.08174	220	230	250
134	78	79	0.0054	0.0244	0.00648	220	230	250
135	79	80	0.0156	0.0704	0.0187	220	230	250

136	80	96	0.0356	0.182	0.0494	220	230	250
137	80	97	0.0183	0.0934	0.0254	220	230	250
138	80	98	0.0238	0.108	0.0286	220	230	250
139	80	99	0.0454	0.206	0.0546	220	230	250
140	81	80	0	0.0370	0	220	230	250
141	82	83	0.0112	0.03665	0.03796	220	230	250
142	82	96	0.0162	0.0530	0.0544	220	230	250
143	83	84	0.0625	0.132	0.0258	220	230	250
144	83	85	0.0430	0.148	0.0348	220	230	250
145	84	85	0.0302	0.0641	0.01234	220	230	250
146	85	86	0.0350	0.123	0.0276	220	230	250
147	85	88	0.0200	0.102	0.0276	220	230	250
148	85	89	0.0239	0.173	0.0470	220	230	250
149	86	87	0.0282	0.2074	0.0445	220	230	250
150	88	89	0.0139	0.0712	0.01934	440	460	500
151	89	90	0.0518	0.0320	0.0320	660	230	250
152	89	91	0.00990	0.0320	0.0650	220	220	220
153	89	92	0.00990	0.0505	0.0650	220	690	750
154	90	91	0.0254	0.0505	0.0650	660	230	250
155	91	92	0.0387	0.1272	0.0320	220	230	250
156	92	93	0.0258	0.0320	0.0218	220	230	250
157	92	94	0.0481	0.158	0.0406	220	230	250
158	92	100	0.0648	0.295	0.0472	220	230	250
159	92	102	0.0123	0.0559	0.01464	220	230	250
160	93	94	0.0223	0.0732	0.0187	220	230	250
161	94	95	0.0132	0.0434	0.0111	220	230	250
162	94	96	0.0269	0.0869	0.0230	220	230	250
163	94	100	0.0178	0.0580	0.0604	220	230	250
164	95	96	0.0171	0.0547	0.01474	220	230	250
165	96	97	0.0173	0.0885	0.0240	220	230	250
166	98	100	0.0397	0.179	0.0476	220	230	250
167	99	100	0.0180	0.0813	0.0216	220	230	250
168	100	101	0.0277	0.1262	0.0328	220	230	250
169	100	103	0.0160	0.0525	0.0536	440	460	500
170	100	104	0.0451	0.204	0.0541	220	230	250
171	100	106	0.0605	0.229	0.0620	220	230	250
172	101	102	0.0246	0.112	0.0294	220	230	250
173	103	104	0.0466	0.1584	0.0407	220	230	250
174	103	105	0.0535	0.1625	0.0408	220	230	250
175	103	110	0.0390	0.1813	0.0461	220	230	250
176	104	105	0.00990	0.0378	0.00986	220	230	250

177	105	106	0.0140	0.0547	0.01434	220	230	250
178	105	107	0.0530	0.183	0.0472	220	230	250
179	105	108	0.0261	0.0703	0.01844	220	230	250
180	106	107	0.0530	0.183	0.0472	220	230	250
181	108	109	0.0105	0.0288	0.00760	220	230	250
182	109	110	0.0278	0.0762	0.0202	220	230	250
183	110	111	0.0220	0.0755	0.0200	220	230	250
184	110	112	0.0247	0.0640	0.0620	220	230	250
185	114	115	0.0023	0.0104	0.00276	220	230	250

TABLE IV
TAP CHANGING TRANSFORMER DATA

Transformer No.	**From Bus**	**To Bus**	**Circuit ID**	**Tap Initial**	**Tap Max**	**Tap Min**	**Angle Initial**	**Angle Max**	**Angle Min**
1	8	5	1	0.985	0	0	0	0	0
2	26	25	1	0.96	0	0	0	0	0
3	30	17	1	0.96	0	0	0	0	0
4	38	37	1	0.935	0	0	0	0	0
5	63	59	1	0.96	0	0	0	0	0
6	64	61	1	0.985	0	0	0	0	0
7	65	66	1	0.935	0	0	0	0	0
8	68	69	1	0.935	0	0	0	0	0
9	81	80	1	0.935	0	0	3.57	-15	15

TABLE V
GENERAL LOAD DATA

Bus No.	**P_d (MW)**	**Q_d (MVar)**	**VOLL ($/MWh)**
1	51	27	4822.6
2	20	9	5600.331
3	39	10	3144.692
4	39	12	5017.304
6	52	22	4691.259
7	19	2	3715.387
8	28	0	4239.845
11	70	23	4705.575
12	47	10	6647.038
13	34	16	6161.662
14	14	1	3690.068

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