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

Economic outage scheduling of transmission line for long-term horizon under demand scenarios

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IEPG Intelligent Electrical Power Grids

TU Delft Delft University of Technology

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Title

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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 (e.g., demand scenarios) 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. 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 asset in the cluster of network which can be brought out of service for maintenance. In this thesis we are particularly considering transmission lines as the transmission asset for outage schedule. 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 in this research work incorporating different demand scenarios. With the help of demand scenarios, different outage scenarios are evaluated and the corresponding schedule is obtained using stochastic programming. Stochastic programming provides an adequate modelling framework for this two-stage optimization problem. Optimization under different demand scenarios, spanning two-stage stochastic programming approach is used in this research study. For validation, medium (modified IEEE RTS-24 bus) and large (modified IEEE-118 bus) systems are studied, all in the GAMS environment.

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Nomenclature

List of symbols

γ_l Susceptance (Siemens) 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

f Power flow at peak load

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_{it} Real power interruption at bus i in time t

s Maintenance variable

t Time period

X_{lt} Number of candidate line to be operated in right of way at time t of transmission line l

Z Optimized cost

List of acronyms

GAMS General Algebric Modelling System

RBTS Roy Billinton Test System

RTS Reliability Test System

SoS Security of Supply

TSO Transmission System Operator

TWh TeraWatt Hours

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 to the latest report from International renewable energy agency of renewable energy highlight, 1 July 2017, as in 2015, the total amount of electricity generated from renewables was 5512 TWh [4]. An increase in 3.5 percent of renewable energy generation was observed compared to 2014 [4]. 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 21st 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 (TSOs) 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

Massive integration of renewable energy sources into the primary grid has resulted in a multi-way energy flow in the existing power system. Till the year 2000, there was a one-way energy flow where the demand was met by the generation companies. As the market became more liberated and renewables came into picture contributing towards sustainability, a two-way energy flow is observed until recently. Similarly, in the future, it can be expected that the energy flow will be either way which is quite uncertain. Demand growth, new technologies, and evolvement of prosumers will become significant. Foreseeing the future, the backbone of the power system [5] i.e. transmission system has to get upgraded in terms of capacity to transfer power and increase in network connectivity. Increase in transfer capacity leads to the expansion of existing grid topology, for instance building new transmission lines in the network. Apart from building new transmission corridor, the utilities or transmission system operators (TSOs) also need to take care of the existing infrastructure by following a proper maintenance schedule. Not to be forgotten, the transmission line is one of the most important components of the transmission system. Failure in transmission line has a direct impact on the demand side as well as generation side of the power system. Large arguments have been made on different transmission system components that are as important as the transmission line, but it can be said that the transmission line is the most important component as its proper and uninterrupted working results in smooth working of other components. Other components such as insulators, transformers, bus-bars, protective devices are also important components of the power system, but in this thesis, we have specifically considered transmission line maintenance and not any other component of the transmission system.

Maintenance of the transmission line plays an important role in checking lower loss of revenue for the TSOs over the long-term period of time. Failure in transmission line due to some unfortunate scenario or uncertain events result in large revenue loss for the TSOs. These unfortunate scenarios can occur at any period of time and the TSOs should be ready to counter it at all point of time. The loss of revenue experienced by the TSOs has a cumulative effect on the price of the electricity paid by the consumer side. Therefore, if a proper maintenance outage schedule is performed for the transmission line network, early detection of faults, as well as pre-knowledge of the condition of the transmission line, will help the TSOs to perform qualitative work at a lower loss of revenue. This was the main motivation behind the selection of the specific topic "Economic outage schedule for transmission lines for long-term horizon under demand scenarios".

In today's world, the 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 scenarios developed around the power system have become more uncertain and unreliable to fathom. Moreover, these uncertain scenarios develop a 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].

With the increasing 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)
- 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 [7] 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 the 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 a more optimal management of resources as well as perform different development in a system which would result in optimization of the current infrastructure cost for different component with respect to their life span and durability. In the development of the power system for maintaining reliability as to obtain an optimal result and lower

[1]: It is a German word to test the limit or net stress of the current transmission system due to an increase of renewable penetration and other distributed energy sources into the primary grid [6].

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 is 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.

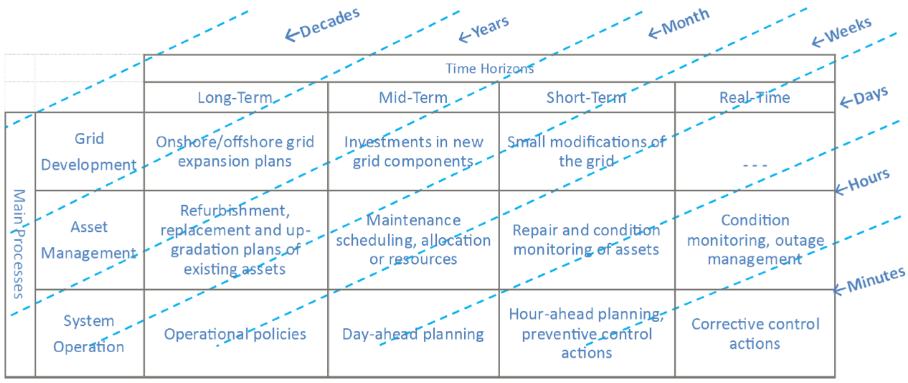

Figure 1.1: Action taken during different time-horizon[1]

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 important 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 to the budget and workforce in order to make the resource allocation more smooth and less complex [8].

Progress in the field of transmission line capacity for high voltage as well as for low voltage basically started around 1960's [9]. 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 an increase in the 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 is approaching towards cleaner and environmentally friendly consumption of energy. Due to such adaptation, there has been an enormous increase in consumption electrical energy. Therefore, large demand on consumer side led to an 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 the 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 fulfil 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 fulfil all the desired network constraint and reliability at all point of time in the network.

1.2 Literature study

It is well known now that the power system is growing rapidly with the involvement of high in-feed renewable energy to the grid and maintenance of the assets are one of the important factors 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. In the last decade, significant penetration of renewable energy in form of wind and solar in the primary grid is noticeable. Due to such increase in infrastructure and development in renewable sector technology, we observed an increase in penetration of energy into the grid, which results in the increase in transmission capacity of the existing power system network. Moreover, the increase in the capacity led to an 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 [10]. 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 constituents for a reliable power system.For instance, the GARPUR project [8] carried out a survey on different assets considered under asset management by different European TSOs. The results from the 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 the key decision-making process to maximize the profit for the TSOs. Since transmission line outplays all other assets considered by TSOs, this research work undertook transmission line maintenance outage scheduling and came up with an efficient maintenance schedule for the TSOs.

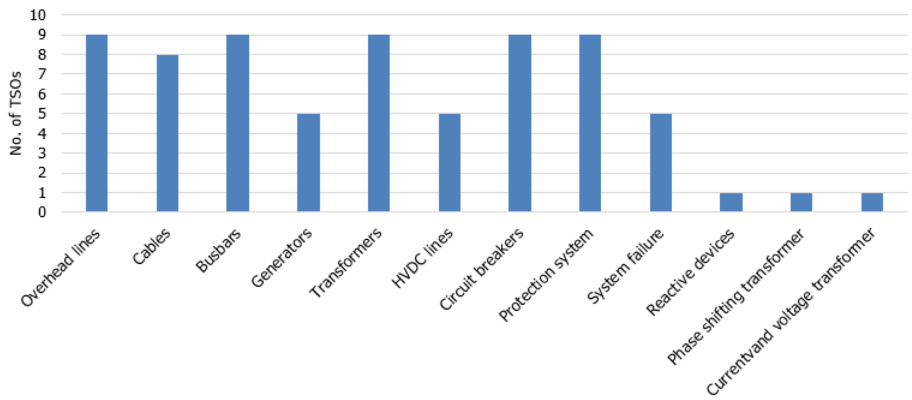

Figure 1.2: Number of transmission system operators considering different component under asset management [2]

From the figure 1.2 we can infer that not only transmission line but also bus-bars, transformers, protection system and circuit breakers are also equally important under asset management as transmission lines. Specifically, in this thesis we are just considering maintenance of the transmission lines for outage scheduling for the specific reason mentioned as follows:

- Transmission line, circuit breaker, bus bar, transformers and insulators are some of the important components of the transmission system, but in all of them transmission line maintenance is considered to be one of the important tasks because maintenance of transmission line results in a reliable and stable power system network.
- Other components of the transmission system are also important but we can say that during transmission line maintenance various other sub maintenance can be carried out during same time period. This provides TSOs to work more efficiently towards the reduction of the total loss of revenue.
- More versatile maintenance of the transmission system can be performed during the transmission line maintenance.
- The transmission line maintenance also provide a valuable feedback to the TSOs regarding the present condition of the transmission line network as well as give an overview of the idea of the current state of the power system.

Literature study suggests that asset management plays an important part in the transformation of the power system industry. Analysis and research work on the asset management suggest a compelling work about different asset management and their classification in terms of maintenance methods and research work. The study also suggests that the majority of the maintenance work is focused on generator maintenance scheduling and it does not take into consideration the transmission system network constraints. For a complete overview and update biblical survey, refs. [11][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 a crucial role in maintaining the power system more stable and reliable at the point of calamities and fault. As generating facilities size were increasing a model was introduced for automated scheduling of maintenance of generating facility in [12]. This led to the foundation for future research work related to the generating facilities which can be seen in [13]. Decomposition approach was introduced to solve a very large linear optimization problem. The most famous benders decomposition algorithm was first used in [14] to obtain the 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 [15] which used the stochastic programming approach. Application of benders decomposition in deep understanding for power plant scheduling was first observed in [16]. Integrated generation and transmission maintenance scheduling with network constraint and deterministic approach for generation and transmission maintenance scheduling network constraint were first introduced in [10] and [17]. Introduction to long-term generation and maintenance scheduling with network fuel constraint using benders decomposition approach was proposed in [18]. A probabilistic approach for the generator maintenance scheduling was proposed in [19]. 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 [20]. A mixed integer approach for scheduling in generating unit provided in [21]. Development in long-term transmission line scheduling which explicitly considered the market environment by using the bi-level approach as seen in [5]. 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 conveys a strong 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 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 the 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 a 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 cost and asset to a minimum while maintaining the reliability of the system. The scheduling plays an important role in fulfilling all the network constraint associated 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 the 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

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.

There exist some gaps in existing literature that have to be addressed. Some of the gaps mentioned have been later formulated into research questions for this research work. As we tried to tackle some of the gaps we observed that not all the gaps in literature can be tackled and addressed, and are listed below:

- Integration of distributed generation subjected to exogenous uncertainty into the primary grid. This aspect takes into account different variable associated with the exogenous uncertainty and modelling the distributed generation for such conditions.
- Unavailability of customizable tools for the maintenance of the transmission line for a specific area and time. A customizable tool enables the user to change the input data of the network easily and also facilitate selection of the transmission lines of the network for a specific time period. Further, the tool can be easily adapted for new or modified algorithms.
- Uncertainty plays important not only on demand side but also on generation side of the power system. Uncertainty in both demand and generation in the transmission line for maintenance outage schedule has not been accomplished.
- Integrated generation and transmission maintenance scheduling considering uncertainties have not been answered yet.

1.3 Objective and research question

The objective of this research work is to perform economic outage scheduling of transmission line for long term horizon under different demand scenarios.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 also a stable 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 of the transmission lines?
- What can be the suitable optimization approach to solve the maintenance problem of transmission lines for a specific period of time?
- How to address maintenance outage schedule for different demand scenarios in long-term horizon?

1.4 Research approach

To provide the research approach in a more synthetic way with sufficient technical data and analysis, we have ordered the document from the basic theoretical understanding of the problem formulation to its implementation in GAMS environment, and then to the final case study associated with results.

Outage scheduling problem is a multi-stage optimization problem that provides schedule for the transmission lines 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. An important aspect of problem formulation is to confirm if it is a tight mixed integer linear programming (MILP) problem or a relaxed MILP problem with relaxed constraints and assumption. The assumptions taken into consideration for the problem formulation are mentioned in details in chapter 3. The primary goal is to satisfy the operating constraint for the all plausible scenarios. 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. The solution provides with outage schedule and the optimized cost of maintenance. All the equations and constraints corresponding to the model for defining the outage schedule are modelled in general algebraic modelling system (GAMS) environment. The decomposition technique taken into consideration is the benders decomposition technique.

The importance of problem formulation in GAMS and solving using benders decomposition approach is listed below:

- GAMS allows you to formulate your model without direct reference to a specific data set and you can, therefore, use the same model code with different data sets or different aggregations of the same data set.
- Benders decomposition is useful in solving large complex integer problem. The mathematical problem formulation in the thesis is a mixed integer linear programming problem. This makes the bender decomposition algorithm the best suit for the solving.
- GAMS modelling is easy to implement and easy to debug.

A standardized test case is taken into consideration to provide benchmark result which can be used for future reference of work by different researcher in the same field.

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

The overall timeline 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.

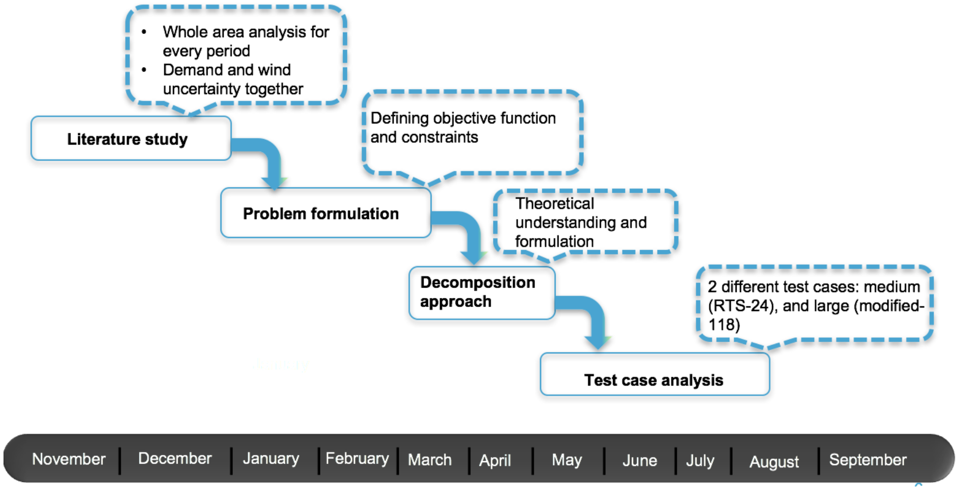

Figure 1.3: Timeline and work flow

1.5 Outline

The outline of this thesis is as follows:

- ***Chapter 1*** discuss the background information with the motivation for choosing the topic. It also includes the literature survey associated with the topic and the approach associated with the research work.
- ***Chapter 2*** 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.
- Then, ***chapter 3*** 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.
- ***Chapter 4*** discuss two case study and their respective results.
- Then, ***chapter 5*** concludes the research work from informative results, studied on test systems of different size and scale. Recommendations for future work are included in this chapter too.

Chapter 2

Benders decomposition

Benders decomposition was first introduced by J. F. Benders for solving a large-scale mixed integer programming problem. This mixed integer programming problem may include linear, nonlinear, continuous or integer problem. The benders decomposition methodology is also considered in solving the 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 as well as the flow-chart of the generalized benders decomposition is shown in figure 2.1.

$$\begin{aligned} Maximize \quad & z = c(x) + d(y) \\ S.t. \quad & Ax \geq b \\ E(x) + & F(y) \geq h \\ x \geq 0, & \quad y \epsilon Y \end{aligned} \tag{2.1}$$

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

A and b are the coefficient of the constraint equation;

c and d are the scalar valued function of x and y respectively;

x and y are vectors of continuous variables;

Y is set of integers.

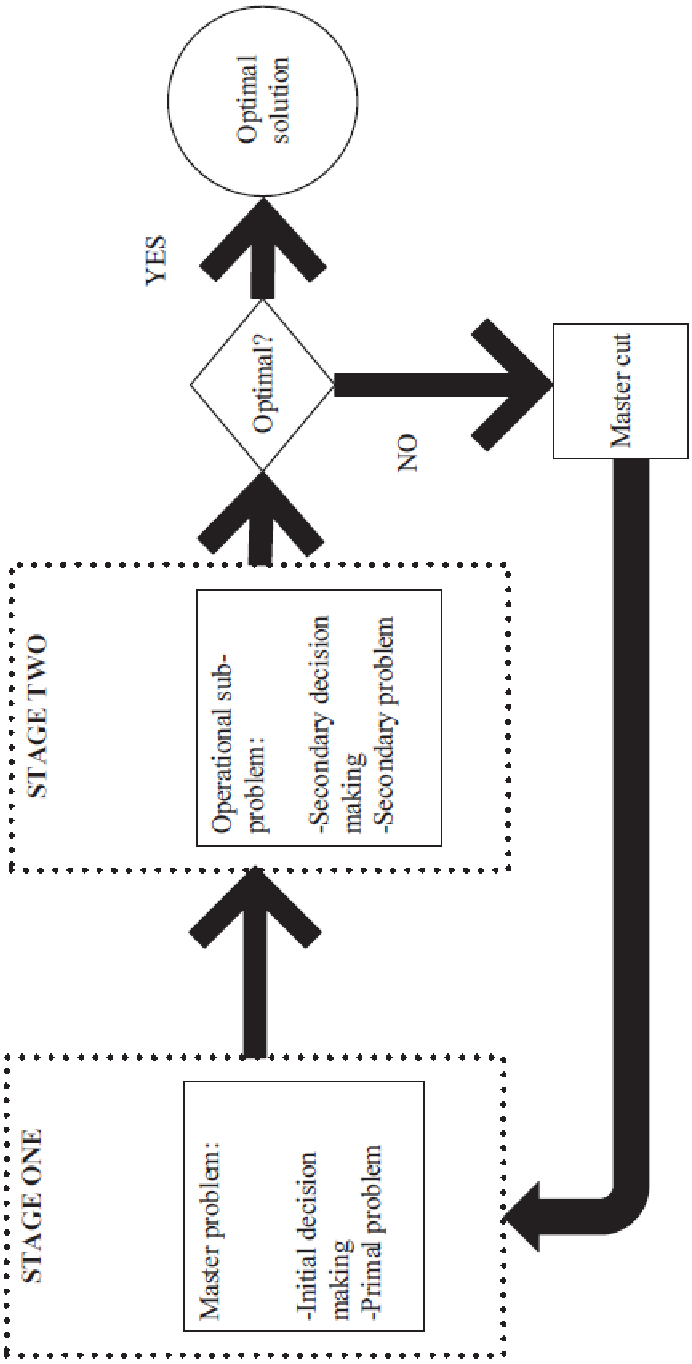

Figure 2.1: Typical benders decomposition methodology

2.1 Benders decomposition methodology

The equations in the complicated integer programming problem take 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. Repeating the equation 2.2 here,

$$
\begin{aligned}
Maximize \quad & z = c(x) + d(y) \\
\textit{S.t.} \quad & Ax \geq b \\
& E(x) + F(y) \geq h \\
& x \geq 0, y \epsilon Y
\end{aligned}
\tag{2.2}
$$

The benders equations observed in equation 2.2 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. This master problem is subjected to the master constraints in the problem. The sub-problem is considered to be the second half of the decomposition approach. This sub-problem is subjected to sub-problem constraint.

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 2.2.

  $$
  \begin{aligned}
  Maximize \quad & \bar{z} = c(x) + \alpha(x) \\
  & S.t Ax \geq b
  \end{aligned}
  \tag{2.3}
  $$

  The master problem is formulated in equation 2.3 and it can be observed that the y^* variable is omitted as it corresponds to the sub-problem. $\alpha(x)$ is added to the master problem equation as it considered the piece-wise function of the optimality sub-problem. This is done in order to prove 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 2.2. 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 a 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.

  $$v + \lambda E(x^* - x) \leq 0 \tag{2.4}$$

  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 2.5. The value w is the value of$\alpha(x)$ at x^*.

  $$w = Min \quad d(y) \tag{2.5}$$

  Similarly to the feasibility sub-problem approach, If the obtained solution from equation 2.5 is not optimal then an optimal cut is generated and this optimal cut is added to the master problem for further analysis.

  $$w + \pi E(x^* - x) \leq \alpha \tag{2.6}$$

  From equation 2.6 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 checks the optimality of the objective problem with respect other constraints and displays the optimal result with help of optimal cut which is being applied to the master problem.

2.1.1 Benders decomposition rule

The optimal solution obtained from the optimal sub-problem is subjected to follow some specific set of bender rules, which 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 into 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.
- The final optimal solution is considered as an optimal solution when ϵ value is greater than the difference of upper bound and lower bound value previously calculated.

2.2 Benders decomposition algorithm

A typical procedure of the benders decomposition algorithm is illustrated in this section: The overall algorithm is shown with the help of pseudo code in algorithm 1.

Algorithm 1 Benders decomposition algorithm

Input: Upper bound (UB) is set, Lower bound (LB) is set and Tolerance value of epsilon ϵ is set.

Output: Optimal Result

procedure ALGORITHM
    $UB = +infinity, LB = -infinity$
    while $LB < UB = \epsilon$ **do**
        Obtain Master solution seen in equation 2.2
        Update the LB
        Solve the sub-problem
        if *sub-problem is feasible* **then**
            Update UB
        else
            Generate Master-cut for master problem seen in equation 2.6
    if *Check for the tolerance by UB-LB* $< \epsilon$ **then**
        Solve the master problem with master cut
    else
        Display the optimal result if UB-LB $> \epsilon$
        End

1. **Initialization**

A limit is set on the 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 into consideration to solve the sub-problem.

2. **Sub-problem solution**

   The 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 2.4 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 master 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 master cut added to the master problem. Once the solution is obtained then the algorithm continues to step 2.

2.3 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 an optimized answer when subjected to two constraint equation.

$$Maximize \quad z = 3x_1 + 2y_1 \tag{2.7}$$

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

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

$$x_1, y_1 \geq 0$$

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;

$$Maximize \quad z = 3x_1 \tag{2.8}$$

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

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

$$x_1 \geq 0$$

In equation 2.8 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 2.8 becomes $(3x_1 + constant)$ and therefore, we can right now ignore a constant in linear programming.

Now, writing the dual of the equation 2.8 as follows;

$$Minimize \quad w \begin{bmatrix} 6 - u_1 \\ 20 - u - 1 \end{bmatrix} \quad \begin{bmatrix} u_1 & u_2 \end{bmatrix}; \tag{2.9}$$

$$u_1 + 5u_2 \geq 3$$

$$u_1, u_2 \geq 0$$

Since we don't know the solution to the equation 2.9 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 is an upper bound to the optimal solution to the equation 2.9. 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 to the dual is greater than or equal to the objective function value of every feasible solution to the primal. The objective function refereed in equation2.7 becomes $z \leq 3(6 - y_1)$.

Therefore, rewriting the problem by referring to equation 2.7 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 2.8.

Therefore,

$$Minimize\, w = 6u_1 + 20u_2 \tag{2.10}$$

$$u_1 + 5u_2 \geq 3$$

$$u_1, u_2 \geq 0$$

Solving equation 2.10 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 2.9 becomes $3/5(20 - 2y_1)$.

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

$$Minimize \quad z \tag{2.11}$$

$$z \leq 18 - y_1$$

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

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

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.

Table 2.1: Optimal value of y_1

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

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 2.8 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.

Now, substituting the value of y_1 to the master problem in equation 2.8 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 and similarly 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.

2.4 Computational example

For the computational example, a generic mixed integer linear program is taken into consideration. The following computational example has one objective equation which is supposed to provide with optimized answer subjected to two constraint equation. The flow-chart corresponding to the following example is shown in figure 2.2. The pseudo code for solving the following computational problem can be seen in algorithm 2. The GAMS code for the computational example is given in appendix A.

$$\begin{aligned} Maximize \quad z &= 3x_1 + 2y_1 \\ S.T: .x_1 + y_1 &\leq 6 \\ 5x_1 + 2y_1 &\leq 20 \\ x_1, y_1 &\geq 0 \end{aligned} \tag{2.12}$$

The above problem 2.12 has a a similar format as of in equations 2.7. Therefore the following term A and B can be formulated as follows:

$$A = \begin{bmatrix} 1 \\ 2 \end{bmatrix}; B = \begin{bmatrix} 1 \\ 5 \end{bmatrix}; C = \begin{bmatrix} 2 \end{bmatrix}; D = \begin{bmatrix} 3 \end{bmatrix}; rhs = \begin{bmatrix} 6 & 20 \end{bmatrix};$$

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

1. Data file is created with all the matrices A, B, C, and D. The parameters corresponding to the right-hand side of the constraint are introduced and different sets are created. The approach can be seen in figure 2.3

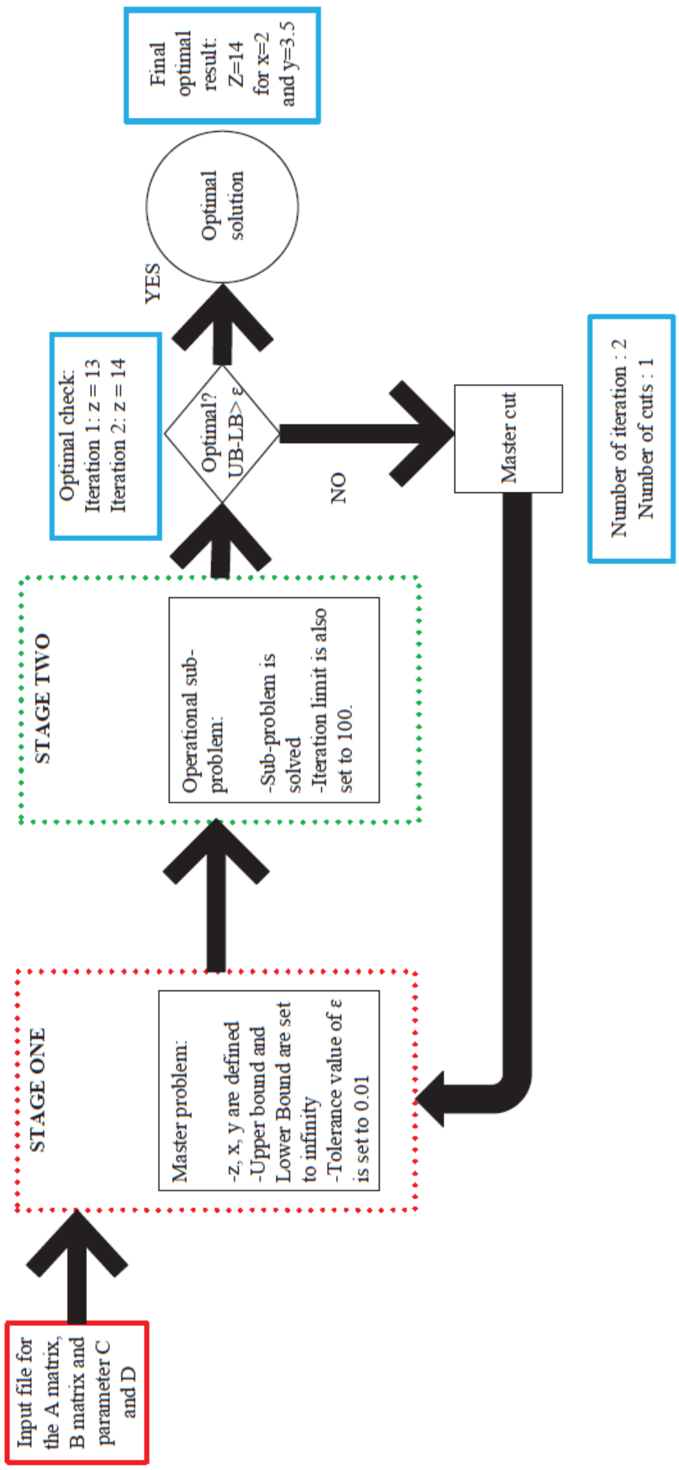

Figure 2.2: Computational flowchart of the implementation of the benders decomposition

Algorithm 2 Pesudo code for the computational example

Input: Objective equation z, constraint equations, Upper bound (UB) is infinity, Lower bound (LB) is infinity, Tolerance value of epsilon ϵ is 0.01, $A = \begin{bmatrix} 1 \\ 2 \end{bmatrix}$; $B = \begin{bmatrix} 1 \\ 5 \end{bmatrix}$; $C = \begin{bmatrix} 2 \end{bmatrix}$; $D = \begin{bmatrix} 3 \end{bmatrix}$; $rhs = \begin{bmatrix} 6 & 20 \end{bmatrix}$;

Output: Optimal Result

procedure ALGORITHM
    $UB = infinity, LB = -infinity$
    while $LB < UB = \epsilon$ **do**
        Obtain Master solution seen in equation 2.2
        Update the LB
        Solve the sub-problem
        if *sub-problem is feasiblel* **then**
            Update UB
        else
            Generate Master-cut for master problem seen in equation 2.6
    if *Check for the tolerance by UB-LB* $< \epsilon$ **then**
        Solve the master problem with master cut
    else
        Display the optimal result if UB-LB $> \epsilon$ **Optimal result z = 14**
        End

```
SET m  / 1 * 2 /;
SET n1 / 1 * 2 /;
SET n2 / 1 * 2 /;

TABLE A(i, j1)
       1
  1    1
  2    2

TABLE B(i, j2)
       1
  1    1
  2    5

PARAMETER c(j1)   / 1 = 2 /;
PARAMETER d(j2)   / 1 = 3 /;
PARAMETER rhs(i) / 1 = 6, 2 = 20 /;

PARAMETER ux(j1) / 1 = 2 /;
PARAMETER uy(j2) / 1 = 10000, 2 = 10000 /;
```

Figure 2.3: Input file

2. Algorithm file is created separately and the data filled is called in the algorithm file by using $\$include$ command in GAMS.

3. In master problem and its variables and the equations are modelled and the master problem is solved using the maximization command in GAMS. The approach can be seen in figure 2.4.

```
* Set up the main problem:
  EQUATIONS MainObj, MainCon(i);
  VARIABLE z, x(j1), y(j2);

  MainObj       .. z =E= sum( j1, c(j1) * x(j1) ) +
                         sum( j2, d(j2) * y(j2) );

  MainCon(i)    ..       sum( j1, A(i,j1) * x(j1) ) +
                         sum( j2, B(i,j2) * y(j2) ) =L= rhs(i);
```

Figure 2.4: Master problem formulation

4. 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. The approach can be seen in figure 2.5, figure 2.6 and figure 2.7 respectively.

```
* SUBPROBLEM: A model in y-variables only. (and z, and p...)
*
  EQUATIONS SubObj, SubCon(i);
  POSITIVE VARIABLE p;          # Penaltx

  SubObj       .. z =E= sum( j1, c(j1) * x.L(j1) )     +
                        sum( j2, d(j2) * y(j2) )       + BigM * p;

  SubCon(i)    ..         sum( j1, A(i,j1) * x.L(j1) ) +
                          sum( j2, B(i,j2) * y(j2) )    + p =L= rhs(i);


  MODEL Sub /SubObj, SubCon /;
```

Figure 2.5: Sub-problem formulation

```
* MASTER PROBLEM: A model in x-variables only (and z...)
*
  EQUATIONS MasterCut(It);

  MasterCut(cut)   ..
        z  =E= sum( j1, c(j1) * x(j1) ) +
               sum( j2, d(j2) * y_sol(cut, j2) ) -
               sum(i, pi(cut,i) *
                      (sum( j1, A(i,j1) * x(j1) ) +
                       sum( j2, B(i,j2) * y_sol(cut,j2) ) - rhs(i)
                      )
                  );
```

Figure 2.6: Master cut formulation

5. If the tolerance is with in the limit then the iteration is stopped and the final optimal result is displayed. The approach can be seen in figure 2.7.

```
WHILE ( UpperBound - Lowerbound > Epsilon,

  this(Iter) = yes $ (ord(Iter) eq counter);
  DISPLAY this, x.L;

  SOLVE Sub maximizing  z using LP;

*   Save primal and dual solution from the Sub:
  y_sol(this, j2) = y.L(j2);
  pi(this, i) = SubCon.M(i);
  UpperBound  = min(UpperBound, z.L);
  DISPLAY counter, y_sol, pi, UpperBound;

  cut(Iter)  = yes $ (ord(Iter) le counter);
  DISPLAY cut;

  IF ( UpperBound - Lowerbound > Epsilon,
    SOLVE Master maximizing z using LP;
    LowerBound  = max(LowerBound, z.L);

    DISPLAY LowerBound;
    counter = counter + 1;
  );
);
```

Figure 2.7: Iteration modelling

The objective problem in equation 2.12 is solved using two GAMS file. The optimal answer obtained from solving the problem is found to be $z = 14$.

From the theoretical to GAMS computational solving of benders decomposition we can conclude few points:

- The output obtained through GAMS computation is more optimized compared to theoretical approach
- The time taken to solve the theoretical approach is a lot more when compared to GAMS computation approach. The GAMS computation took almost 6 seconds to solve the problem.
- If the constraints in the problem formulation are increased, it becomes very difficult to solve the problem through theoretical approach. Therefore, a computational approach is preferred for large complex problems.

Chapter 3

Problem definition

In this thesis, the objective of the proposed approach is to perform economic outage scheduling of transmission line for long-term horizon under different demand scenarios. The various future demand scenarios are one way of dealing uncertainty in future. In the end, the approach will provide an optimal schedule for a selected set of transmission lines in the power system network to be maintained 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. As described before, the transmission component considered in this research work is a transmission line, and the reason for choosing it is described in detail in section 1.2 of chapter 1. Formulating the objective function for outage scheduling is a key task because the solution should give two important outputs; one is the lowest maintenance cost and other is the lowest lost load incurred due to maintenance. This section explicitly defines the problem formulation along with the various constraints that hold the problem, inputs required to solve the problem and (if any) relaxed constraints.

The objective problem is a mixed integer linear programming (MILP) problem. A solution to the mixed integer linear programming problem of the objective problem will provide an optimal outage schedule for the selected network. As the model taken into consideration is a lossless DC power flow model, therefore the main aim of the problem formulation is to provide optimal outage schedule while satisfying the DC network security constraints.

An important aspect of problem formulation is to confirm if it is a tight MILP problem or a relaxed MILP problem with relaxed constraints and assumption. Some of the assumptions taken into consideration for the transmission line outage scheduling problem are as follows:

- Lossless DC power flow model is considered.

- The scheduler has no knowledge of the planned outage of the generation facility.
- Component degradation in the term of failure rate and life reduction is not considered.
- The whole network is considered to be working without any failure or fault.

The model considered is the DC power flow model and, therefore, existing power system operating criteria are taken into consideration. Some of the operating criteria of the power system that are considered in this study are mentioned below [26]:

- **Nodal balance equations:**

  Nodal balance equation imposes generation and demand balance at each node of the system.
- **Power flow through existing transmission lines:**

  This equation specific the power flowing through existing transmission line in the network.
- **Generation limits:**

  Generation limits refers to the restriction imposed on the power produced by the different generating units.
- **Limits on transmission line power flow:**

  Limit on transmission line power flow works as a capacity limit on the power flow through the existing transmission lines.
- **Limit to voltage angle at reference node:**

  Limit on the voltage angle is done by imposing bound on the voltage angle and voltage angle at the reference node is fixed to zero.

3.1 Problem inputs

The key to obtaining optimal schedule as well as proper result from the model defined is to have adequate input data for the problem formulation. The input data has to be modelled as per the requirement of the TSOs. As all the operating constraints of the DC power flow model have to considered, the input data is formulated accordingly. An overview of input data file can be seen in figure 3.1.

Below are the input data which are to be considered and with their respective parameters corresponding units and layout:

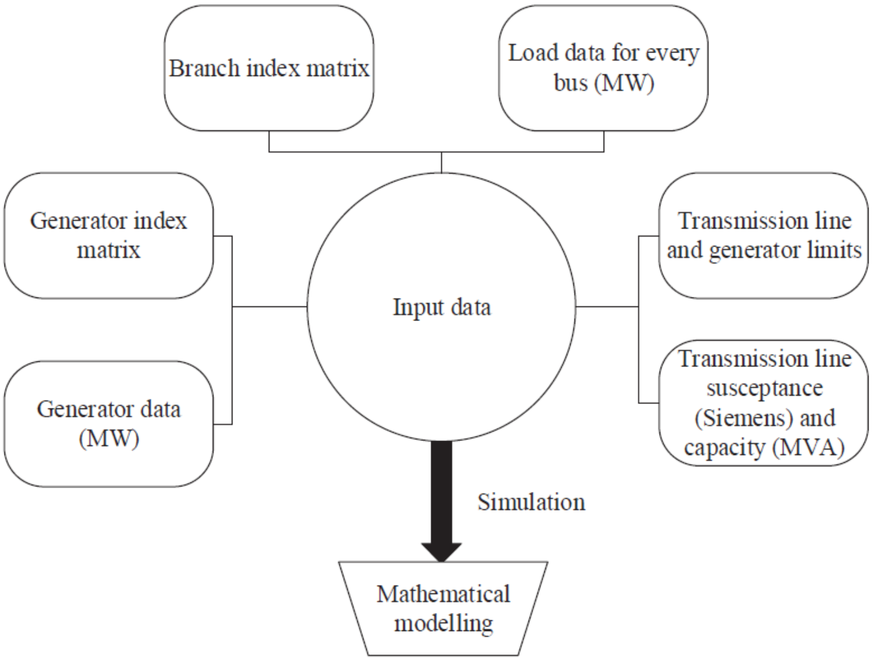

Figure 3.1: Overview of the input data

- **Branch index matrix:**

  The input file created for the branch index matrix takes in account the transmission line and bus matrix. As of the file specifies the start of a transmission line for a specified bus to the bus where the transmission line ends. The illustration of the input file in shown in figure 3.2.

	Bus 1	Bus 2	.	.	Bus 24
Line 1	1	-1	.	.	.
Line 2	1	0	.	.	.
Line 3	1	0	.	.	.
Line 4	0	1	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
Line 38	.	.		.	.

Figure 3.2: Branch index matrix overview for IEEE RTS-24 bus test case [3]

- **Generator index matrix:**

  The input file created for the generator index matrix takes in account the generator in the network and buses and form a generator and bus matrix. The file specifies the location of a generator for a specific bus in the network. The illustration of the input file is shown in figure 3.3.

	Bus 1	Bus 2	.	.	Bus 24
Generator 1	1	0	.	.	.
Generator 2	0	1	.	.	.
Generator 3	0	0	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
Generator 11	.	.	.	.	.

Figure 3.3: Generator index matrix overview for IEEE RTS-24 bus test case [3]

- **Generator data (MW):**

  The input file takes in account the capacity limit of the generating unit in megawatts(MW). The illustration of the file can be seen in figure 3.4.

	Capacity limit (MW)
Generator 1	12
Generator 2	12
Generator 3	20
.	.
.	.
.	.
Genrator 11	.

Figure 3.4: Generator data overview for IEEE RTS-24 bus test case [3]

- **Transmission line capacity and susceptance:**

  The input file created for the transmission line susceptance and capacity takes into account the susceptance (Siemens) of the transmission line and the capacity of the transmission line in MVA. The illustration of the input file can be seen in the figure 3.5.

	Line capacity (MVA)
Line 1	193
Line 2	208
Line 3	208
.	.
.	.
.	.
Line 38	.

	Susceptance (Siemens)
Line 1	7194.244
Line 2	473.484
Line	1183.431
.	.
.	.
.	.
line 38	.

Figure 3.5: Transmission line capacity (MVA) and susceptance (Siemens) for IEEE RTS-24 bus test case [3]

- **Load data:**

  For the modelling, the input file created for the load data takes in account the annual peak load of the system. As of the network, the total installed capacity in megawatts (MW) is considered. Load in megawatts (MW) for the selected time for every bus in the network is represented in the file. The load at each bus is calculated by taking into consideration the weekly peak load in percent of annual peak, daily peak load in percent of weekly peak, hourly peak load in percent of daily peak, the annual peak load of the system and percent distribution of the load at each bus. Finally, the calculated result is presented for each bus at each period of time. In the figure 3.6 we can observe the load data bus matrix [3].

Week	Days	Hours		Weekly loa	Daily load	Hourly loa	ak Load (MW)		Time(hours)	Bus 1 (MW)	Bus 2	.	Bus 24
1	1	1		0.862	0.93	0.67	3135		t1	63.986	57.25	.	74.089
1	1	2		0.862	0.93	0.63	3135		t2	60.166	53.832	.	69.666
1	1	3		0.862	0.93	0.6	3135		t3	57.301	51.269	.	66.358
1	1	4		0.862	0.93	0.59	3135		t4	56.346	50.414	.	65.242
1	1	5		0.862	0.93	0.59	3135		t5	54.346	50.414	.	65.242
.	.	.		.	.	.	.		.	.	.	.	.
.	.	.		.	.	.	.		.	.	.	.	.
.	.	.		.	.	.	.		.	.	.	.	.
52	365	8736		.	.	.	.		t8736	.	.	.	.

Figure 3.6: Load data overview for IEEE RTS-24 bus test case [3]

3.2 Problem definition:

The objective of the proposed approach is to perform economic outage scheduling of transmission line for long-term horizon under different demand scenarios, while satisfying all the constraints.

Alternating current (AC) power flow model is generally considered for calculating the state of grid injection and grid flow. But the AC power flow model takes into consideration a nonlinear system to describe the energy flow in transmission lines. Due to this non-linearity, AC power flow model is not elected for large network analysis. The simplified version of AC power flow model is used to perform analysis for a large network and is called DC power flow model. The advantage of using the DC power flow model is described below:

- The losses occurring in the grid are neglected.
- The voltage amplitude is equal for all nodes.
- The voltage angle difference between each node is very small.

Generally, maintenance scheduling is a complicated stochastic nonlinear optimization problem. The scheduling is especially complicated when multiple objectives have to be optimized in order to provide optimal maintenance solution. The proposed approach described in the thesis for solving the problem formulation is a multi-objective approach. The main objective function 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 [27] as follows:

$$Min \quad Z \quad = \sum_{t}(\sum_{l} C_{lt}(X_{lt}) + \sum_{i}(c_{it}r_{it})) \tag{3.1}$$

The objective function in equation 3.1 is a multi-objective function equation. The advantage of implicating multi-objective approach over single-objective approach is the large historical data considered for determining the result of each objective function. Another drawback of having single-objective approach is that only single optimal solution is generated for every optimization process. The single output does not provide enough information regarding the system reliability or other parameter associated in the system. To tackle all these defects, a multi-objective optimization approach has been selected in order to solve the problem formulation.

Equation 3.1 is a two-stage minimization optimization problem. The first stage determines the total maintenance cost of the selected transmission line maintenance for outage schedule and the second stage determines the total loss of revenue by the TSOs due to loss of load when the transmission line is subjected to maintenance. The overall problem 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 3.1 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 optimized solution for the maintenance problem. In the thesis, two main types of the constraints are defined. Maintenance constraints and network constraints are the two type of constraints defined for the scheduling problem.

3.2.1 Maintenance constraints:

The maintenance constraint takes in to account the number of candidate lines in right of way and the maximum number of lines allowed in right of way. While deciding the candidate line, the candidate line should be available after the earliest period e_l and before the latest period l_l. The maintenance constraint can be stated as [10]:

$$X_{lt} = 0, \quad \text{for} \quad t \leq e_l \quad or \quad t \geq l_l \tag{3.2}$$

$$X_{lt} = 0 \quad or \quad 1, \quad \text{for} \quad e_l \leq t \leq l_l$$

$$\sum X_{lt} \quad \geq \quad (1, 2, 3, ...m), \quad \text{for} \quad t \geq e_l \quad and \quad t \leq l_l$$

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.

3.2.2 Network constraints:

The system constraint takes into account the voltage, power and the reliability aspect of the transmission network. The system constraints for every scenario are as follows [27]:

$$sf + p + r = d \tag{3.3}$$

Equation 3.3 is the nodal balance equation. This equation result in generation and demand balance at each node.

$$f_k - \gamma_k(\theta_k - \theta n) = 0 \tag{3.4}$$

Equation 3.4 is the power flow through existing line in the power system.

$$-PL_{jmax} \leq f_k \leq -PL_{jmin} \tag{3.5}$$

$$P_{Gi_{min}} \leq P_{Gi_{bt}} \leq P_{Gi_{max}} \tag{3.6}$$

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

3.3 Cost integration

The purpose of the maintenance schedule is not only for generating an optimal schedule but also to reduce the total maintenance cost expected by the TSOs. The cost incurred during maintenance is a very important and fundamental issue experienced by the TSOs. Many resolutions and efforts are made by the TSOs in order to reduce the maintenance cost. Therefore, the cost function is an important attribute in the problem formulation. In the problem formulation, two different aspects of costs are taken into consideration. The first aspect being the maintenance cost of the selected transmission line. This maintenance cost takes into consideration various section of the maintenance cost and together provides a single value maintenance cost. Generally, the maintenance cost of the transmission line considers the service cost of the resource available, man power required to get the maintenance done and various auxiliary costs. Therefore, in the problem formulation, we have considered a single scalar value of maintenance cost required for a single transmission line maintenance. The second aspect of the maintenance cost is the loss of revenue experienced by the TSOs. The loss of revenue observed by the TSOs is due to unserved load experienced during the outage of the transmission lines. The unserved load is multiplied by the potential loss of revenue at the specific bus for the specific transmission line.

The reason behind the integration of the cost function in developing the maintenance outage schedule is, to perform analysis in such a way as to get an optimal maintenance cost for an outage schedule. Maintenance cost for a specific transmission line can keep on changing because of the external auxiliary costs. The TSOs in such case has the power to perform large outage schedule and maintenance work at a place in the network where the maintenance cost of the transmission line is the lowest. If a specific area in the network is selected during a specific period of time, at the point of time of lowest cost of maintenance, then the overall maintenance cost of the selected network will be lowest and the TSO will face a lower loss of revenue.

3.4 Convex optimization

As we explained in chapter 2, the benders decomposition approach decomposes the objective function problem into two problems. The first part of the problem being a master problem and the second part of the problem is the sub problem. Each part of the problem is subjected to their specific constraints. The objective function problem is called an objective problem global variable (OPGV) [28]. This OPGV implies that the benders decomposition has objective problem subjected to a global variable. This also implies that benders decomposition also effectively deals with a convex approach towards OPGV. The OPGV has the master problem with a global variable and the sub problem with local variable. Generally, there are two types of variables, the first one being the global variable and the second one being the local variable. The global variable in the case of the problem formulation is considered in the master problem and the local variable is considered in the sub problem. The selection of the global variable has an overall effect on the sub problem as well as the objective function problem, and that is the reason it is called the global variable. As local variables are present in the problem formulation, this becomes one of the reasons as to the selection the bender decomposition algorithm. Benders decomposition is generally used to deal with those objective equations whose constraints are linear and have a local variable. In benders decomposition, the master problem is relaxed for every iteration by adding addition cuts to the master problem. This addition of cuts results in more optimized master problem resulting in more optimized objective function problem. The objective and constraints considered in benders decomposition are convex in the local variables. Therefore, the main reason behind solving of the problem formulation by convex approach being that the master cuts added to the master problem are generated by the means of convex duality theory. The basic concept of the duality is explained in the subsection 3.4.1.

3.4.1 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 should also have an unfeasible or unbounded solution.

The primal problem can be expressed as following notation:

$$Maximize \quad z = c^T.x \tag{3.7}$$
$$S.tAx \leq b$$
$$x \leq 0$$

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:

$$Maximize \quad z = b^T.x \tag{3.8}$$

$$S.t Ax \geq b$$

$$x \geq 0$$

In the above notation for the primal problem, we can observe that the constraints indicated for the objective function act 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 the 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 increase, which helps in solving the objective function. Increase in inequalities reduces the complexity of the linear programming problem.

3.5 Relaxed constraints

The constraints in the problem formulation act as bounds and limit to the objective function equation. The objective function equation is a two-stage optimization equation. The first stage of the objective function equation is subjected to maintenance constraints and the second stage is subjected to network constraints which can be seen in the figure. The network constraints in the problem formulation are considered to be the technical constraints. These technical constraints fulfil the operating system criteria of the network. The maintenance constraints are the bound constraints of the time period. The selection of the transmission line in the specific time period for a specific section of the network is considered in the maintenance constraints. Also, the total number of transmission line that can be considered for maintenance for a specific period of time is also considered for maintenance constraint. The only constraint which is subjected to relaxation is the cost constraint. The cost constraint takes into consideration the maintenance cost associated with transmission line during its outage condition. The maintenance cost takes into account various costs such as service cost, resource cost and component cost. As all these various costs cannot be considered in the problem formulation, we consider a single cumulative value that takes into consideration all the cost associated with maintenance of the transmission line. However, during the problem formulation, the relaxation of the maintenance cost was performed. The relaxation of the cost was done in terms of making all the maintenance cost of the transmission in the network to be same. This approach especially gave an overview as well as point of study in understanding the optimal schedule and the optimal maintenance cost of the objective function problem. Another relaxation of the constraint was done to the total transmission line that the maintenance can be performed at a specific period of time.

3.6 Methodology

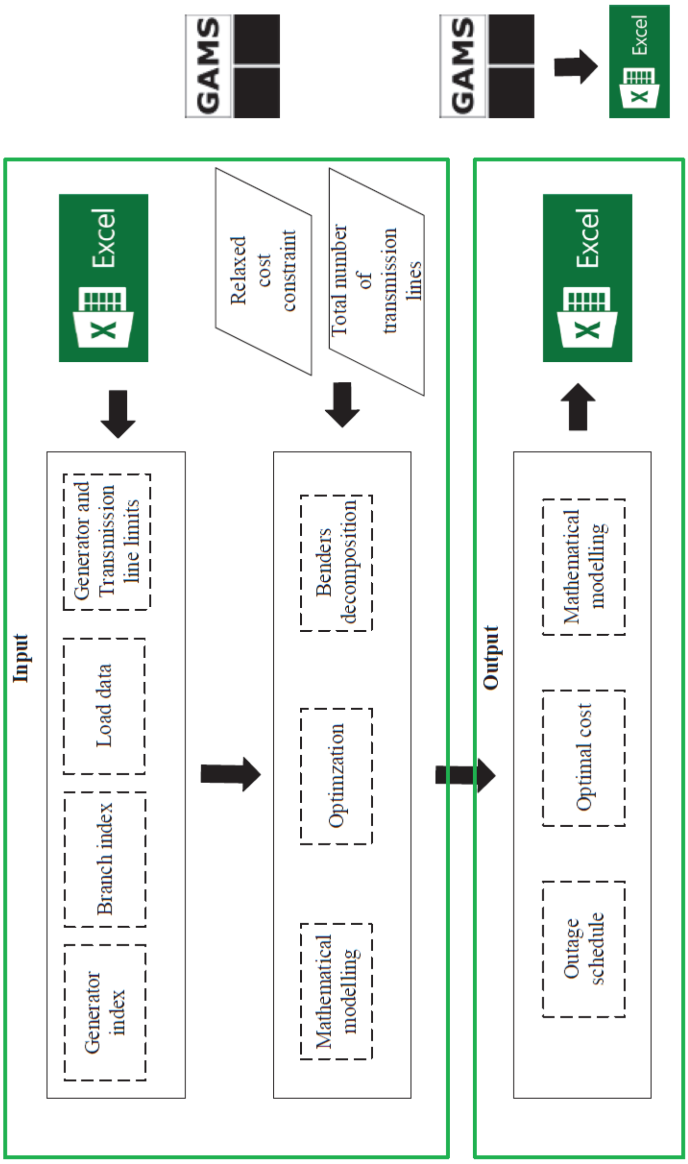

Figure 3.7: Methodology overview

Figure 3.7 show the overview of the methodology incorporated in solving the problem formulation. The input file is imported through MS-Excel software into the GAMS and subjected to the bender decomposition algorithm to generate optimal result and schedule.

3.7 Step by step procedure for benders decomposition execution

For a better and clear explanation, benders decomposition has been applied for the following RBTS 6-bus system. The 6-bus RBTS test case is considered as small system test case. The main reason for considering the 6-bus RBTS test case is to show step by step methodology of solving the problem formulation with the help of benders decomposition. Every step in the methodology will describe and illustrate the approach incorporated in solving the problem formulation using benders decomposition. Figure 3.8 shows the basic layout of the RBTS 6-bus test system.

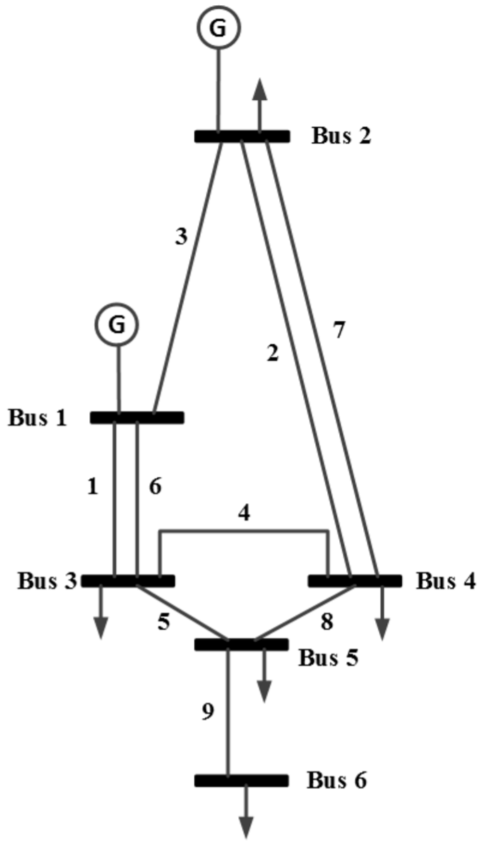

Figure 3.8: RBTS 6-bus system

- **Step 1:**

The input data file is created as per the section 3.1. The input data file should be imported in the GAMS software with help of xls2gms command.

```
table aux11(l,column)
$call =xls2gms r=line_admittance!a2:b11 i=input_14.xlsx o=aux11.inc
$include aux11.inc
;
```

Figure 3.9: Importing data from excel sheet

- **Step 2:**

Sets are created with respect the input data. The sets correspond to the overview of the network in terms of the transmission lines, generators and loads.

```
***********************************
******* SETS
************************************
Sets w            Weeks                        / w1   /
     t            Hours of the year            / t1*t93 /;
set i             generators                  /i1*i2/    ;
set s             buses                        /s101*s106/      ;
set l             lines                       /l1*l9/          ;
set column        auxiliary                   /column1/;
set sfirst(t,l);
set slast(t,l);
alias(t,tt);
```

Figure 3.10: Modelling of sets

- **Step 3:**

Variables are to be declared. The variables are the key element for equation formulation in GAMS.

```
*********************************************
$include 6bus_inpu.gms
*********************************************

*********************************************
*Variable
*********************************************
variable obj objective function varibale
binary variable x(t,l)
variable start(t,l)
semicont variable shift(l)
positive variable ll(t,s) unserved load
variable theta(t,s)
variable pf(t,l) power flow through line
variable c_aux(t) auxilliary variable
positive variable g(t,i) generator output
positive variable c(t,l)
positive variable p
;
```

Figure 3.11: Modelling of variables

- **Step 4:**

  The equations are to be modelled. The pseudo code mentioned in chapter 2 is to be incorporated to model all the equation.

  - The Master problem is modelled in the beginning.

```
*************************************************
**** Equations for Master Problem
*************************************************
cost..
         obj=e=sum(sfirst(t,l),linecost(l)*(x(t,l)))+
                  (sum((t,s),ll(t,s)*6.75));
```

Figure 3.12: Modelling of master problem

  - The sub-problem is modelled.

```
************************************************
****Equations for Sub-Problem
***********************************************

cost2..
         obj=e=sum(sfirst(t,l),linecost(l)*(x.L(t,l)))+
                 (sum((t,s),ll(t,s)*6.75)) + BigM * p;

power_balance(w,t,s,i)..
        sum(l$(line_map(l,s) <> 0),pf(t,l)*line_map(l,s))
         +ll(t,s)+p =e= (-sum(ii$(gen_map(i,s)),g(t,i)))+
         (d(t,s));
```

Figure 3.13: Modelling of sub-problem

– The master cut is modelled.

```
************************************************
****Benders Cut
***********************************************

  EQUATIONS MasterCut(It);

  MasterCut(cut)   ..
        obj   =G=sum(  (t,s), 6.75 * ll_sol(cut,t,s)  ) +
               sum(sfirst(t,l), piu(cut,t)  * x(t,l));
```

Figure 3.14: Modelling of master cut

– The loop equation is modelled as to create iteration and obtain optimal result.

```
************************************************
**** Applying the decomposition
***********************************************

SCALAR counter / 1 /;

  x.L(t,l)  = 0; ll.L(t,s)  = 0;
  cut(Iter)  = NO;

  WHILE  ( UpperBound - Lowerbound > Epsilon,

    this(Iter)  = yes $  (ord(Iter)  eq counter);
    DISPLAY this, x.L;
```

Figure 3.15: Modelling for iteration

- To run the simulation gdx=tmp should be mentioned in the execution command as to observe the optimal schedule and optimal cost of the outage schedule.

The main advantage of choosing bender decomposition over Pareto optimization was that the benders decomposition always converges to an optimal solution compared to Pareto optimization which may or may not reach the optimal solution due to its nature of approach towards solving the multi objective problem.

Chapter 4

Result analysis

For the result analysis, two different sized test cases are taken into consideration. The first test case being the IEEE RTS-24 bus (Reliability test case) test case and the second being the modifies IEEE-118 bus test case. The two test cases are termed as medium and large test cases respectively. The main reason for considering two different test cases is to check the computation efficiency of different test cases. This is an important aspect taken into consideration by the TSOs. The main reason being that the TSOs will not accept a slow running program for larger test cases.

The resulting analysis for the test case of IEEE RTS-24 bus and IEEE 118-bus is explained in the subsequent sections of the chapter. Every test case analysis takes into consideration the input data file as explained in chapter 2 of problem formulation. Every input file is modified according to their respective network. The expected outcome of the test case analysis will display the optimal outage schedule for the respective network, the optimal maintenance cost as well as the improvement in time for convergence of the algorithm.

The maintenance cost taken into consideration for solving the test case takes into account the service cost, man power cost and various auxiliary cost. Therefore a single scalar cost for the transmission line maintenance was taken into consideration. For the result analysis involving the maintenance cost will depict the change of optimal maintenance cost before and after the cost constraint is relaxed.

4.1 IEEE RTS-24 bus test case

The IEEE RTS-24 bus (Reliability test system) test system was proposed in the year 1979. It's a special test case because it acts as a benchmark for various reliability test case analysis. Figure 4.1 shows the basic layout of the 24 bus test system.

In this test case, we have load data provided for every hour of the load at every bus for a year in the network. The IEEE RTS-24 bus system consists of 32 generators ranging from (12 to 400) MW, 24 loads and 38 transmission lines [3].

The input data required for solving the model as per the methodology in problem formulation in chapter 3 is depicted below. All the input data is formulated in excel sheet and imported to the GAMS software.

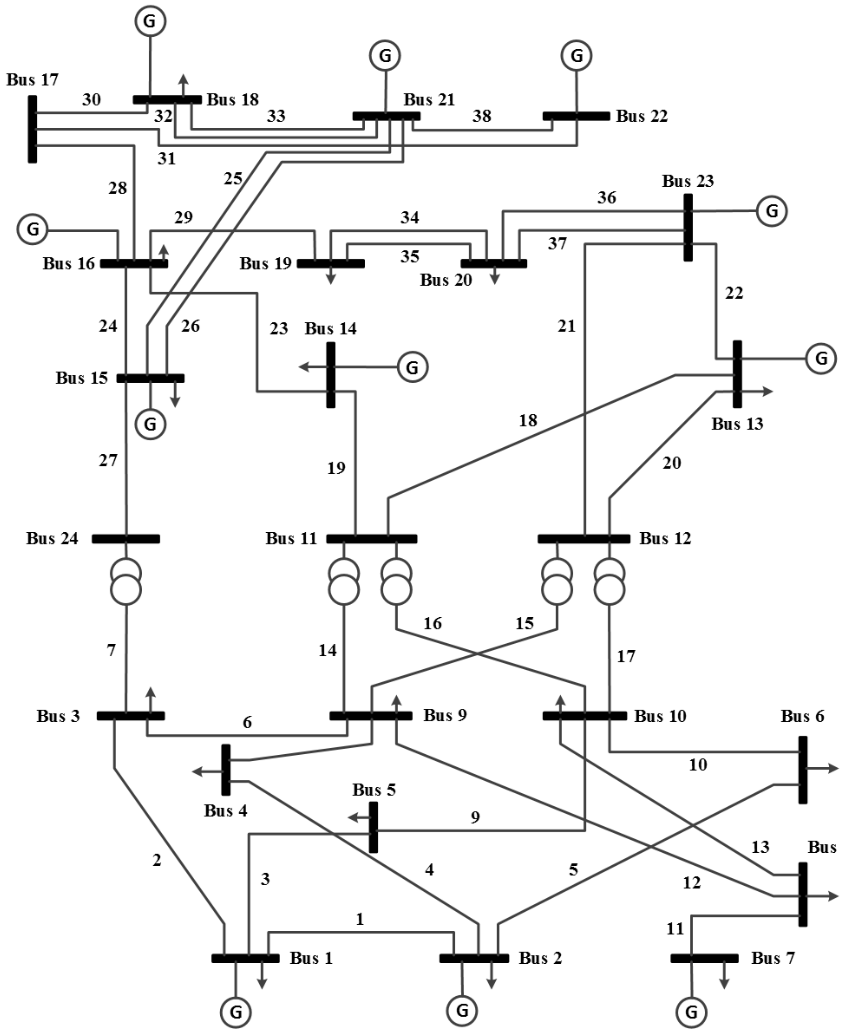

Figure 4.1: IEEE RTS-24 bus system

Table 4.1: Transmission line data for IEEE RTS-24 bus system

Transmission line	From node	To node	Max capacity (MVA)
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 4.2: Weekly peak load in percentage of annual peak for IEEE RTS-24 bus system

Week	Peak load (percentage)
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 4.3: Generating unit data for IEEE RTS-24 bus system

Generator number	$P^{max} MW$	$P^{min} MW$
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

4.1.1 Result analysis

In order to understand and depict the difference in the outage schedule, total maintenance cost and time required for the algorithm to finish, we are going to present two different case analysis for the IEEE RTS-24 bus system. The first test case analysis is considered for a section in the network for 3 months before the summer period and the second case analysis is considered for the other section of the network for 3 months after the summer period. In this set of analysis, we have also considered the change of demand scenario by an increase in 5 percent. The maintenance cost considered for the analysis takes into account the service cost for the resources, labour cost and some auxiliary costs.

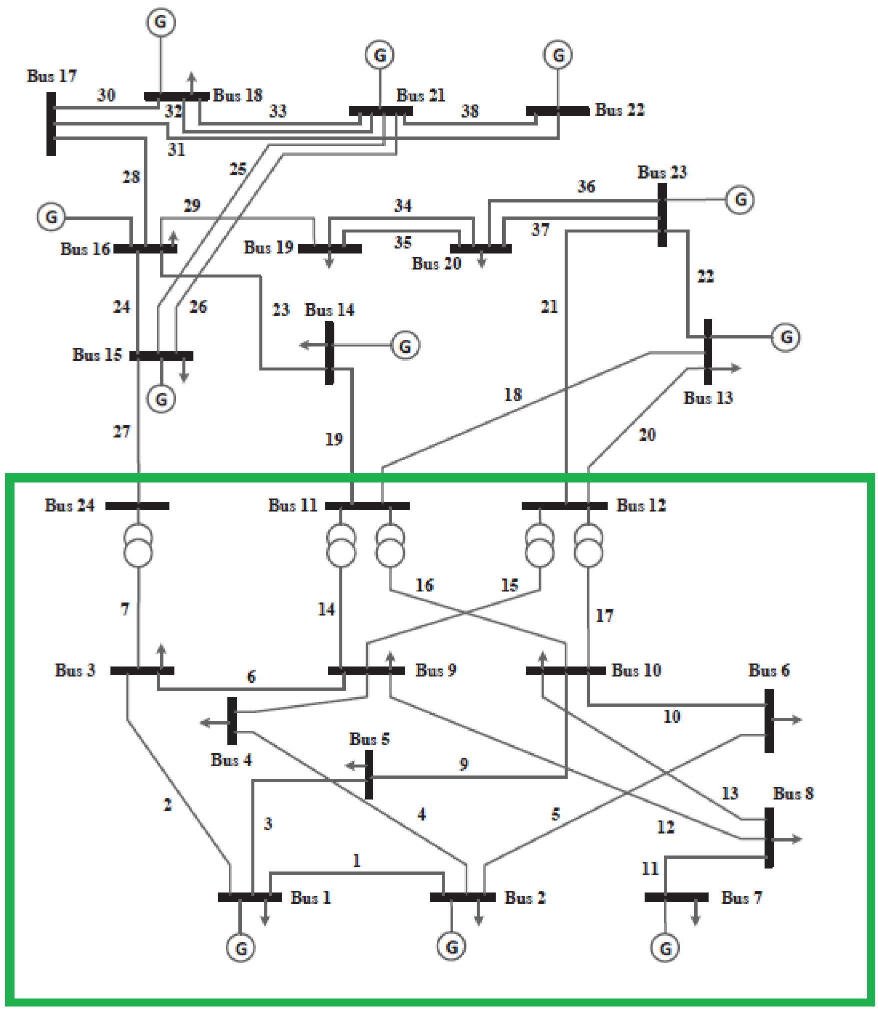

Figure 4.2: The section in green border of IEEE RTS-24 bus system is taken into consideration for the analysis

4.1.1.1 Before summer time

The area considered for the analysis can be seen in figure 4.2. The highlighted area has been specifically selected because the total demand is high and the number generating units are less.

Applying the bender decomposition approach to the problem formulation seen in chapter 3, we were able to develop optimal outage schedule for the selected network of IEEE RTS-24 bus system. Figure 4.4 shows an optimal outage schedule for the IEEE RTS-24 bus system. The selected lines for the selected time period are highlighted in the schedule. The schedule gives an overview and knowledge to the TSO as to which transmission line is to be selected for the specific period of time. Figure 4.5 shows the change in outage schedule for the IEEE RTS-24 bus system when subjected to 5% change in demand scenario.

Figure 4.3 shows the maintenance cost graph. Moreover, it shows the comparison in terms of identical maintenance cost to different maintenance cost for a specific section of the network. The graph in figure concludes that the total maintenance cost for the selected network drops down when a section of the network has lower maintenance cost for the selected transmission lines. Therefore, a conclusion can be drawn in terms of maintenance cost stating that the TSOs have the advantage to perform the outage schedule for a specific area of the network so as to reduce the total maintenance cost.

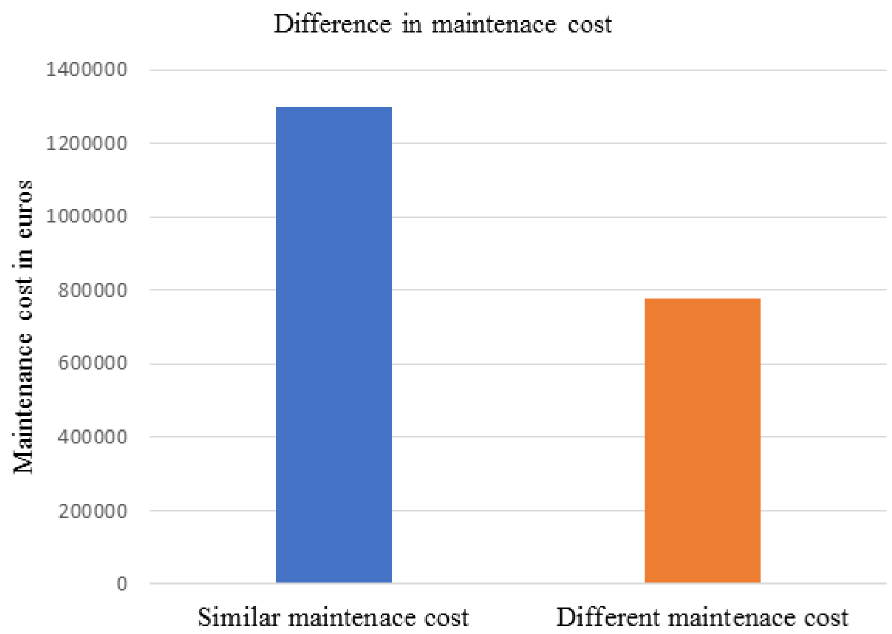

Figure 4.3: Transmission line maintenance cost

Transmission Lines (units)		Time Periods(Days)						
		...	T11	T12	T13	...	T84	85	...
	L1	...				...			...
	L2	...				...			...
	L3	...				...			...
	L4	...				...			...
	L5	...				...			...
	L6	...				...			...
	L7	...				...			...
	L8	...				...			...
	L9	...				...			...
	L10	...				...			...
	L11	...				...		1	...
	L12	...				...	1		...
	L13	...				...			...
	L14	...	1		1	...			...
	L15	...				...			...
	L16	...				...			...
	L17	...		1		...			...

Figure 4.4: Outage schedule of the selected area for before summer analysis of a section of IEEE RTS 24-bus system

Transmission Lines (units)		Time Periods(Days)							
		...	T11	T12	T13	...	T84	85	...
	L1	...		1		...			...
	L2	...				...			...
	L3	...				...			...
	L4	...			1	...			...
	L5	...				...			...
	L6	...				...			...
	L7	...				...			...
	L8	...				...			...
	L9	...				...			...
	L10	...				...			...
	L11	...				...			...
	L12	...				...			...
	L13	...				...	1		...
	L14	...	1			...			...
	L15	...				...		1	...
	L16	...				...			...
	L17	...				...			...

Figure 4.5: Outage schedule with 5% change in demand scenario of the selected area for before summer analysis of a section of IEEE RTS 24-bus system

Figure 4.6 depict the change in convergence time of the algorithm. From the figure, we observe that the total time to convergence is reduced after deleting the previous equation formulated in the software. As the equation formulated in the past iteration are erased, it gives an extra storage space in the memory which helps in the fast convergence of the algorithm.

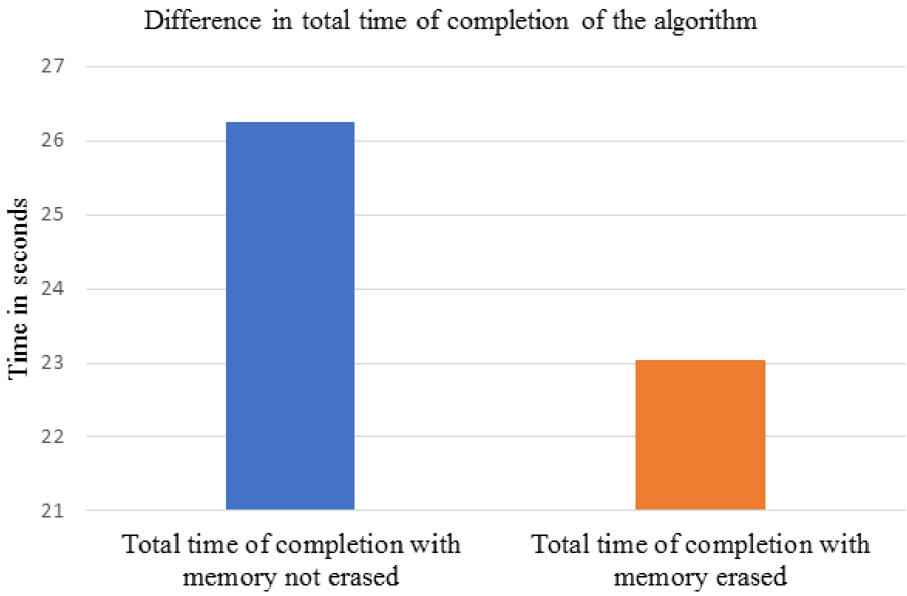

Figure 4.6: Total time for completion of the algorithm

4.1.1.2 After summer time

The area considered for the analysis can be seen in figure 4.7. The highlighted area has been specifically selected because the total demand is low and the number generating units are high.

Applying the bender decomposition approach to the problem formulation seen in chapter 3, we were able to develop optimal outage schedule for the selected network of IEEE RTS-24 bus system. Figure 4.8 shows an optimal outage schedule for the IEEE RTS-24 bus network. The selected lines for the selected time period are highlighted in the schedule. The schedule gives an overview and knowledge to the TSO as to which transmission line is to be selected for the specific period of time. Figure 4.9 show the change in outage schedule for the IEEE RTS-24 bus system when subjected to 5% change in demand scenario.

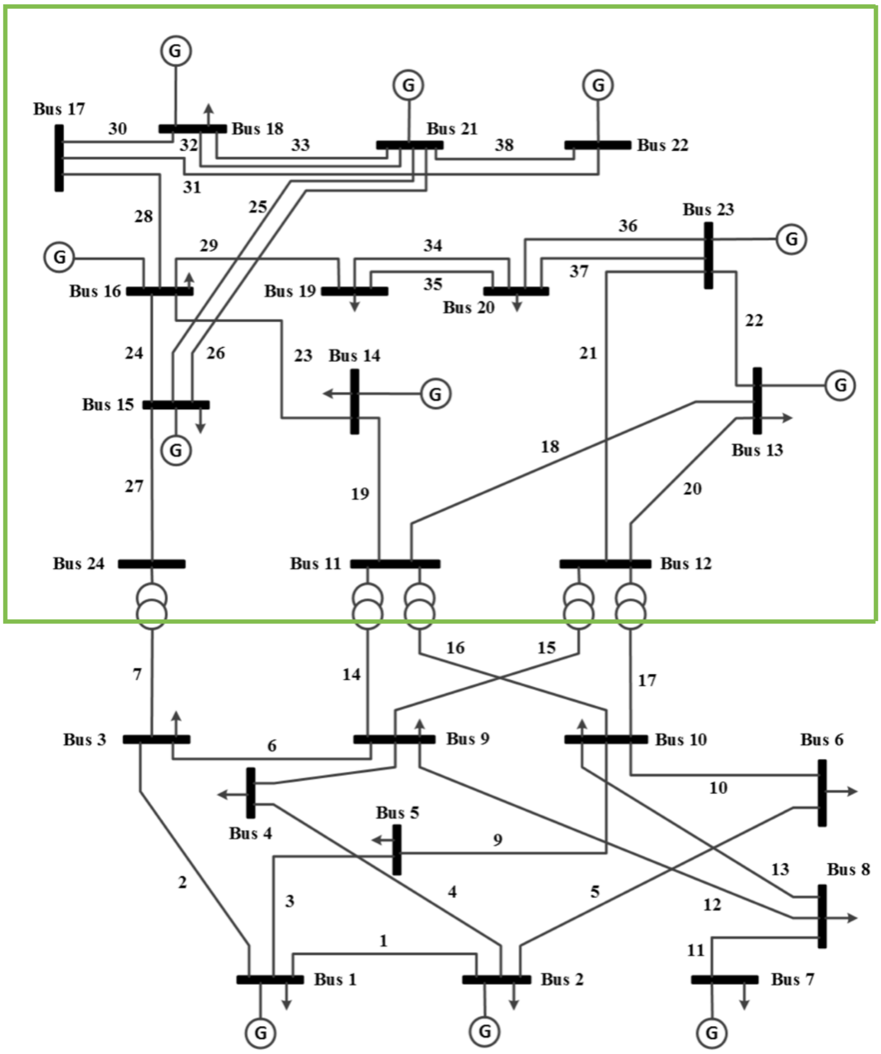

Figure 4.7: The section in green border of IEEE RTS-24 bus system is taken into consideration for the analysis

Transmission Lines (units)	Time Periods(Hours)							
	...	T11	T12	T13	...	T84	T85	...
L18	...	1			...			...
L19	...				...			...
L20	...			1	...			...
L21	...				...			...
L22	...				...			...
L23	...				...			...
L24	...				...			...
L25	...				...			...
L26	...				...			...
L27	...				...			...
L28	...				...			...
L29	...				...			...
L30	...				...			...
L31	...				...			...
L32	...				...	1		...
L33	...				...			...
L34	...				...			...
L35	...		1		...			...
L36	...				...			...
L37	...				...		1	...
L38	...				...			...

Figure 4.8: Outage schedule of the selected area for after summer analysis of a section of IEEE RTS 24-bus system

Transmission Lines (units)		Time Periods(Hours)							
		...	T11	T12	T13	...	T84	T85	...
	L18	...				...			...
	L19	...	1			...			...
	L20	...				...			...
	L21	...				...			...
	L22	...				...			...
	L23	...				...			...
	L24	...				...			...
	L25	...				...			...
	L26	...				...			...
	L27	...				...			...
	L28	...				...			...
	L29	...				...			...
	L30	...				...			...
	L31	...				...			...
	L32	...				...	1		...
	L33	...				...			...
	L34	...				...			...
	L35	...		1		...			...
	L36	...			1	...			...
	L37	...				...		1	...
	L38	...				...			...

Figure 4.9: Outage schedule with 5% change in demand scenario of the selected area for after summer analysis of a section of IEEE RTS 24-bus system

Figure 4.10 shows the maintenance cost graph. Moreover, it shows the comparison in terms of identical maintenance cost to different maintenance cost for a specific section of the network. The graph in figure concludes that the total maintenance cost for the selected network drops down when a section of the network has lower maintenance cost for the selected transmission lines. Therefore, a conclusion can be drawn in terms of maintenance cost stating that the TSOs have the advantage to perform the outage schedule for a specific area of the network so as to reduce the total maintenance cost.

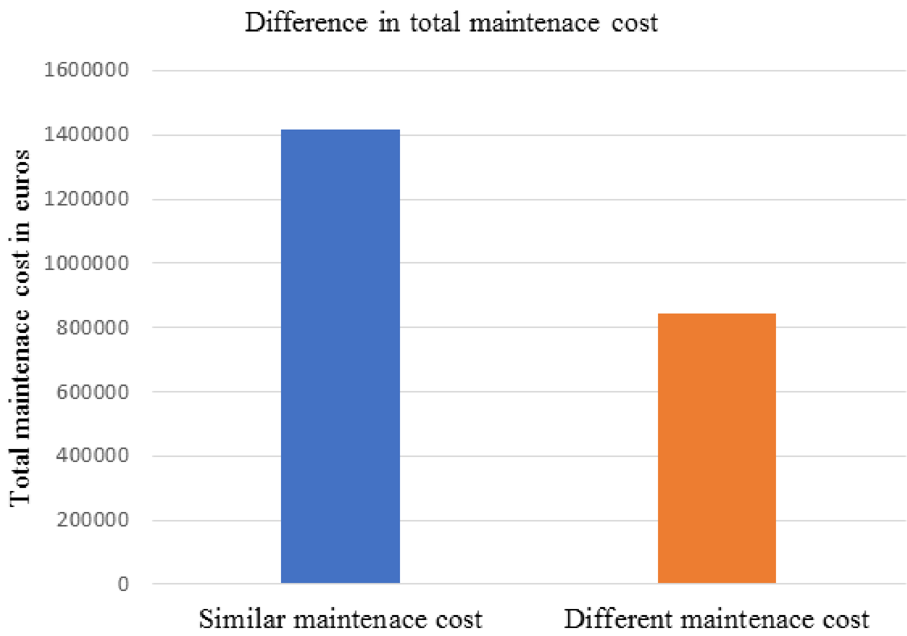

Figure 4.10: Transmission line maintenance cost

Figure 4.11 depict the change in convergence time of the algorithm. From the figure, we observe that the total time to convergence is reduced after deleting the previous equation formulated in the software. As the equation formulated in the past iteration are erased, it gives an extra storage space in the memory which helps in the fast convergence of the algorithm.

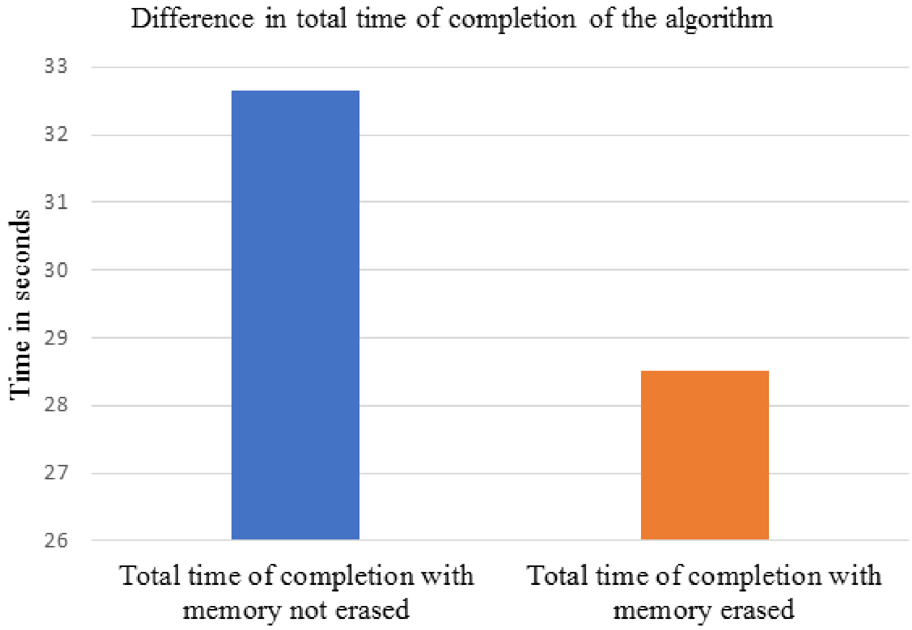

Figure 4.11: Total time for completion of the algorithm

4.2 IEEE 118-bus system

In order to test the scheduling method, an 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 4.12. The total installed capacity for the IEEE 118 bus system is 31250 MW. The generator data, transmission line data, demand data and bus data for the analysis have been considered from the reference [29].

4.2.1 Result analysis

The proposed model in problem definition is applied to IEEE 118-bus test from [29] as shown in figure 4.12. The system includes 118 buses, 19 generators, 118 demands and 185 lines.

The presented case of the 118-bus system is divided into three sections. The algorithm for the outage schedule has been adopted for one of the section highlighted in red. The highlighted section has 46 transmission line, 31 demands, 5 generating units and 32 buses.

The presented case study only takes into account only one section of the network as the whole network simulation requires high-end computer processor with high-

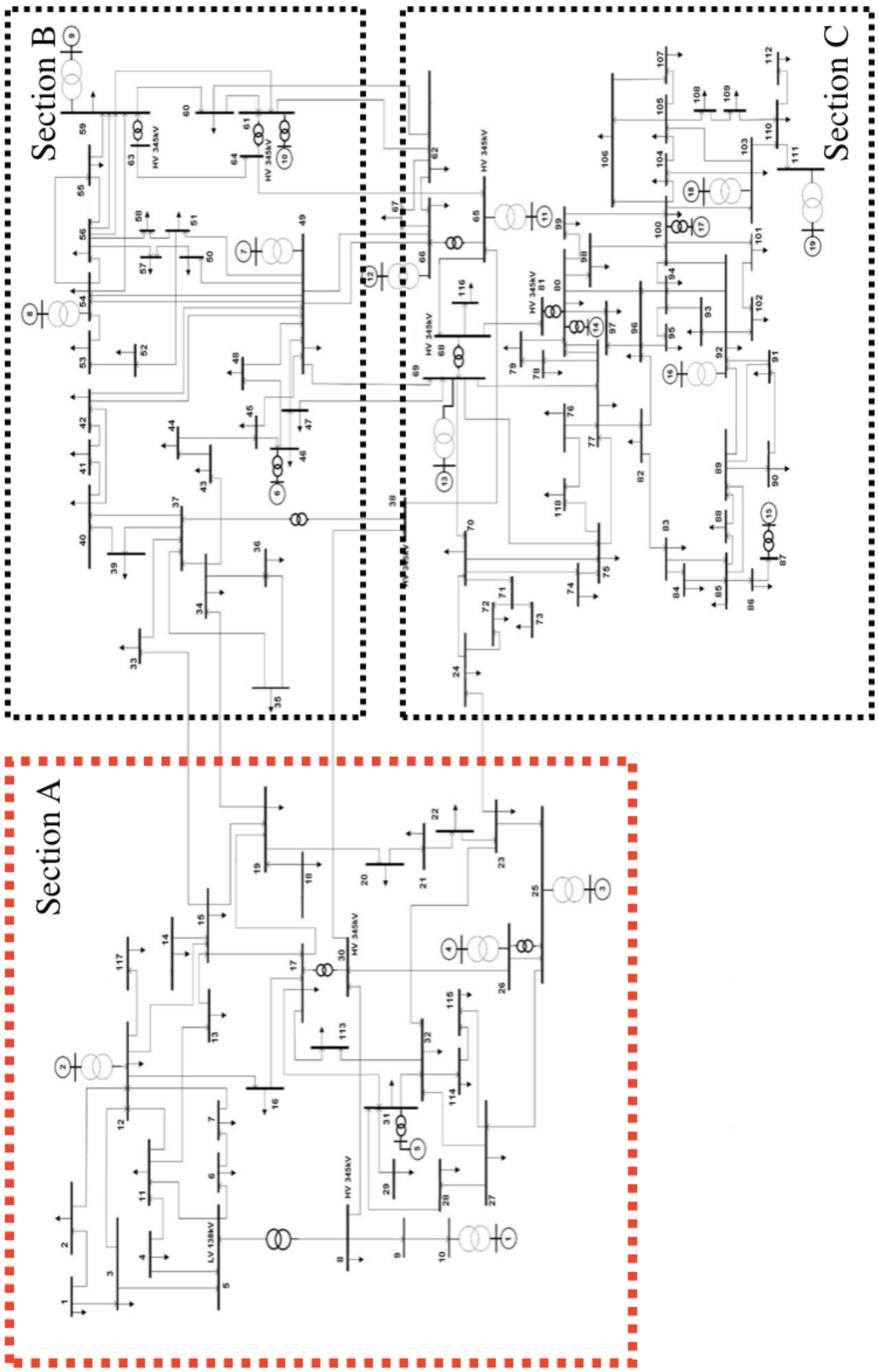

Figure 4.12: IEEE 118-bus system

end RAM memory to complete the simulation.

Applying the bender decomposition approach to the problem formulation seen in chapter 3, we were able to develop optimal maintenance cost and schedule for the selected network of IEEE 118 bus system.Figure 4.14 shows an optimal outage schedule for the IEEE 118 bus network. The selected lines for the selected time period are highlighted in the schedule. The schedule gives an overview and knowledge to the TSO as to which transmission line is to be selected for the specific period of time. Figure 4.15 show the change in outage schedule for the IEEE 118-bus system when subjected to 5% change in demand scenario.

Figure 4.13 shows the maintenance cost graph. Moreover, it shows the comparison in terms of identical maintenance cost to different maintenance cost for a specific section of the network. The graph in figure concludes that the total maintenance cost for the selected network drops down when a section of the network has lower maintenance cost for the selected transmission lines. Therefore, a conclusion can be drawn in terms of maintenance cost stating that the TSOs have the advantage to perform the outage schedule for a specific area of the network so as to reduce the total maintenance cost.

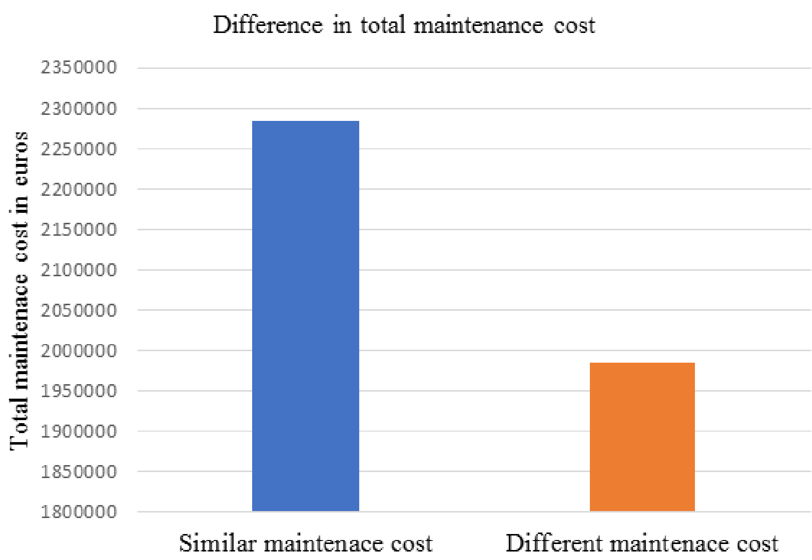

Figure 4.13: Transmission line maintenance cost

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

Figure 4.14: Outage schedule of IEEE 118-bus system

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

Figure 4.15: Outage schedule with 5% change in demand scenario of IEEE 118-bus system

Figure 4.16 depict the change in convergence time of the algorithm. From the figure, we observe that the total time to convergence is reduced after deleting the previous equation formulated in the software. As the equation formulated in the past iteration are erased, it gives an extra storage space in the memory which helps in the fast convergence of the algorithm.

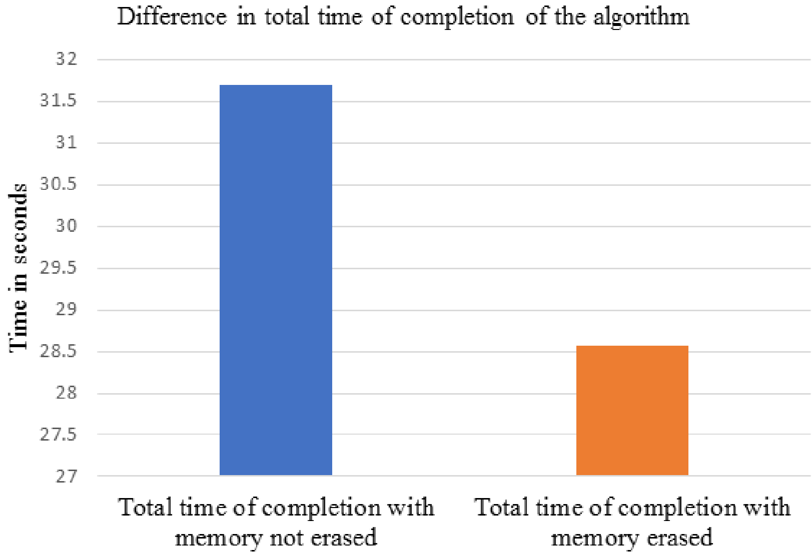

Figure 4.16: Total time for completion of the algorithm

4.3 Memory

The presented case studies are solved in GAMS 23.5 on Windows based 64-bit operating system with five processors clocking 3.19 GHz and 8 GB of RAM. GAMS software tends to store all the generated equation during the iterative process. This storing of data for every iteration results in a slowdown of the algorithm convergence. If the computer hardware has limited RAM storage, then the time taken by the algorithm to converge generally rises. But the algorithm can be optimized if the data stored during the iteration process is deleted. This can be done by adding the following command in equation 4.1 in the modelling. The following command deletes the previous equation generated and reduces the time of convergence. The graph in the result analysis section 4.1.1.1 and section 4.1.1.2 shows the reduction in time of the converge after the command was added to the modelling of the problem formulation.

$$\begin{gathered} option \quad kill = power\_balance; \\ option \quad kill = line\_flow; \end{gathered} \tag{4.1}$$

Chapter 5

Conclusion & future work

This chapter concludes the research work carried out on outage scheduling for IEEE RTS 24-bus system and IEEE 118-bus system. The main reason for selection of the two different test system was to test the computation efficiency of the algorithm developed. 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.

5.1 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. Since the input and output files are maintained in Excel, TSOs have the flexibility to use the output in any other software platforms for further study.
- 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 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 different demand scenarios affecting the power system.
- The developed modelling algorithm gives a direct freedom for the scheduler to increase or decrease the number of lines that can be carried out for maintenance at a specific period of time.
- The developed modelling algorithm has been tested on medium and large test case system which is accepted by IEEE standards.
- The developed modelling algorithm will work as a base work for future research work in order to optimize the algorithm and get the optimal result.

5.2 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 of the transmission line?** The loss of revenue experienced by the TSOs during maintenance of transmission lines is due to loss of load and maintenance cost of the maintenance of transmission line. Loss of load results in zero or negative revenue for the TSOs, and maintenance cost of the transmission line results in a higher expenditure of the fund by the TSOs. The developed model takes into account both the factors responsible for the loss of revenue. The developed modelling algorithm is designed specifically for providing outage schedule for the required network of transmission lines. The optimization problem provide with an optimal outage schedule for the selected network at the lowest possible maintenance cost. This implies that if a transmission line is selected for maintenance for the specific period of time, then the loss of revenue experienced by the TSOs will be the lowest.
2. **What can be the suitable optimization approach to solve the maintenance problem of transmission lines for a specific period of time?** The optimization approach used in the modelling of the problem formulation takes into account stochastic programming approach. The programming approach provides an adequate modelling framework for decision making in

the maintenance of transmission line in specific time-period. The developed modelling algorithm has two main aspects in problem formulation, firstly, the maintenance constraints and secondly, network constraints. The maintenance constraints are modelled in such a way that flexible period can be integrated into the model according to the requirement for a specific area and the optimal schedule is presented. The optimal schedule will fulfil the requirement of the TSO involving the transmission lines in a specific area and specific time.

3. **How to address maintenance outage schedule for different demand scenarios in long-term horizon?** Demand scenario plays an important role in determining the behaviour pattern of the maintenance of the transmission lines. The behaviour pattern refers to the change in outage schedule when the load on the demand side may change in the future. Change in demand scenario is considered while developing the modelling algorithm. A deterministic change has been applied to the load profile and the outage scheduling is performed for long-term horizon. The result obtained for the test cases shows that due to change in demand scenario the outage schedule changes. This effect of change in the outage schedule implies that the demand scenario plays a very important role in maintenance of the transmission line.

5.3 Contribution

1. Formulated the two-stage optimization problem for maintenance outage scheduling both theoretically as well as in GAMS environment. Also, successfully validated the model for test-cases as detailed in this report.

2. Developed a deep understanding of the software GAMS and the unique coding which helped to model the outage schedule for transmission lines under different demand scenarios.

3. Results of the research work accepted in the prestigious PSCC'18 conference in Dublin, Ireland.

5.4 Future work

The developed model in this thesis can be considered a base case model as few assumptions and simplified constraints were used in designing the model. New maintenance constraint has been developed but they have to be improved 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 points for the future work are provided below, which would help in developing a 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. Test the developed methodology on real life test system.

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.

Appendix A

Appendix

```
Two sets of GAMS file is created in order to run the problem.
The first file consist of the input data corresponding to
the matrices of A, B, C and D. The file is given name as
input.inc which is to be called through \$include command
in the output file.

*********************************
**SETS DECLARATION
*********************************
 SET m  / 1 * 2 /;
 SET n1 / 1 * 2 /;
 SET n2 / 1 * 2 /;


*********************************
**DATA TABLE
*********************************
TABLE A(i, j1)
        1
   1    1
   2    2

 TABLE B(i, j2)
        1
   1    1
   2    5
```

```
*********************************
**PARAMETER DECLARATION
*********************************
 PARAMETER c(j1)   / 1 = 2 /;
 PARAMETER d(j2)   / 1 = 3 /;
 PARAMETER rhs(i) / 1 = 6, 2 = 20 /;

 PARAMETER ux(j1) / 1 = 2 /;
 PARAMETER uy(j2) / 1 = 10000, 2 = 10000 /;



************************************
*** Output file
*************************************
  SET m, n1, n2;
  ALIAS (m, i), (n1, j1), (n2, j2);

  PARAMETER A(i,j1), B(i,j2), c(j1), d(j2), rhs(i),
            ux(j1), uy(j2);


  SCALAR BigM /    10000 /;    # Obj. Coeffient for
                                   variable p
  SCALAR Epsilon / 0.01 /;     # Termination tolerance.

  OPTION LP = CPLEX;

\$include "input.inc"

* Set up the main problem:
  EQUATIONS MainObj, MainCon(i);
  VARIABLE z, x(j1), y(j2);

  MainObj       .. z =E= sum( j1, c(j1) * x(j1) ) +
                         sum( j2, d(j2) * y(j2) );

  MainCon(i)    ..       sum( j1, A(i,j1) * x(j1) ) +
                         sum( j2, B(i,j2) * y(j2) ) =L=
                         rhs(i);

  x.LO(j1) = 0;       y.LO(j2) = 0;
  x.UP(j1) = ux(j1); y.UP(j2) = uy(j2);
```

```
  MODEL MainModel /MainObj, MainCon/;
  SOLVE MainModel Maximizing z USING LP;

************** END SOLVING MAIN PROBLEM. *******************



************** SET UP BENDERS DECOMPOSITION ****************

*
* Iteration control:
*
  SET Iter / BendIt_1 * BendIt_1000 /; ALIAS(Iter, It);
  SET Cut(Iter);      # Benders iterations alreadx performed
  SET this(Iter);     # Current Benders iteration

  PARAMETER y_sol(iter, j2), pi(iter, i);
  y_sol(iter, j2) = 0; pi(iter, i) = 0;

  PARAMETER UpperBound, LowerBound;
  UpperBound = INF; LowerBound = -INF;

*
* SUBPROBLEM: A model in y-variables only. (and z, and p...)
*
  EQUATIONS SubObj, SubCon(i);
  POSITIVE VARIABLE p;

  SubObj      .. z =E= sum( j1, c(j1) * x.L(j1) )    +
                       sum( j2, d(j2) * y(j2) )
                        + BigM * p;

  SubCon(i)   ..        sum( j1, A(i,j1) * x.L(j1) ) +
                        sum( j2, B(i,j2) * y(j2) )   + p
                            =L= rhs(i);


  MODEL Sub /SubObj, SubCon /;

*
* MASTER PROBLEM: A model in x-variables only (and z...)
*
  EQUATIONS MasterCut(It);
```

```
MasterCut(cut)  ..
      z  =E= sum( j1, c(j1) * x(j1) ) +
             sum( j2, d(j2) * y_sol(cut, j2) ) -
             sum(i, pi(cut,i) *
                   (sum( j1, A(i,j1) * x(j1) ) +
                    sum( j2, B(i,j2) * y_sol(cut,j2) )
                    - rhs(i)
                   )
                 );

z.LO = -100000;

MODEL Master /MasterCut /;



SCALAR counter / 1 /;

x.L(j1) = 0; y.L(j2) = 0;
cut(Iter) = NO;

WHILE ( UpperBound - Lowerbound > Epsilon,

  this(Iter) = yes \$ (ord(Iter) eq counter);
  DISPLAY this, x.L;

  SOLVE Sub maximizing  z using LP;

*   Save primal and dual solution from the Sub:
  y_sol(this, j2) = y.L(j2);
  pi(this, i) = SubCon.M(i);
  UpperBound  = min(UpperBound, z.L);
  DISPLAY counter, y_sol, pi, UpperBound;

  cut(Iter)  = yes \$ (ord(Iter) le counter);
  DISPLAY cut;

  IF ( UpperBound - Lowerbound > Epsilon,
    SOLVE Master maximizing z using LP;
    LowerBound  = max(LowerBound, z.L);

    DISPLAY LowerBound;
    counter = counter + 1;
```

```
    );
);

DISPLAY "Benders Terminated!", counter,
          LowerBound, UpperBound, x.L, y.L,z.L;
```

Bibliography

[1] S. R. Khuntia, B. W. Tuinema, J. L. Rueda, and M. A. M. M. van der Meijden, "Time-horizons in the planning and operation of transmission networks: an overview," *IET Generation, Transmission Distribution*, vol. 10, no. 4, pp. 841–848, 2016.

[2] S. Khuntia, J. Rueda Torres, S. Bouwman, and M. van der Meijden, "A literature survey on asset management in electrical power [transmission and distribution] system," *International Transactions on Electrical Energy Systems*, vol. 26, pp. 2123–2133, 2 2016.

[3] C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S. Haddad, S. Kuruganty, W. Li, R. Mukerji, D. Patton, N. Rau, D. Reppen, A. Schneider, M. Shahidehpour, and C. Singh, "The ieee reliability test system-1996. a report prepared by the reliability test system task force of the application of probability methods subcommittee," *IEEE Transactions on Power Systems*, vol. 14, pp. 1010–1020, Aug 1999.

[4] IRENA, "Renewable energy highlight, 1 july 2017," http://www.irena.org/.

[5] H. Pandzic, A. J. Conejo, I. Kuzle, and E. Caro, "Yearly maintenance scheduling of transmission lines within a market environment," *IEEE Transactions on Power Systems*, vol. 27, pp. 407–415, Feb 2012.

[6] T. Germany, "Network stress test," https://www.tennet.eu/de/unser-netz/rund-um-den-netzausbau/netzstresstest/.

[7] B. S., "Asset management in a de-regulated environment," *CIGRE Joint Task Force 23.18 and Australian Working Groups 2002, CIGRE Paris*, 2002.

[8] "Generally accepted reliability principle with uncertainty modelling and through probabilistic risk assessment," *EU project no. 608540*, 2015. http://www.garpur-project.eu.

[9] F. Rimmer, "Transmission line operation and control," http://www.electricenergyonline.com/.

[10] M. K. C. Marwali and S. M. Shahidehpour, "Integrated generation and transmission maintenance scheduling with network constraints," *IEEE Transactions on Power Systems*, vol. 13, pp. 1063–1068, Aug 1998.

[11] S. R. Khuntia, J. L. Rueda, S. Bouwman, and M. A. M. M. van der Meijden, "Classification, domains and risk assessment in asset management: A literature study," pp. 1–5, Sept 2015.

[12] W. R. Christiaanse and A. H. Palmer, "A technique for the automated scheduling of the maintenance of generating facilities," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-91, pp. 137–144, Jan 1972.

[13] L. L. Garver, "Adjusting maintenance schedules to levelize risk," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-91, pp. 2057–2063, Sept 1972.

[14] J. Yellen, T. M. Al-Khamis, S. Vemuri, and L. Lemonidis, "A decomposition approach to unit maintenance scheduling," *IEEE Transactions on Power Systems*, vol. 7, pp. 726–733, May 1992.

[15] E. L. Silva, M. Morozowski, L. G. S. Fonseca, G. C. Oliveira, A. C. G. Melo, and J. C. O. Mello, "Transmission constrained maintenance scheduling of generating units: a stochastic programming approach," *IEEE Transactions on Power Systems*, vol. 10, pp. 695–701, May 1995.

[16] S. P. Canto, "Application of benders' decomposition to power plant preventive maintenance scheduling," *European Journal of Operational Research*, vol. 184, no. 2, pp. 759–777, 2008.

[17] M. Marwali and S. Shahidehpour, "A deterministic approach to generation and transmission maintenance scheduling with network constraints," *Electric Power Systems Research*, vol. 47, no. 2, pp. 101 – 113, 1998.

[18] M. K. C. Marwali and S. M. Shahidehpour, "Long-term transmission and generation maintenance scheduling with network, fuel and emission constraints," *IEEE Transactions on Power Systems*, vol. 14, pp. 1160–1165, Aug 1999.

[19] M. Marwali and S. Shahidehpour, "A probabilistic approach to generation maintenance scheduler with network constraints," *International Journal of Electrical Power Energy Systems*, vol. 21, no. 8, pp. 533 – 545, 1999.

[20] M. K. C. Marwali and S. M. Shahidehpour, "Short-term transmission line maintenance scheduling in a deregulated system," *IEEE Transactions on Power Systems*, vol. 15, pp. 1117–1124, Aug 2000.

[21] A. J. Conejo, R. Garcia-Bertrand, and M. Diaz-Salazar, "Generation maintenance scheduling in restructured power systems," *IEEE Transactions on Power Systems*, vol. 20, pp. 984–992, May 2005.

[22] Y. Lin, P. Dong, C. Qin, and Y. Feng, "Shorting-time transmission line maintenance scheduling method based on credibility theory," in *2015 6th International Conference on Power Electronics Systems and Applications (PESA)*, pp. 1–6, Dec 2015.

[23] G. Poyrazoglu and H. Oh, "Scheduling maintenance for reliable transmission systems," in *2016 IEEE/PES Transmission and Distribution Conference and Exposition (T D)*, pp. 1–5, May 2016.

[24] M. K. C. Marwali and S. M. Shahidehpour, "Coordination of short-term and long-term transmission maintenance scheduling in a deregulated system," *IEEE Power Engineering Review*, vol. 18, pp. 46–48, Feb 1998.

[25] A. J. Conejo, L. B. Morales, S. J. Kazempour, and A. S. Siddiqui, *Investment in Electricity Generation and Transmission: Decision Making Under Uncertainty*. Springer Publishing Company, Incorporated, 1st ed., 2016.

[26] J. Liu, M. Kazemi, A. Motamedi, H. Zareipour, and J. Rippon, "Security-constrained optimal scheduling of transmission outages with load curtailment," *IEEE Transactions on Power Systems*, vol. PP, no. 99, pp. 1–1, 2017.

[27] D. Shirmohammadi, P. R. Gribik, E. T. K. Law, J. H. Malinowski, and R. E. O'Donnell, "Evaluation of transmission network capacity use for wheeling transactions," *IEEE Transactions on Power Systems*, vol. 4, pp. 1405–1413, Nov 1989.

[28] D. Miguel, "Two decomposition algorithms for nonconvex optimization problems with global variables," *PHD thesis Stanford university USA*, 2001.

[29] P. Dehghanian and M. Kezunovic, "Probabilistic decision making for the bulk power system optimal topology control," *IEEE Transactions on Smart Grid*, vol. 7, pp. 2071–2081, July 2016.