Transmission Expansion Planning with Large Scale Renewable Resource Integration

by

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ABSTRACT

Due to economic and environmental reasons, several states in the United States of America have a mandated renewable portfolio standard which requires that a certain percentage of the load served has to be met by renewable resources of energy such as solar, wind and biomass. Renewable resources provide energy at a low variable cost and produce less greenhouse gases as compared to conventional generators. However, some of the complex issues with renewable resource integration are due to their intermittent and non-dispatchable characteristics. Furthermore, most renewable resources are location constrained and are usually located in regions with insufficient transmission facilities. In order to deal with the challenges presented by renewable resources as compared to conventional resources, the transmission network expansion planning procedures need to be modified. New high voltage lines need to be constructed to connect the remote renewable resources to the existing transmission network to serve the load centers. Moreover, the existing transmission facilities may need to be reinforced to accommodate the large scale penetration of renewable resource.

This thesis proposes a methodology for transmission expansion planning with large-scale integration of renewable resources, mainly solar and wind generation. An optimization model is used to determine the lines to be constructed or upgraded for several scenarios of varying levels of renewable resource penetration. The various scenarios to be considered are obtained from a production cost model that analyses the effects that renewable resources have on the transmission network over the planning horizon. A realistic test bed was created using the data for solar and wind resource penetration in the state of Arizona. The results of the production cost model and the optimization model were subjected to tests to ensure that the North American Electric Reliability Corporation

(NERC) mandated N-1 contingency criterion is satisfied. Furthermore, a cost versus benefit analysis was performed to ensure that the proposed transmission plan is economically beneficial.

DEDICATION

To my family, especially my grandfather Prof. V. Ramakrishnan, for being an inspiration and for always believing in me.

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First and foremost, my thanks are due to my advisor Prof. Vijay Vittal for giving me the opportunity to work with him, for guiding me through every step of this project, and for constantly providing me with insightful feedback on my work. His work ethic is a true source of inspiration and working with him has taught me a lot. I'd like to take this opportunity to thank the members of my committee, Prof. Gerald Heydt and Dr. Kory Hedman, for taking the time to serve on my defense committee and for providing me with their valuable inputs along the course of this project.

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NOMENCLATURE

$branch\_x_{ij}$	Reactance of branch between bus *i* and bus *j*
c_{ij}	Coefficient corresponding to the i^{th} decision variable (general representation of the objective function),
CLMP	Congestion component of the location marginal price
DC	Direct current
ELMP	Energy component of the location marginal price
F	Fixed cost of generator
f_{ij}	Line flow from bus *i* to bus *j* in the DC formulation
f_x	Latitude of bus *f*
f_y	Longitude of bus *f*
G_{ij}	Conductance of the line between bus *i* and bus *j*
ISO	Independent systems operator
L_j	Load at bus *j*
L_{ft}	Length of line from bus *f* to bus *t*
LLMP	Loss component of the location marginal price
LMP	Location marginal price
n	Number of sub-periods to consider within a year for planning
NERC	North American Electric Reliability Corporation
NPV	Net present value (cost of constructing the transmission line)
P_{ij}	Real power flow from bus *i* to bus *j*
P_{min}, P_{max}	Minimum and maximum capacity of generator
PV	Photovoltaic
Q_{ij}	Reactive power flow from bus *i* to bus *j*
r	Annual rate of interest
RPS	Renewable portfolio standard

t_x	Latitude of bus t
t_y	Longitude of bus t
TEP	Transmission expansion planning
V_{OM}	Variable cost coefficient
V_i	Voltage magnitude at bus i
WECC	Western Electricity Coordinating Council
WREZ	Western Renewable Energy Zones
x	Binary variable to decide if a line should be added to a right of way
X_i	Decision variable (general representation of constraints and objective function)
x_{ij}	Reactance of line between bus i and bus j
y	Typical life time of transmission line, usually 25-30 years
θ_i	Voltage angle at bus i
θ_{ij}	θ_i - θ_j

CHAPTER 1

INTRODUCTION

1.1 Motivation

Over the last decade, the increase in economic and environmental concerns has resulted in the fast growth of renewable resource penetration in the electric power grid. In order to ensure increased penetration of renewable resources several states have a mandated renewable portfolio standard (RPS) which requires a certain percentage of the load to be served by renewable resources. The RPS also states by which year the standard has to be met. In California, for example, the RPS requirement is 20% by the year 2012 and 33% by the year 2020 [1]. As a result of accelerated increase of renewable resource development, there is a need for sufficient transmission facilities to deliver this renewable energy to the load centers.

Transmission expansion planning (TEP) addresses the problem of expanding an existing transmission network to serve load centers subject to a set of economic and technical constraints. The problem of insufficient export capability of the transmission system could occur for any type of generation interconnected to the grid. However, the variable and intermittent nature of renewable resources would affect the transmission expansion planning procedure. Hence, the inclusion of renewable resources needs to be treated differently as compared to conventional sources of energy while upgrading the transmission system over the planning horizon. Furthermore, there is a significant variation in the available renewable energy, especially solar and wind energy over a year's time period.

Taking into consideration this intermittent nature of renewable resources, a procedure for transmission expansion planning has been developed in this thesis. The procedure was tested using a realistic test bed created with the renewable resource information for the state of Arizona, USA.

1.2 Research objectives

The main objectives of this thesis on TEP for large scale renewable resource penetration are:

- To identify locations that have already been projected for likely development of large scale renewable resources in the Western Electricity Coordinating Council (WECC) region of the USA.
- To develop a system theoretic basis for the identification of new transmission corridors to accommodate these large scale renewable energy resources.
- To develop a realistic test bed to test the proposed planning procedure.

1.3 Organization of the thesis

The principal contents of the thesis are developed in 7 chapters and one supplemental section. Chapter 1 presents an overview of the motivation for the study and the study objectives. Chapter 2 presents a literature review of pertinent topics that include previously proposed TEP methods, renewable resource integration, and a brief introduction of the various software tools used in this thesis. Chapter 3 deals with the identification of locations in the WECC region that have been projected for likely development of large scale renewable energy resources, with a focus on wind and solar resources. Chapter 4 outlines the specialized TEP procedure proposed and discusses the various steps involved in the same. Chapter 5 deals with the optimization model proposed to determine the most economical and feasible set of lines to be included in the grid to best accommodate the renewable resources. The realistic test bed created for the purpose of testing the

TEP procedure is discussed in Chapter 6 along with the results of the simulations and studies for the test bed. The required reliability test and a cost versus benefit analysis are also discussed in Chapter 6. Finally, suitable conclusions of the research work are drawn in Chapter 7 along with the scope for future work in this field.

CHAPTER 2

LITERATURE REVIEW

2.1 Transmission planning methods proposed in literature

Transmission planning models can be broadly classified into optimization models, heuristic models, or a combination of these two types of models [2]. The formulation of the optimization model includes an objective function, which needs to be either minimized or maximized while ensuring that the constraint equations of the model are not violated. In the case of TEP, the objective is usually to minimize the sum of the cost of construction of new lines, the cost of reinforcing existing transmission lines and the operational costs of generators over the planning horizon. The constraint equations of the optimization model ensure that the system is modeled in compliance with the power flow equations and operates reliably.

The main mathematical optimization formulations used for transmission planning are the transportation model, the DC model, the AC model, or a hybrid of these three models [3]. The AC model is the most accurate representation of the system as it models reactive power calculations and system losses, which the other two formulations do not model these aspects. However, since the AC formulation for transmission planning is non-linear and has non-convex constraints, it is the most computationally complex formulation. Furthermore, the non-linear characteristics of the AC model cannot ensure a solution which is the global optimum. The DC model and the transportation model are simplified versions of the AC model that can be represented with linearized system constraints, and hence they are computationally less complex to solve and guarantee a global optimum solution.

Heuristic models usually use a sensitivity index or perform local searches with some logical guidelines specified. Furthermore, heuristic models are usually experience based techniques used to speed up the process of finding a satisfactory solution where an exhaustive search is impractical or the problem is computationally complex. However, heuristic models, unlike linear optimization models cannot guarantee an optimal solution. Many heuristic algorithms have been suggested in the literature to reduce the complexity of the AC model and obtain a solution. These heuristics include a constructive heuristic algorithm implemented for the interior point method [4], a genetic algorithm approach [5], a greedy randomized adaptive search technique [6], and a tabu search approach [7]. Some other methods that have been suggested to solve the optimization problem include a Benders decomposition technique [8] [9] and a Monte Carlo simulation method that considers the uncertainties in long term transmission planning [10]. Additionally, since the optimization model is usually formulated as a mixed integer problem, several heuristics that use the branch and bound algorithm for transmission planning have been proposed in literature [11] [12] [13] [14].

The optimization models suggested in literature for transmission planning tend to use test systems that are small and not representative of a realistic large scale system. A realistic test system usually comprises of an area or multiple areas and could contain thousands of elements (buses, branches, loads etc.). Furthermore, the planning procedure requires several power system software packages to perform reliability studies and economic analyses of transmission plans before they can be approved for construction. An optimization model may be developed to take into consideration all of these factors. However, optimization solvers are not sophisticated enough to efficiently solve for an optimal expansion plan, incorporating all planning requirements, for a realistic system.

The use of an optimization model along with other software to ensure reliability requires system data to be available in all input formats. In order to avoid all of these complications, despite the vast array of transmission planning methods suggested in literature, most utilities prefer to use a case based transmission planning procedure. A limited number of cases are considered over the planning horizon and simulations (mainly power flows) are run for these scenarios along with transient stability studies and short circuit studies. The planner then determines the most economical transmission additions to the grid that will not affect the reliability of the system [15].

2.2 Specialized planning algorithms for renewable resource integration

The idea of using a modified procedure for transmission expansion planning with renewable resource interconnection has been previously proposed in literature. Different planning methods and models are used by the power industry to plan transmission for renewable resources. For example, the Midwest ISO mainly uses a power flow tool for transmission expansion planning with renewable resources [16]. In order to ensure reliability of the proposed expansion plan dynamic simulations, voltage stability and small signal oscillation analysis tools are also employed. The transmission planning process for renewable resources employed at the Midwest ISO can be summarized as follows:

1. Renewable resource forecasting and placement in power flow models
2. Copper sheet analysis (power flow with no limits on transmission capacity) to identify a preliminary transmission plan. This preliminary plan is supplemented with area based contour plots that take into consideration areas lacking in transmission facilities that do not show up in the copper sheet analysis.
3. Use production cost model to identify an expansion plan.

4. Perform reliability assessment and a cost versus benefit analysis for the proposed set of transmission paths to come up with a consolidated transmission plan.

In order to model the intermittent nature of renewable resources, a stochastic model to economically plan transmission expansion was proposed in [16]. This paper highlights the importance of developing a comprehensive transmission planning framework which considers RPS requirements, the available renewable generation in the form of the interconnection queues, and the location of load pockets in the system.

2.3 Software tools

This section briefly describes the key features of the various software tools used in this thesis.

2.3.1 AMPL

AMPL is a modeling language for linear and nonlinear optimization problems, in discrete or continuous variables [17]. AMPL has the capability to interface with several solvers that include CPLEX, CONOPT, KNITRO, and GUROBI. The optimization model developed in this thesis is modeled in AMPL as a linear, mixed integer problem and is solved using the GUROBI solver. GUROBI is a commercial software package that is capable of solving optimization problems with linear constraints and linear or quadratic objective functions [18].

Some non-linear models evaluated in this thesis are solved using the KNITRO solver since GUROBI cannot handle non-linear constraints in the optimization model. KNITRO is an effective solver for non-linear optimization problems and is capable of handling mixed integer problems as well [19].

2.3.2 MATLAB

MATLAB is a high level technical computing language used for algorithm development, data visualization, data analysis, and numerical computations. Some of the features of MATLAB used for this research are listed below:

- Shape files

A shape file is a digital vector storage format for storing geometric locations and associated attributed information. MATLAB is capable of reading and performing operations on the information in the shape files. The shape files were used to read in the bus, branch, generator, and load information of the system to be studied. This information includes the latitude and longitude of all the buses in the system which was used to calculate the lengths of the transmission lines in the system.

- Read/write Excel and *.dat files

MATLAB has inbuilt function that can read in data from Microsoft files, perform calculations on them and then output them in any specified format to either an Excel file or a data file. This function comes in extremely handy while handling large amounts of data that cannot be processed manually. Furthermore, since the transmission planning process requires the data to be available to several power system software packages, MATLAB is an excellent medium to read in data from one software package and output to a file format compatible with other software packages. In this thesis, using shape files and Microsoft Excel files as input to the MATLAB code, the input files to the optimization model (bus and branch data) were created in MATLAB in the data file

2.3.3 PowerWorld

The PowerWorld simulator is a power system simulation package designed to simulate high voltage power systems operation. PowerWorld supports map projections on the one line diagram, i.e., elements on the one line diagram can be represented on a map according to the element's latitude and longitude. This map view helps visualize the power system effectively. Furthermore, PowerWorld is capable of performing the optimal power flow (OPF), transient stability studies and static N-1 reliability tests, and visualizing contour plots which are useful to observe trends across the grid.

2.3.4 PROMOD

PROMOD is a package used for production cost modeling. PROMOD IV is a generator and portfolio modeling system used for nodal LMP forecasting and transmission analysis. PROMOD takes into consideration the detailed generating unit operations characteristics, renewable generation profiles over the time period under consideration, load variations in the system, transmission grid topology and constraints, , and market system operations.

2.3.5 PSLF

The GE PSLF software is designed to perform power flow studies, dynamic simulations and short circuit analyses [20]. Large systems, up to 60,000 buses, can be modeled in PSLF. In this thesis, The SSTOOLS in PSLF may be used to perform N-1 contingency studies to ensure that the outage of a line or generator does not result in overloading in the rest of the system. The ProvisoHD software tool was used to analyze post-contingency data produced by SSTOOLS. ProvisoHD reads the output produced by the SSTOOLS and presents them in an excel file format, clearly indicating those lines that are overloaded in the contingency study.

CHAPTER 3

LOCATING RENEWABLE GENERATION IN WECC

The Western Electricity Coordinating Council [22] is a regional reliability entity in the United States responsible for coordinating the bulk electric system in the Western Interconnection. The WECC has the largest geographic area and most diverse system of the eight regional entities under the purview of the North American Electric Reliability Corporation (NERC). Figure 1 shows the WECC region [22]. This chapter of the thesis presents the potential for likely development of large scale solar PV, solar thermal and wind energy generation in the WECC region.

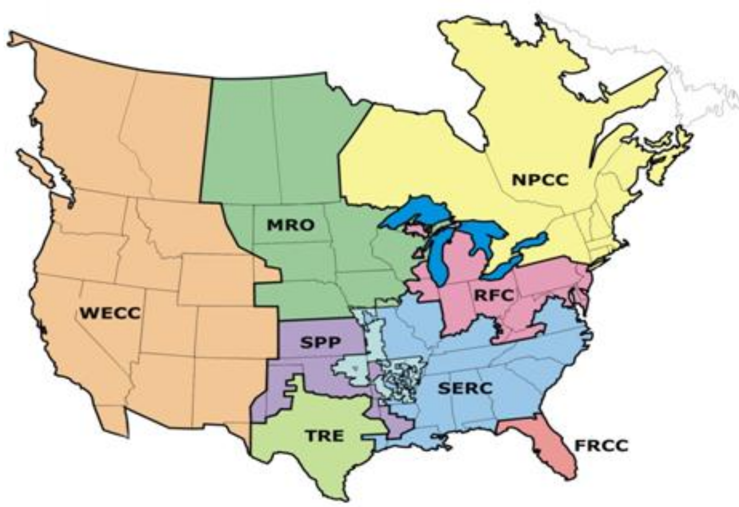

Figure 1Western Electricity Coordinating Council region [22]

In order to ensure integration of large scale renewable resources in the power grid, several states mandate a Renewable Portfolio Standard (RPS). The RPS is a regulation which states that a specific percentage of the demand in an area has to be met by renewable energy resources. As of March 2009, RPS requirements or goals have been established in 33 states in the US [23]. There is tremendous diversity among these states with respect to the minimum requirements of renewable energy, implementation timing, and eligible technologies and resources. The feasibility of complying with these renewable standards depends on several factors which include the availability of renewable sources of energy, the ability to develop these sources and interconnect them to the grid, and the availability of sufficient transmission capacity to deliver this renewable energy to the load centers. Figure 2 shows the RPS requirements, implementation timings, and the potential solar and wind power generation for different states in the WECC region.

Although there is abundant scope for renewable resources across the WECC, it is important to ensure that the inclusion of these resources is an economical decision and does not result in an increase in costs to the system. Several initiatives like the Western Renewable Energy Zones project (WREZ) are in place to identify the impacts of renewable resource penetration in WECC.

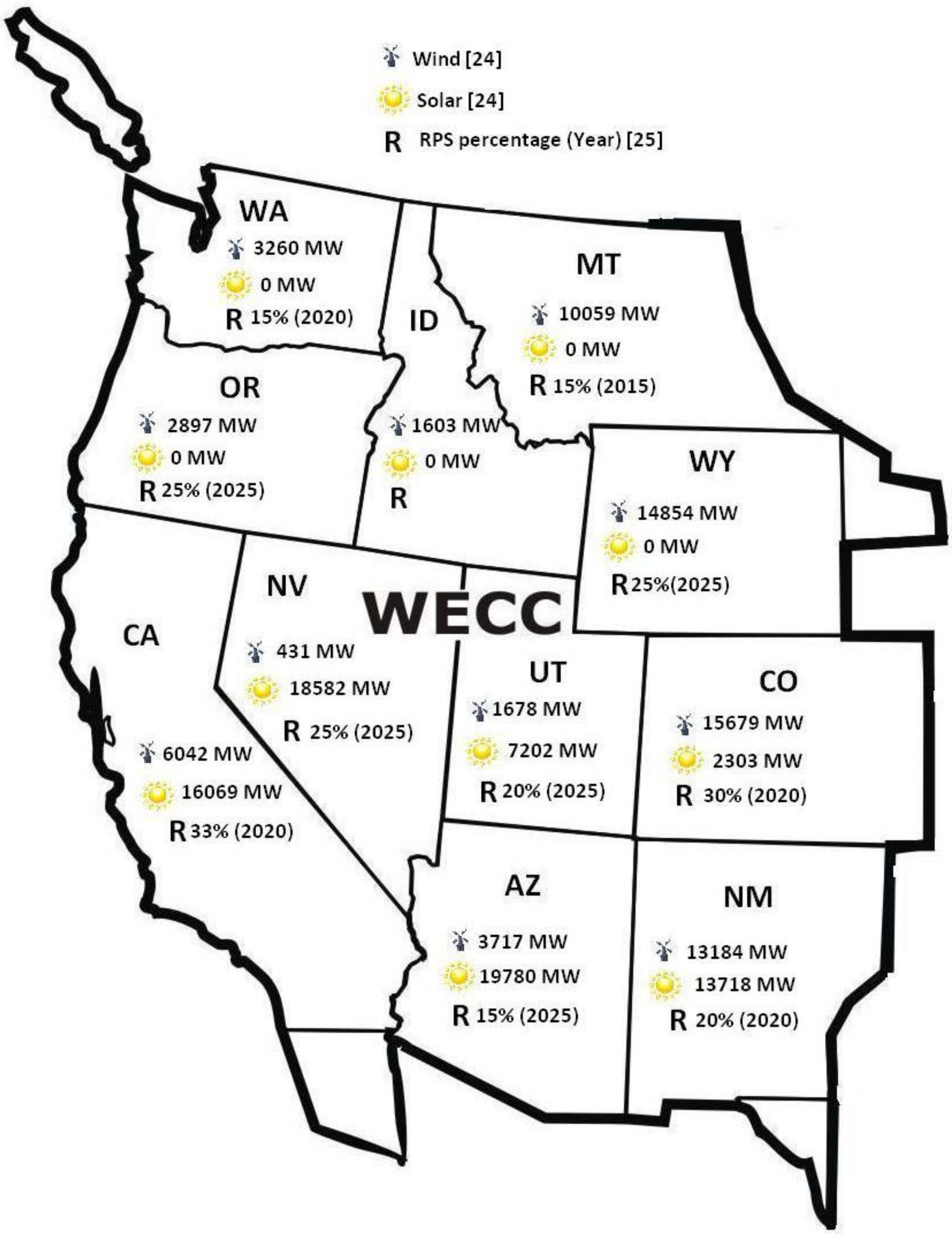

Figure 2 Map of solar and wind generation capacity and RPS requirements in WECC region [23] [24]

CHAPTER 4

PROPOSED TRANSMISSION PLANNING PROCEDURE

This chapter of the thesis discusses the proposed transmission planning procedure for the inclusion of large scale renewable resources. The various steps of the planning procedure and the software tools used are discussed below.

4.1 Step 1: Locating renewable resources

Using the test bed information, a corresponding case is created in PowerWorld. Figure 3 shows a screen shot of the PowerWorld simulator one line diagram.

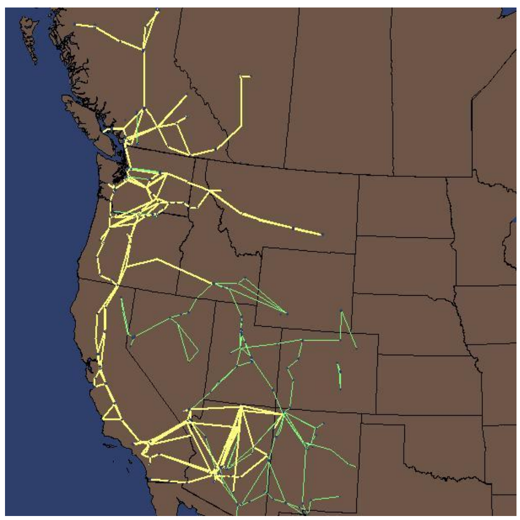

Figure 3 PowerWorld simulator screen shot of the WECC system one-line diagram

The system bus, branch, generator and load parameters along with the corresponding geographic coordinates are output to a shape file. The shape files were processed in MATLAB to calculate the line lengths of the available paths for transmission expansion planning. Furthermore, MATLAB code was written to create the input files to the optimization model. The code for reading the shape files and creating the input files for the optimization model are shown in Appendix A.

4.2 Step 2: Production cost modeling

Production cost modeling software solves the optimal dispatch of all the power plants in a region over a time period while taking into consideration not only the variable cost of operating each plant, but also the large number of generator and system constraints. Although the production cost simulation may not represent the actual operations of the power system, it may be used to study the impacts of large scale renewable resource penetration in the system. In this thesis, a production cost model is used to determine scenarios to be considered in the transmission planning process with the large scale integration of renewable resources. It is also used to determine a set of transmission paths to be considered for expansion planning. PROMOD IV is used to perform production cost simulations over the planning horizon and the results are used to identify transmission congestion in the test system.

The location marginal price (LMP) at a location is the cost of serving an incremental amount of load at the location. LMPs result from the application of a linear programming process, which minimizes the total energy costs for the entire region under consideration, subject to a set of constraints reflecting physical limitations of the power system. The process yields three components of the LMP at every bus as: LMP ($/MWh) = Energy component (ELMP) + Loss component (LLMP) + Congestion component (CLMP). The ELMP is the same for all buses in the system. The LLMP reflects the marginal cost of system losses specific to each location, while the CLMP represents the individual locations marginal transmission congestion cost. In a lossless model, the LMP at any bus is the sum of the energy cost of the system and the congestion component at that bus. In PROMOD, LMPs may be reported for selected zones, or user defined hubs; this may be further broken down into a reference price, a congestion price (showing individual flow gate contributions to congestion), and a marginal loss price. The CLMP is noteworthy in the case of transmission planning as it can be used to decide paths to be considered for transmission expansion. The CLMP represents the cost of congestion for the binding constraints in the market model of the system. If none of the lines in the system are operating at their limits, then the CLMP will be zero for all the buses.

The CLMP obtained from the production cost model is plotted as a contour map in PowerWorld to identify a set of paths that require additional transmission capacity to accommodate large scale renewable resource penetration over the planning horizon. Furthermore, contour maps that exhibit a large difference in the congestion component were observed to represent those scenarios in the planning horizon with a high availability of renewable resources (mainly solar and/or wind).

4.3 Step 3: Optimization model

An optimization model is used to determine an optimum set of lines to be constructed to accommodate large scale penetration of renewable resources. A binary, linear optimization formulation of the DC model was developed. The optimization model was developed in AMPL and solved using the linear solver GUROBI. The input to the optimization model includes the bus and branch data of the system along with the available right of ways for TEP determined in the production cost modeling stage. This data is input in the form of bus and branch data files that are created using the MATLAB code shown in Appendix A.

The objective of the optimization model is to minimize the cost of construction of new lines and the operational cost of the system with the availability of large scale renewable resources. The optimization model is run for several scenarios identified in the production cost modeling step. The results obtained from all these scenarios are combined to form a comprehensive expansion plan for the planning horizon. Chapter 5 presents a more detailed description of the optimization model developed.

4.4 Step 4: Test to ensure *N*-1 reliability

Once a comprehensive expansion plan is found using the scenarios from the production cost model and the optimization model results, it is necessary to ensure that the system is robust against contingencies. According to the NERC standards, power systems are required to be planned and operated such that they can withstand one contingency, i.e., the *N*-1 contingency criterion. A contingency is defined as the unexpected failure or outage of a system element such as a generator, transmission line, circuit breaker, or switch. To ensure that the inclusion of the proposed plans in the system is *N*-1 secure, it is required to ensure that a contingency in the system does not cause any system limits to be violated. For example, the outage of any one transmission line in the system should not cause the loading on the other transmission lines to exceed their emergency ratings. The *N*-1 contingency studies in this thesis were performed using PSLF.

4.5 Step 5: Cost versus benefit analysis

The comprehensive transmission expansion plan was devised considering only the scenarios identified in the production cost modeling stage. Hence it is important to justify the construction of new lines for the whole planning horizon, which includes those scenarios that don't have high levels of penetration of renewable resources. This justification is provided through means of a cost versus benefit analysis, which compares the cost of expanding the existing transmission infrastructure and the operational cost savings with the inclusion of renewable resources.

The expected benefits with the integration of large scale renewable resources are:

1. Decrease in operational costs of the system due to the zero fuel costs of the renewable resources, and

2. Greater possibility of meeting the state mandated renewable portfolio standard.

4.6 Summary of transmission planning procedure

A flowchart summarizing the planning procedure is shown in Figure 5.

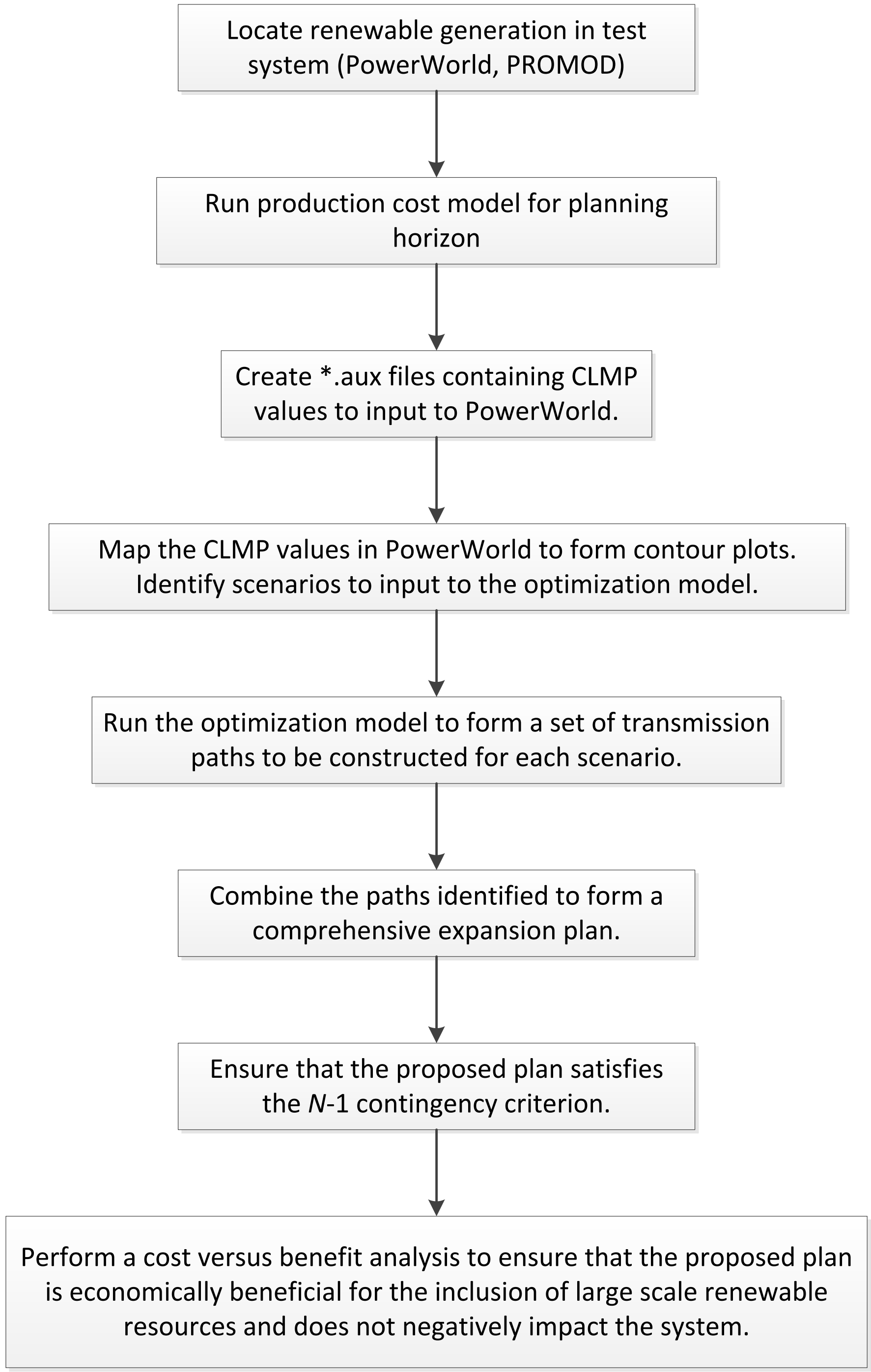

Figure 4 Summary of proposed transmission planning procedure

CHAPTER 5

OPTIMIZATION MODEL

5.1 Optimization formulations for TEP

The main mathematical optimization formulations used for transmission planning are the transportation model, the DC model, the AC model, or a hybrid of these three models [3].The objective function in these three models aims to minimize the cost of construction of new lines in the system. Some of the constraints specified include a line flow constraint, a power balance constraint, and a constraint to limit the generator dispatch values. These formulations are described below along with a comparative study using three test cases in order to determine the most appropriate model to be developed for transmission expansion planning with renewable resource penetration.

- AC model

The AC model for TEP is a non-linear, mixed integer formulation. The AC model is the most accurate representation of the power system. It takes into consideration both the real and reactive power equations that govern the operation of the power system. However, due to its computational complexity, full blown AC models are usually considered only in the later stages of the planning procedure. Furthermore, the non-linear nature of the AC optimization model could result in a solution that is not the global optimum.

The non-linear line flow equations of the AC model are shown below in equation (1) and (2).

$$P_{ij} = V_i^2 G_{ij} - V_i V_j (G_{ij} \cos(\theta_{ij}) - B_{ij} \sin(\theta_{ij})) \tag{1}$$

$$Q_{ij} = -V_i^2 B_{ij} - V_i V_j (G_{ij} \sin(\theta_{ij}) + B_{ij} \cos(\theta_{ij})) \tag{2}$$

where,

P_{ij} = real power flow from bus i to bus j

Q_{ij} = reactive power flow from bus i to bus j

V_i = voltage magnitude at bus i

θ_i = voltage phase angle at bus i

$\theta_{ij} = \theta_i - \theta_j$

G_{ij} = conductance of the line between bus i and bus j

B_{ij} = susceptance of the line between bus i and bus j

- DC model

The DC power flow model for transmission expansion planning can be represented as a linear, mixed integer optimization model. The DC formulation for transmission expansion planning is an approximation of the AC model that considers only the real power components of the power system. Furthermore, the DC model assumes a voltage magnitude of 1 per unit at all buses in the system. The line flow equation is approximated as follows

$$f_{ij} = \frac{1}{branch\_x_{ij}}\left(\theta_{ij}\right) \tag{3}$$

where,

f_{ij} = real power line flow between bus i and bus j

$branch\_x_{ij}$ = reactance of line between bus i and bus j

θ_i = voltage angle at bus i

$\theta_{ij} = \theta_i - \theta_j$

Although the DC model is not as accurate a representation of the system as the AC model, it is computationally less complex. Furthermore, since the DC formulation can be represented as a set of linear constraints, with a linear objective function for a feasible set of data this formulation guarantees a global optimum solution as compared to the AC formulation which can only provide a local optimal solution.

- Transportation model

The transportation model for transmission expansion planning is obtained by relaxing the branch real power flow equation of the DC model. Thus, the line flow calculation equations considered in the AC and DC model are ignored in the transportation model. Only the line limit constraints are used to limit the power flow in the transmission lines. The transportation model could result in an optimal expansion plan which may not be feasible for the DC or AC model of the system.

The three mathematical formulations for transmission expansion planning were tested using three test systems to determine the most suitable model for the transmission planning process with a realistic system. The three test beds are the Garver's 6 bus model [3], the IEEE 14 bus system [25] and IEEE 118 bus system [26].

Garver's 6 bus test system

The 6 bus test system is one of the most popular test systems in transmission expansion planning research endeavors. The system has 6 buses and 15 right-of-ways for the addition of new circuits. The network topology of the 6 bus system is shown below in Figure 6. The data for this system is given in Appendix B.

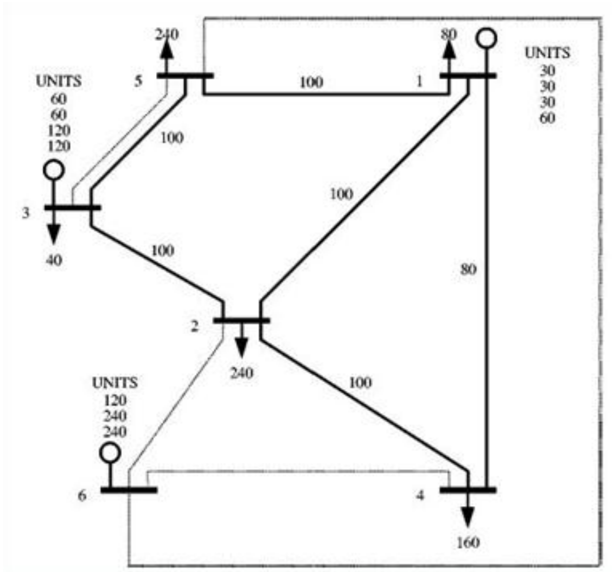

Figure 5 Garver's 6 bus test system

Table 1 TEP Optimization model results for the 6 bus test system

Test model	**Model type**	**Objective function value**	**Computational time (s)**	**Results**
DC	Non-linear	100	0.281	6,11,14,14
Transportation	Linear	80	0.156	11,14,14
AC	Non-linear	Infeasible	N/A	N/A

IEEE 14 bus test system

The IEEE 14 bus test case represents a small system in the Midwest region of the American Electric Power Co. system. The system has 14 buses and 19 branches. The bus, branch, generator and load data is shown in Appendix B. The one line diagram of the 14 bus system is shown in Figure 7.

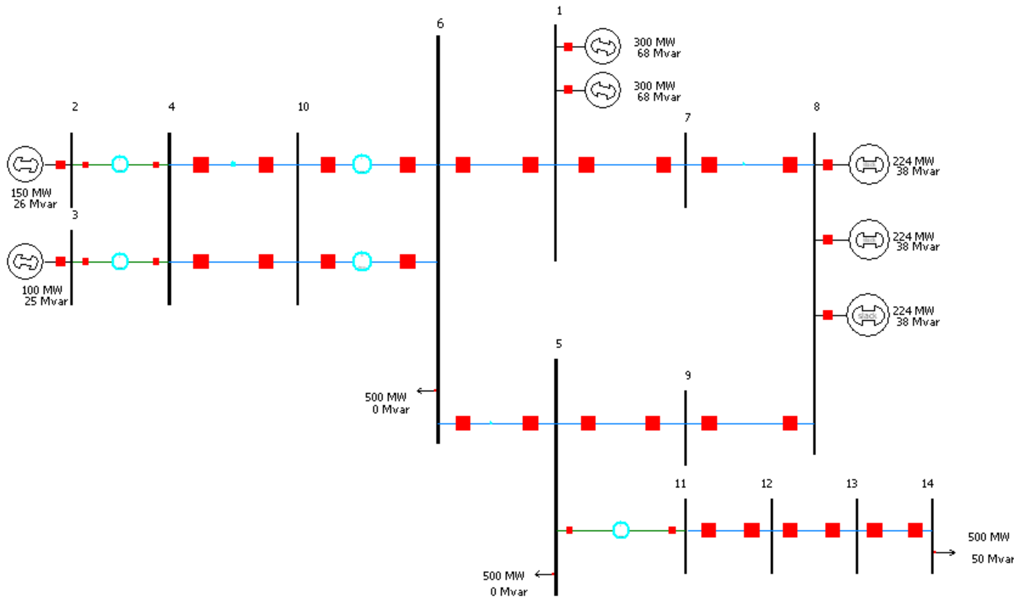

Figure 6 One line diagram of IEEE 14 bus test system

Table 2 summarizes the results of the 14 bus system when tested with the three optimization models.

Table 2 TEP Optimization model results for the 14 bus test system

Test Model	Model Type	Objective Function Value	Computational time (s)	Results
DC	Non-linear	14.17	5.695	1-5 (1) 1-6 (1) 8-14 (1)
Transportation	Linear	12.12	0.47	1-5 (1) 8-14 (1)
AC	Non-linear	Infeasible	35.913	N/A

IEEE 118 bus test system

The IEEE 118 bus test case is a standard test system whose bus, branch, generator and load data is shown in Appendix B. The 118 bus test system has 186 branches and is often used in literature to test various transmission planning procedures. The results of the three optimization models when tested with the 118 bus system are shown in Table 3.

Table 3 TEP Optimization model results for the 118 bus test system

Test Model	Model Type	Objective Function Value	Computational time (s)
DC	Non-linear	47.51	132.203
Transportation	Linear	40.12	0.796
AC	Non-linear	Infeasible	N/A

The conclusions to be drawn from the above comparative study are as follows:

- The transportation model solves the fastest among the three models. However, when the decision variables obtained from the transportation model were tried on a DC and AC power flow formulation, it was found that the transportation model is not necessarily feasible and results in an infeasible AC and DC power flow solution.
- The DC formulation solves faster than the AC model and is more accurate than the transportation model. The solution obtained in the DC model is closer to the actual optimal power flow solution than the transportation model solution.
- Although the test systems represent feasible systems, the AC solution indicates the test systems are infeasible. The AC model results are greatly

dependent on the initial conditions provided. Based on these initial conditions a solution that is locally optimal is obtained. The non-linear characteristics of the AC formulation cannot guarantee a global optimum solution.

The need for an approximate DC formulation arises mainly as a result of the limitations of existing optimization solvers and solution techniques that are used for non-linear formulations. Thus, based on the above observations a linear, mixed-integer, DC formulation based optimization model was developed for this thesis. The details of the developed model are further elaborated upon in Section 5.2 of this thesis.

5.2 Optimization model details

A linear, binary optimization model based on the DC model is formulated in AMPL to solve for an optimum set of transmission lines to be constructed to accommodate renewable resources. The optimization model is solved using the GUROBI solver, which is capable of solving linear, mixed-integer problems. The model needs to consider all the planning scenarios identified in the production cost modeling stage. Hence, it is run for each scenario. The input to the optimization model, the objective function, the system constraints, the output of the optimization model, and other aspects of the optimization model developed are further elaborated upon in the following sub-sections. The full AMPL code written is shown in Appendix C.

5.2.1 Input to the optimization model

MATLAB is used to generate the input files to the optimization model. The input is split over three data files: static bus data that does not change with time, branch data, and generator capacity and load requirement values that vary over time. The different fields included in each of these data files are listed below in Table 4

Table 4 Input to the optimization model

Static bus data (For each bus)	Static branch data (For each branch)	Time varying data (at each bus for every hour of scenario time period)
• Bus number • Slack bus (If slack, then 1, else 0), • Generator type • Generator cost function coefficients	• From bus • To bus • Initial state (existing (1) or available for expansion planning (0)) • Admittance • Real power limit • Cost of construction	• Max MW generation capacity • Load MW

5.2.2 Decision variables

The purpose of an optimization model is to find the values for the decision variables such that all the constraints are satisfied and the objective function is optimized. The objective function is a function of the decision variables and it is up to the solver to determine appropriate values of the decision variables to ensure that an optimal solution set is obtained. These decision variables can be of different types: binary variables, integer variables, or real variables. The type of decision variables in an optimization model will affect the method used to solve the problem.

The decision variables for the optimization model used for transmission expansion planning are:

1. A binary variable to decide if a line should be added to a right of way (x),
2. Bus voltage angle (θ), in radians, required to calculate branch flows in the optimization model,

3. Branch real power flows (*f*) in per unit, and
4. Generator real power dispatch (*bus_pgen*) in per unit.

5.2.3 Objective function

The objective function of an optimization model is the value that needs to be either minimized or maximized without violating the system constraints specified. The objective function needs to be a function of at least one decision variable. The general form of the optimization model is

$$\text{minimize} \sum_{i=1}^{n} c_i X_i \tag{4}$$

where

c_i = coefficient corresponding to the ith variable

X_i = decision variable

For the purpose of transmission expansion planning, it is desired to determine an expansion plan that minimizes the sum of the operation costs of the generators and the cost to construct new lines required for large scale renewable resource penetration. The operational cost of generators is represented as a linear function of the real power output of the generator. The generator cost model is defined by equation (5).

$$C(P_i) = F + V_{OM} P_i \tag{5}$$

where,

P_i = Real power output of generator

F = Fixed cost of generator

V_{OM} = Variable cost coefficient

The cost of constructing transmission lines per unit length varies according to voltage levels. In order to make the operational cost of the system over the time frame of the scenarios considered comparable to the cost of constructing new lines, the cost of transmission line construction is scaled as described by equation (6) [27].

$$C = \frac{r * NPV}{n\left[1-\left(\frac{1}{1+r}\right)^{y}\right]} \tag{6}$$

Where,

C = cost of transmission line to be considered for each scenario

NPV = net present value of transmission line

y = typical life time of transmission line, usually 25-30 years

n = number of sub-periods to consider within a year

r = annual rate of interest

The *NPV* is the cost of construction of the transmission line. It is represented as the sum of a time series of present values (C) calculated for a scenario's time period. The present values calculated are paid as a series of installments over the lifetime of the transmission line, which is usually assumed to be around 25-30 years. This scaling method is often used to determine the value of an investment over a period of time, especially for long term projects. A discount rate (r) is applied to this calculation to adjust for risk and variations of C over time [28]. One of the major drawbacks of using the *NPV* method to scale transmission costs to each scenarios duration is that the value of C is very sensitive to the discount rate. Minor variation in r will result in significant variations in C.

5.2.4Constraints

The constraints of the optimization model place a bound on the values of the decision variables or ensure that their values are found in keeping with certain system conditions. System constraints usually take on the following general form:

$$\text{Subject to } a_{ij} X_i \le b_j \quad \text{j} = 1,2,3..\text{n} \tag{7}$$

where

X_i = decision variable

a_{ij} = the coefficient of X_i in the constraint, and

b_j = the right hand side coefficient

n = the number of constraints

The set of constraints for the transmission planning model are to ensure that the solution obtained does not violate node and branch equations of the power system. Furthermore, they impose bounds on generator output and line flows. Each of the constraints included in the optimization model for expansion planning with renewable resource integration are elaborated upon below.

- Real power conservation at each node

$$\sum_{(k,:)} f_{ki} - \sum_{(:,k)} f_{ik} - P_i + L_i = 0 \quad \forall\, i \in \, Bus, (k,i) \; \in Branch \tag{8}$$

- Line Flow constraints

$$\left| f_{ij} - \frac{1}{branch\_x_{ij}} \left(\theta_{ij}\right) \right| \le M\left(1 - x_{ij}\right) \tag{9}$$

$$\left|f_{ij}\right| \leq f\max_{ij}\, x_{ij} \qquad (10)$$

- Generator dispatch limits

$$P_{\min} \leq P \leq P_{\max} \qquad (11)$$

- Angle constraint

$$\left|\theta_i - \theta_j\right| \leq 0.6 \quad \forall (i,j) \in Branch \qquad (12)$$

- RPS constraint, if applicable

$$\sum_i P_i \geq RPS * \sum_j L_j \quad \forall\ j \in Bus, i \in \text{Renewable generator} \qquad (13)$$

Where,

f_{ij}= real power flow from bus *i* to bus *j*

P_i = real power generation dispatched at bus *i*

L_i = real power load at bus *i*

RPS = renewable portfolio standard, represented as a fraction

$branch\_x_{ij}$ = reactance of line between bus *i* and bus *j*

M = a very large number

θ = bus voltage phase angle

5.2.5 Output of optimization model

The optimization model determines the optimum transmission expansion plan for each of the input scenarios. These output sets are all combined suitably to formulate a comprehensive transmission expansion plan for the planning horizon considered.

CHAPTER 6

REALISTIC TEST BED

One of the main objectives of this thesis was to test the proposed transmission expansion planning procedure with a realistic test system. Based on the planning procedure outlined in Chapter 4, the realistic test system was tested and an optimum transmission expansion plan was obtained. The results obtained at each stage of the planning process are discussed below.

Step 1: Creation of a realistic test bed

A test system was created using the renewable resource information for the state of Arizona in the US. The bus, branch, generator, and load data for the WECC region were available. An equivalent system was created in PowerWorld considering all elements within Arizona as the study system and the elements in the other areas as the external system. The external system was modeled as equivalent loads at the inter area tie line buses. A figure of the equivalent system is shown in Figure 8.

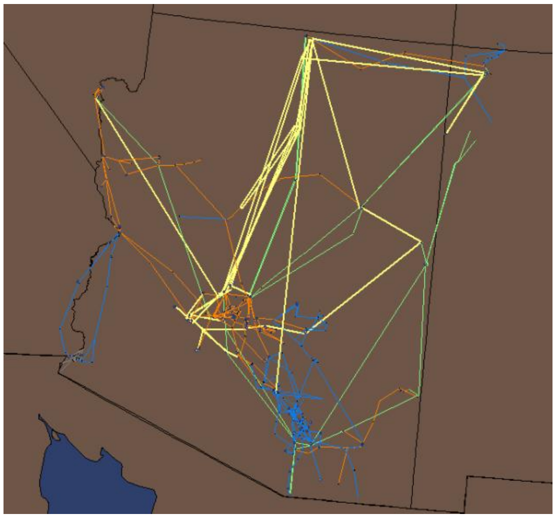

Figure 7 Equivalent test system (AZ) in PowerWorld

Since the slack bus of the WECC system is located outside the state of Arizona, the bus to which the largest generator is connected was defined as the slack bus for the equivalent system. Table 5 summarizes the key parameters of the equivalent system obtained.

Table 5. System parameters of the AZ test bed

No. of Buses	822
No. of Branches	1079
Number of generators	227
Slack bus	15981 – Navajo 1

The available renewable resource information was obtained from the generation interconnection queues of the Arizona Public Service (Appendix D) and the Salt River Project (Appendix D). The renewable resources from these interconnection queues were modeled in the PowerWorld equivalent model. PowerWorld has a GIS interface that can depict the system on a map as was seen in Figure 8 above. A summary of the interconnected renewable resources is presented below in Table 6.

Table 6. Renewable resource integration in test system

Renewable generation type	**Connected capacity (MW)**
Wind	2763
Solar thermal	3555
Solar PV	3690

Step 2: Production cost modeling

In order to limit the scenarios to be considered for transmission planning by the optimization model a production cost model was used. A case was created in PROMOD that contains information regarding the renewable resources interconnected. The planning horizon considered in this case was the year 2020 since all the renewable resources are expected to be interconnected by 2020. The production cost model was simulated and weekly reports were generated containing the generation output, generation costs and the congestion component of the LMP's at all the buses of the test system. The CLMP was plotted in PowerWorld as a contour plot to identify scenarios that result in congestion in the transmission system. Furthermore, buses that exhibit very high or very low (negative) CLMP were combined to form a set of transmission paths that can be used for transmission expansion planning. A preliminary study of these contour plots for different time periods over the planning horizon revealed four scenarios that could be considered by the optimization model. The contour plots for these four scenarios are shown below. Appendix E shows the contour plots of some of the other weeks of the planning period not considered for the optimization model.

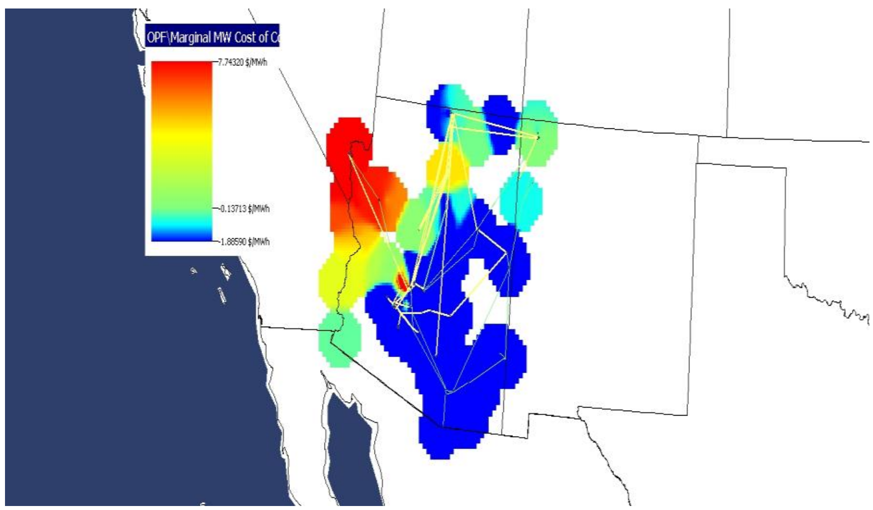

Figure 8 CLMP contour plot for Scenario 1

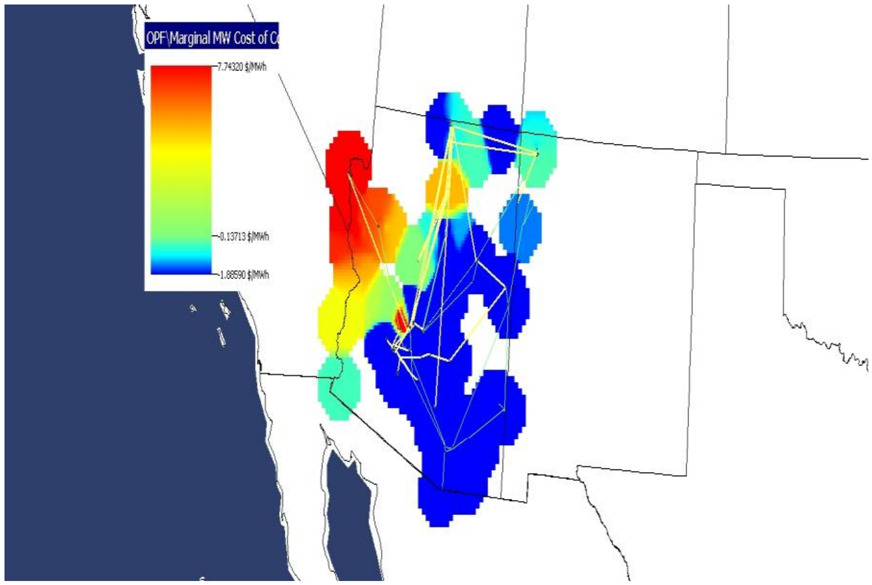

Figure 9 CLMP contour plot for Scenario 2

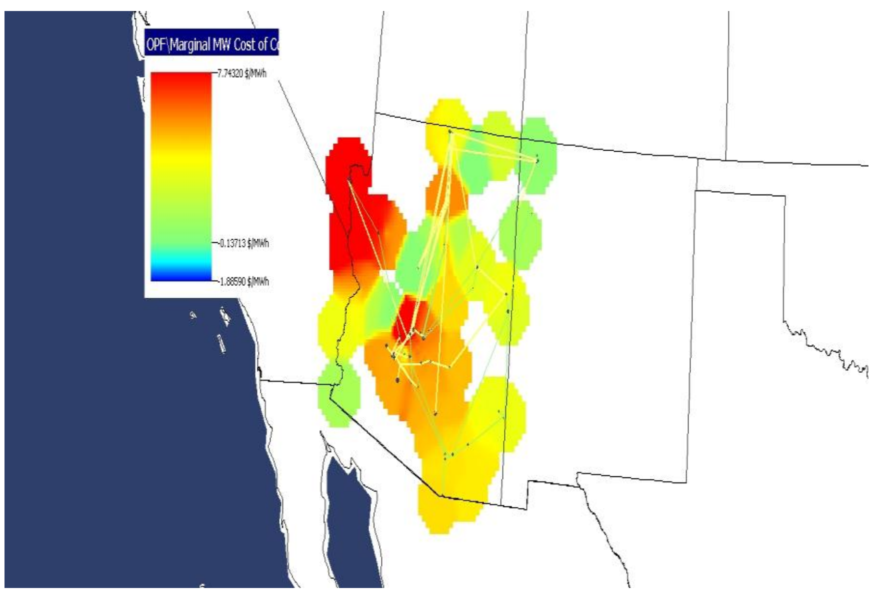

Figure 10 CLMP contour plot for Scenario 3

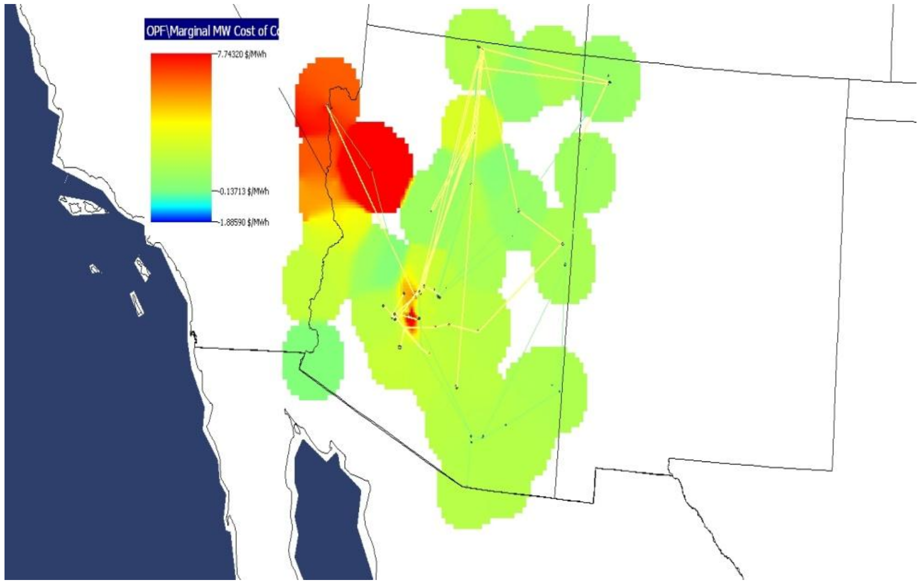

Figure 11 CLMP contour plot for Scenario 4

Step 3 Optimization model

The input files for the optimization model were created using MATLAB. The bus, branch, generator and load shape files from PowerWorld were read in MATLAB. Using the latitude and longitude information of each bus the length of each transmission line was calculated using equation (9)

$$L_{ft} = 3963.1\left[a\cos\left(\sin f_x \ \sin t_x\right) + \cos f_x \cos t_x \cos\left(t_y - t_x\right)\right] \text{miles} \qquad (14)$$

Where,

L_{ft} = length of line from bus *f* to bus *t*

f_x = latitude of bus *f*, in radians

t_x = latitude of bus *t*, in radians

f_y = longitude of bus *f*, in radians

t_y = longitude of bus *t*, in radians

The fuel cost values of various types of generation and the transmission line construction cost values used in the optimization model for this test system are attached in Appendix F. The results of the four scenarios considered in the optimization model are listed below in Table 7.

Table 7. Optimization model results for all scenarios considered

<table>
<tr><th>Scenario</th><th>Week</th><th>Objective function value for week(M$)</th><th colspan="2">Lines to be constructed</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">4</td><td rowspan="2">11.5382</td><td>14235-14238 (2)</td><td></td></tr>
<tr><td>14007-14238</td><td></td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">6</td><td rowspan="2">11.9603</td><td>14235-14238 (2)</td><td>14000-14008</td></tr>
<tr><td>14007-14238</td><td></td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">17</td><td rowspan="2">11.3313</td><td>14235-14238 (2)</td><td></td></tr>
<tr><td>14007-14238</td><td></td></tr>
<tr><td>4</td><td>34</td><td>12.588</td><td colspan="2">No lines to be added</td></tr>
</table>

It was observed from the optimization model results that the suggested set of lines proposed for each scenario was very similar for all of the scenarios. Hence, a union set of the individual lines proposed for each of the scenarios was chosen for the comprehensive transmission expansion plan for the entire planning horizon. The comprehensive expansion plan, along with the key parameters of the lines to be constructed is listed in Table 8.

Table 8 Comprehensive transmission expansion plan for the realistic test bed

From bus	To bus	Voltage (kV)	No. of lines to be constructed	Cost of constructing one line (M$)
14235	14238	230	2	1.3848
14000	14008	500	1	1.7630
14007	14238	500	1	5.8394

Step 4: *N*-1 contingency criterion compliance

A study in PSLF to ensure that the proposed plan satisfies the NERC recommended *N*-1 Contingency criterion on the WECC heavy summer case revealed no overloading beyond the emergency limit rating on any lines of the system due to large scale renewable resource penetration. It was also seen that the voltage magnitudes on some of the buses exceeded the permissible limit of 1.05 p.u. and further study is required in this field to ensure that there are no voltage violations for the proposed transmission plan. This static contingency study was performed using the SSTOOLS in PSLF and the data was presented in an excel file format using the ProvisoHD tool.

Step 5: Cost versus benefit analysis

A cost versus benefit analysis was performed on the proposed transmission expansion plan to ensure that it is economically beneficial to construct these lines in order to better facilitate the inclusion of large scale renewable resources in the system.

Table 9 shown below presents the increase in the amount of renewable resource penetration for each scenario considered in the test system with the construction of the lines proposed in the expansion plan. Table 9 shows that the inclusion of the lines proposed in the expansion plan significantly increases the wind resource penetration and thereby decreases the operational cost of generation for the scenarios identified. Furthermore, from the results presented it can also be inferred that there is sufficient transmission capacity for concentrated solar power and solar photo-voltaic resource penetration and the additional lines to be constructed are mainly to facilitate wind resource penetration.

Table 9 Comparative study of output of optimization model before and after the construction of lines proposed

Scenario	Operational cost (M$/week)		Wind (GWh)		Solar photovoltaic (GWh)		Concentrated solar power (GWh)	
	Before	After	Before	After	Before	After	Before	After
1	10.976	10.673	32.408	82.141	38.946	38.946	16.248	16.248
2	13.294	12.957	37.843	37.843	45.025	45.025	10.506	10.506
3	12.140	11.536	64.017	164.66	81.724	81.724	21.703	21.703
4	12.588	12.588	56.837	56.837	70.677	70.677	15.601	15.601

The net cost of construction of the lines proposed = M$ 8.9872.

Savings obtained in the operational cost for the 4 weeks considered = M$ 1.244

Thus, since just 4 weeks of renewable resource penetration results amount to about 14% payback in terms of savings in operational cost, it can be clearly seen that over the life expectancy of the transmission line (25-30 years) the inclusion of the proposed lines will ensure that cheaper renewable generation will be dispatched in the system and hence the overall operation cost of the generators will be reduced. The cost versus benefit analysis presented here is just a preliminary evaluation to ensure that the proposed plan is cost effective and further study is required in this field.

Additional cost factors that need to be considered include reactive power capacity of lines, availability of increased ancillary services to offset the intermittency of renewable resources, and cost of setting up renewable resource generators as compared to conventional generators. On the other hand, the additional benefits provided by renewable resource integration that need to be considered include increased ease in achieving the RPS, possible profits from carbon credits, and the additional environmental benefit of reduced greenhouse gases.

CHAPTER 7

CONCLUSION AND FUTURE WORK

The WECC region has great potential for large scale development of renewable resources. There is an urgent need for transmission grid expansion to accommodate these resources. Renewable resources like wind and solar differ from conventional sources of energy in that they are usually location constrained, intermittent and non-dispatchable. These factors indicate a need for a specialized transmission planning framework that differs from traditional transmission planning for conventional resources.

The expansion planning procedure proposed in this thesis uses a production cost model to determine scenarios with large scale renewable resources that cause congestion in the existing transmission grid. These scenarios are identified using the CLMP values which are generated for all the buses in the study system over the planning horizon. One of the major drawbacks with the CLMP, as discussed in [29], is that the value of the CLMP may change when a different slack bus is chosen for the study system. Furthermore, different power markets across the world use different methods to calculate the LMP and the CLMP. Therefore, although the CLMP values observed over a long period of time may be used to identify areas prone to transmission line congestion in the system, further work is required to study the impact of the choice of slack bus and the method of calculation of the CLMP on the scenarios identified as input to the optimization model.

The optimization model developed to identify a set of lines to be built for each scenario is based on the DC formulation of the transmission planning procedure. This model is a binary, linear optimization problem that aims to minimize the sum of the operation cost of all the generation dispatched in the system and the cost of transmission line construction. A linear optimization model ensures that the output for a feasible system will be globally optimal. Furthermore, since the optimization model developed takes into consideration the hourly fluctuations in the renewable energy capacity available, it ensures that the savings in operational cost obtained from renewable resource penetration is greater than the cost of constructing lines to accommodate these resources. The optimization model developed in AMPL assumes a lossless system. Several linear loss models have been developed in the literature. However, modeling losses could negatively impact the computational complexity of the optimization model and further work is required to study the impact of losses on the transmission plan obtained.

A major area of concern with renewable resource penetration is the reactive power imbalance created in the system with operating renewable resources. The expansion method proposed in this thesis takes into consideration only the real power component. In order to have a linear optimization model, the DC formulation assumes a voltage magnitude of 1 per unit at all the buses and considers just the real power equations as constraints. However, it is important to ensure that the expansion plan proposed is AC feasible and does not cause voltage or reactive power imbalance in the system.

In order to make the construction cost of new lines comparable to the operational cost of generators in each scenario, a formula (equation (6)) was used to scale the transmission line costs. A more accurate representation of this formula would be as shown in equation (15), where rather than calculating the cost of construction as annual payments equally divided for all weeks across each year, the payments are calculated as equal weekly payments over the entire life period of the line. In other words, in the formula used in the thesis, the interest is calculated annually and then divided by 52 to represent weekly payments. In the formula represented by equation (15), the scaled cost is calculated assuming weekly payments.

$$C = \frac{r * NPV}{n\left[1 - \left(\frac{1}{1+\frac{r}{n}}\right)^{ny}\right]} \tag{15}$$

Where,

C = cost of transmission line to be considered for each scenario

NPV = net present value of transmission line

y = typical life time of transmission line, usually 25-30 years

n = number of sub-periods to consider within a year

r = annual rate of interest

Further study is required to determine the most accurate formulation of the objective function since the transmission plan obtained is directly dependent on this formulation.

One of the challenges faced by transmission planners today is the limitations of the software packages needed to plan transmission. No commercially available software is currently capable of handling all the different phases required while planning transmission. Thus, considering the magnitude of most power grids, large amounts of data need to be maintained in order to accurately represent the system in all the different software and any changes made in one software package need to be reflected in all the other software packages. This drawback of maintaining and manually editing large amounts of data is overcome in this thesis with the use of MATLAB code (shown in APPENDIX A) that reads in the output of one stage of the planning process and creates the necessary input files with the data modifications for the next stage of the planning process

Presently, the accelerated increase in renewable resource penetration in the US is mainly policy driven. In order to encourage renewable resource integration, several incentives like carbon credits are being offered to renewable generator owners. Carbon credits are tradable certificates that permit the emission of greenhouse gases. Efforts like renewable resource integration that produce lesser greenhouse gases are granted carbon credits and these credits may be traded in the energy market. Since these incentives issued to renewable resources are fairly recent, they need to be studied further to ensure that their short term benefits are taken into consideration. Future work is also required to determine how changes in public policy concerned with renewable resources, lack of incentives, and achieving the RPS may impact the need for transmission expansion for renewable resource penetration.

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APPENDIX A

MATLAB CODE

MATLAB codes to read shape files created in PowerWorld and create data files to be input to the optimization model. Output of the program is the bus, branch and time-variant data files.

A.1 MATLAB code to create bus.dat

```
% Base MVA = 100;
% Read Bus.shp which Bus data
% Bus.shp: Geometry X Y idField Name Number PUVolt GenMvar
GenMaxMva
% GenMinMva GenMW  GenMaxMW GenMinMW  Latitude Longitude LoadMvar
LoadMW Radians
B=shaperead('Bus.shp');

% Read Line.shp -> Transmission line data
T=shaperead('Line.shp');

% Read Gen.shp -> Generator data
% Gen.shp:  Geometry X Y idField  UnitType  ID  MaxMvar MinMvar
GenMW
% MaxMW  MinMW  NameOfBus NumberOfB PUVoltOf
G=shaperead('Gen.shp');

%Write data to bus.dat

%nB - number of buses
nB=size(B);
nB=nB(1);

gencost=zeros(nB,1);
gentype=zeros(nB,1);

for i=1:nB
    if strcmp(B(i).LoadMW,'')==1
        B(i).LoadMW=0;
    end
    %To find the gen type at bus i
    for j=1:nG
        if G(j).NumberOfB == B(i).Number
            gentype(i)=gtype(j);
        else
            gentype(i)=0;
        end
    end
end


% Assign gen cost
for i=1:nB
    if gentype(i)==0
        gencost(i)=100;
```

```
    end
end


fid=fopen('bus.dat','w');
%Write to file Bus# Max_MW Min_MW UnitType
for i=1:nB
    if B(i).LoadMW~=0
        LoadMW=str2num(B(i).LoadMW);
    else
        LoadMW=0;
    end


    for j=1:n
        if B(i).Number==bus(j)
            gentype(i)=A(i,2);
            gencost(i)=0;
        end
    end


    %BusNumber  Slack MaxGenMW  LoadMW GenType GenCost
    if B(i).Number==15981 %slack bus
        fprintf(fid,'%d %d %f %f %d %f\n',B(i).Number, 1,
B(i).GenMaxMW/100, LoadMW/100, gentype(i), gencost(i));
    else
        fprintf(fid,'%d %d %f %f %d %f\n',B(i).Number, 0,
B(i).GenMaxMW/100, LoadMW/100, gentype(i), gencost(i));
    end
end
fclose(fid);
```

A.2 MATLAB code to create branch.dat

```
clc
clear all

%Calculate scaled transmission line cost to be considered in each
%scenario
y=25;  %Assumed life time of transmission line
r=.05; %Annual rate of interest
v=[500;345;230;69]; %Voltage levels
npv=1000000*[2;1.5;1;0.4]; %Transmission line costs per mile

A=zeros(4,1);
for i=1:4
    k1=1-((1/(1+r))^y);
    A(i)=npv(i)*r/k1;
end
A=A/52; % Scaled per week cost

% Base MVA = 100;
% Read Bus.shp -> Bus data
% Bus.shp: Geometry X Y idField Name Number PUVolt GenMvar
GenMaxMva
% GenMinMva GenMW  GenMaxMW GenMinMW  Latitude Longitude LoadMvar
LoadMW Radians
B=shaperead('Bus.shp');

nb=size(B);
nb=nb(1);

B1=zeros(nb,3);
for i=1:nb
    B1(i,1)=B(i).Number; %Bus number
    B1(i,2)=B(i).X; %Longitude
    B1(i,3)=B(i).Y; %Latitude
end

%t from to voltage x0 r x limit cost
%Sheet of AZ_branch has new limits
L=xlsread('AZbranch.xlsx');
nl=size(L);
nl=nl(1);

cost=zeros(nl,1);
fid=fopen('br.dat','w');

%Calculating the length of each transmission line
for i=1:nl
    f=L(i,2); %From bus
    t=L(i,3); %To bus

    fp=find(B1==f);
```

```
    fx=B1(fp,3)*pi/180; %Latitude of from bus
    fy=B1(fp,2)*pi/180; %Longitude of from bus

    tp=find(B1==t);
    tx=B1(tp,3)*pi/180; %Latitude of from bus
    ty=B1(tp,2)*pi/180; %Longitude of from bus


    if fx==tx && fy==ty
        length=0;
    else
        length=3963.1 * (acos((sin(fx)*sin(tx)) +
(cos(fx)*cos(tx)* cos(ty - fy)))); % in miles
    end

    %Cost based on voltage
    if L(i,5)==500
        cost(i)=length*A(1);
    else if L(i,5)==345
            cost(i)=length*A(2);
        else if L(i,5)==230
                cost(i)=length*A(3);
            else if L(i,5)==69
                    cost(i)=length*A(4);
                end
            end
        end
    end

    %lt1(i)=length;
    %Write to file from_bus to_bus branch_n0 R X branch_nmax
MW_Limit length
    % Number FromBus    ToBus   Type R  X   MaxMw   cost
    fprintf(fid,'\n %d %d %d %d %f %f %f %f
\n',i,L(i,2),L(i,3),1,L(i,6),L(i,7),2*L(i,8)/100,0);

    %fprintf(fid,'\n %d %d %d %d %f %f %f %f
\n',i,L(i,2),L(i,3),1,L(i,6),L(i,7),100,cost(i));
end


% %Available right of ways
s=1; %scenario number
AR=xlsread('available.xlsx',s);
na=size(AR);
na=na(1);

from=L(:,2);
to=L(:,3);
c=1;
for i=1:na
    p1=find(from==AR(i))
    p2=find(to==AR(i))
```

```
    %Assume an additional fixed cost for constructing lines =
    for j=1:size(p1)
        fprintf(fid,'\n %d %d %d %d %f %f %f %f
\n',nl+c,L(p1(j),2),L(p1(j),3),0,L(p1(j),6),L(p1(j),7),L(i,8)/100
, cost(p1(j)));
        c=c+1;
    end

    for j=1:size(p2)
        fprintf(fid,'\n %d %d %d %d %f %f %f %f
\n',nl+c,L(p2(j),2),L(p2(j),3),0,L(p2(j),6),L(p2(j),7),L(i,8)/100
, cost(p2(j)));
        c=c+1;
    end

end

fclose(fid);
```

A.3 MATLAB code to create time.dat

```
clc
clear all

A=xlsread('queue.xlsx');
W=xlsread('wind.xlsx');
P=xlsread('pv.xlsx');
C=xlsread('csp.xlsx');

%1 - wind, 2 - pv, 3 - csp
n=size(A);
n=n(1);

%Day number
%Read in gen profile at each bus of the interconnection queue
for i=1:n
    if A(i,2)==1 %Wind
        max=A(i,3);
        B=[];
        for j=1:1
            B= [B W(j,2:25)];
        end
        B=max*B;
        xlswrite('Gen_test.xlsx',B',i);
    elseif A(i,2)==2 %PV
        max=A(i,3);
        B=[];
        for j=1:1
            B= [B P(j,2:25)];
        end
        B=max*B;
        xlswrite('Gen_test.xlsx',B',i);

    elseif A(i,2)==3 %CSP
        max=A(i,3);
        B=[];
        for j=1:1
            B= [B C(j,2:25)];
        end
        B=max*B;
        xlswrite('Gen_test.xlsx',B',i);
    end
end

%sum of all generators at a bus

bus=A(:,1);
f=zeros(n,1);
c=1;
i=1;
while(i<n)
    %for i=1:n-1
```

```
    B=xlsread('gen_test.xlsx',i);
    j=i+1;
    while bus(i)==bus(j)
        B=B + xlsread('gen_test.xlsx',j);
        j=j+1;
    end
    f(c)=bus(i);
    xlswrite('gen_test1.xlsx',B,c);
    c=c+1;
    i=j;
end


% create time.dat

X=xlsread('Time.xlsx');
nx=size(X);
nx=nx(1);


fid=fopen('t.dat','w');
n=16;
for i=1:nx
    check=0;
    for j=1:n
        if X(i,1)==f(j)
            check=1;
            Y=xlsread('gen_test1.xlsx',j);
            for k=1:1
                %  hour bus# gen load
                fprintf(fid,'%d %d %f %f \n', k, X(i,1), Y(k)/100
+X(i,2), X(i,3));
            end
        end
    end
    if check==0
        for k=1:1
            fprintf(fid,'%d %d %f %f \n', k, X(i,1), X(i,2),
X(i,3));
        end
        %     end

    end
end

fclose(fid);
```

APPENDIX B

TEST SYSTEMS DATA

B.1 6 BUS TEST SYSTEM

6 Bus test system bus data

Bus	Slack	Max Gen (p.u.)	Max Load (p.u.)
1	0	1.5	0.8
2	0	0	2.4
3	0	3.6	0.4
4	0	0	1.6
5	0	0	2.4
6	1	6	0

6 Bus test system branch data

From bus	To bus	n_0	x	n_{max}	P_{max}	Cost
1	2	1	0.4	2	1	40
1	4	1	0.6	2	0.8	60
1	5	1	0.2	2	1	20
2	3	1	0.2	2	1	20
2	4	1	0.4	2	1	40
2	6	0	0.3	2	1	30
3	5	1	0.2	2	1	20
4	6	0	0.3	2	1	30
2	1	1	0.4	2	1	40
4	1	1	0.6	2	0.8	60
5	1	1	0.2	2	1	20
3	2	1	0.2	2	1	20
4	2	1	0.4	2	1	40
6	2	0	0.3	2	1	30
5	3	1	0.2	2	1	20
6	4	0	0.3	2	1	30
1	3	0	0.38	0	1	38
1	6	0	0.68	0	0.7	68
2	5	0	0.31	0	1	31
3	4	0	0.59	0	0.82	59
3	6	0	0.48	0	1	48
4	5	0	0.63	0	0.75	63
5	6	0	0.61	0	0.78	61
3	1	0	0.38	0	1	38
6	1	0	0.68	0	0.7	68
5	2	0	0.31	0	1	31

4	3	0	0.59	0	0.82	59
6	3	0	0.48	0	1	48
5	4	0	0.63	0	0.75	63
6	5	0	0.61	0	0.78	61

B.2 14 BUS TEST SYSTEM

14 Bus test system bus data

Bus	Slack	Bus_pmax (p.u.)	Bus_pload (p.u.)
1	1	6	0
2	0	1.5	0
3	0	1.5	0
4	0	0	0
5	0	0	5
6	0	0	5
7	0	0	0
8	0	7.5	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	5

14 Bus test system branch data

From bus	To bus	n_0	r	X	P_{max}	Cost
1	6	0	0.019999	0.145999	1.526808	1.4562
1	7	0	0.029999	0.18	0.585774	1.58864
2	4	0	1	0.022859	1.500062	1.191302
3	4	0	1	0.022859	1.000058	1.191195
4	10	0	0.0065	0.07	2.500118	1.588457
4	10	0	0.0065	0.07	2.500118	1.588457
5	11	0	1	0.316599	0.146305	1.5881
6	5	0	0.014999	0.1	1.083266	1.455851
7	8	0	0.019999	0.15	0.592821	1.588702
9	8	0	0.019999	0.15	0.932316	1.588321

10	6	0	0.5	0.01143	2.456932	1.720897
10	6	0	0.5	0.01143	2.456932	1.720897
11	12	0	0.095459	0.253399	0.148736	1.058768
12	13	0	0.158999	0.422369	0.152785	1.058795
13	14	0	0.0636	0.16895	0.154405	0.926468
1	6	1	0.019999	0.145999	1.526808	1.4562
1	7	1	0.029999	0.18	0.585774	1.58864
1	5	1	0.0013	0.07268	10	8.022044
1	5	1	0.0013	0.07268	10	8.022044
1	5	1	0.0013	0.07268	10	8.022044
1	5	1	0.0013	0.07268	10	8.022044
1	5	1	0.0013	0.07268	10	8.022044
2	4	1	1	0.022859	1.500062	1.191302
3	4	1	1	0.022859	1.000058	1.191195
5	9	1	0.029999	0.18	0.914862	1.588259
5	11	1	1	0.316599	0.146305	1.5881
6	5	1	0.014999	0.1	1.083266	1.455851
7	8	1	0.019999	0.15	0.592821	1.588702
8	14	1	0.0013	0.07268	10	4.102237
8	14	1	0.0013	0.07268	10	4.102237
8	14	1	0.0013	0.07268	10	4.102237
8	14	1	0.0013	0.07268	10	4.102237
8	14	1	0.0013	0.07268	10	4.102237
9	8	1	0.019999	0.15	0.932316	1.588321
11	12	1	0.095459	0.253399	0.148736	1.058768
12	13	1	0.158999	0.422369	0.152785	1.058795
13	14	1	0.0636	0.16895	0.154405	0.926468

B.3 118 Bus test system

118 Bus test system bus data

Bus	Slack	Pmax	Pload
1	0	0	0.51
2	0	0	0.2
3	0	0	0.39
4	0	1	0.3
5	0	0	0
6	0	1	0.52
7	0	0	0.19
8	0	1	0

9	0	0	0
10	0	5	0
11	0	0	0.7
12	0	3	0.47
13	0	0	0.34
14	0	0	0.14
15	0	1	0.9
16	0	0	0.25
17	0	0	0.11
18	0	1	0.6
19	0	1	0.45
20	0	0	0.18
21	0	0	0.14
22	0	0	0.1
23	0	0	0.07
24	0	1	0
25	0	5	0
26	0	5	0
27	0	1	0.62
28	0	0	0.17
29	0	0	0.24
30	0	0	0
31	0	1	0.43
32	0	1	0.59
33	0	0	0.23
34	0	1	0.59
35	0	0	0.33
36	0	1	0.31
37	0	0	0
38	0	0	0
39	0	0	0.27
40	0	1	0.2
41	0	0	0.37
42	0	1	0.37
43	0	0	0.18
44	0	0	0.16
45	0	0	0.53
46	0	1	0.28
47	0	0	0.34
48	0	0	0.2
49	0	3	0.87

50	0	0	0.17
51	0	0	0.17
52	0	0	0.18
53	0	0	0.23
54	0	1	1.13
55	0	1	0.63
56	0	1	0.84
57	0	0	0.12
58	0	0	0.12
59	0	3	2.77
60	0	0	0.78
61	0	3	0
62	0	1	0.77
63	0	0	0
64	0	0	0
65	0	5	0
66	0	5	0.39
67	0	0	0.28
68	0	0	0
69	1	5	0
70	0	1	0.66
71	0	0	0
72	0	1	0
73	0	1	0
74	0	1	0.68
75	0	0	0.47
76	0	1	0.68
77	0	1	0.61
78	0	0	0.71
79	0	0	0.39
80	0	5	1.3
81	0	0	0
82	0	1	0.54
83	0	0	0.2
84	0	0	0.11
85	0	1	0.24
86	0	0	0.21
87	0	1	0
88	0	0	0.48
89	0	5	0
90	0	1	0.78

91	0	1	0
92	0	1	0.65
93	0	0	0.12
94	0	0	0.3
95	0	0	0.42
96	0	0	0.38
97	0	0	0.15
98	0	0	0.34
99	0	1	0
100	0	5	0.37
101	0	0	0.22
102	0	0	0.05
103	0	1	0.23
104	0	1	0.38
105	0	1	0.31
106	0	0	0.43
107	0	1	0.28
108	0	0	0.02
109	0	0	0.08
110	0	1	0.39
111	0	1	0
112	0	1	0.25
113	0	1	0
114	0	0	0.08
115	0	0	0.22
116	0	1	0
117	0	0	0.2
118	0	0	0.33

118 Bus test system branch data

1	4	11	0	0.0209	0.0688	0.641	68.8
2	5	6	0	0.0119	0.054	0.884	54
3	8	5	0	0	0.0267	3.382	26.7
4	5	11	0	0.0203	0.0682	0.771	68.2
5	6	7	0	0.0046	0.0208	0.354	20.8
6	7	12	0	0.0086	0.034	0.164	34
7	8	9	0	0.0024	0.0305	4.452	30.5
8	8	30	0	0.0043	0.0504	0.745	50.4
9	9	10	0	0.0026	0.0322	4.5	32.2

10	11	12	0	0.0059	0.0196	0.342	19.6
11	11	13	0	0.0225	0.0731	0.349	73.1
12	12	14	0	0.0215	0.0707	0.181	70.7
13	12	16	0	0.0212	0.0834	0.076	83.4
14	12	117	0	0.0329	0.014	0.201	14
15	13	15	0	0.0744	0.2444	0.006	244.4
16	14	15	0	0.0595	0.195	0.04	195
17	15	17	0	0.0132	0.0437	1.034	43.7
18	15	19	0	0.012	0.0394	0.11	39.4
19	15	33	0	0.038	0.1244	0.054	124.4
20	16	17	0	0.0454	0.1801	0.175	180.1
21	17	18	0	0.0123	0.0505	0.792	50.5
22	30	17	0	0	0.0388	2.312	38.8
23	17	31	0	0.0474	0.1563	0.113	156.3
24	17	113	0	0.0091	0.0301	0.088	30.1
25	18	19	0	0.0112	0.0493	0.184	49.3
26	19	20	0	0.0252	0.117	0.103	117
27	19	34	0	0.0752	0.247	0.055	247
28	20	21	0	0.0183	0.0849	0.285	84.9
29	21	22	0	0.0209	0.097	0.429	97
30	22	23	0	0.0342	0.159	0.539	159
31	23	24	0	0.0135	0.0492	0.121	49.2
32	23	25	0	0.0156	0.08	1.68	80
33	23	32	0	0.0317	0.1153	0.907	115.3
34	24	70	0	0.1022	0.4115	0.039	411.5
35	24	72	0	0.0488	0.196	0.029	196
36	26	25	0	0	0.0382	0.902	38.2
37	25	27	0	0.0318	0.163	1.422	163
38	26	30	0	0.008	0.086	2.238	86
39	27	28	0	0.0191	0.0855	0.312	85.5
40	27	32	0	0.0229	0.0755	0.128	75.5
41	27	115	0	0.0164	0.0741	0.209	74.1
42	28	29	0	0.0237	0.0943	0.14	94.3
43	29	31	0	0.0108	0.0331	0.1	33.1
44	30	38	0	0.0046	0.054	0.628	54
45	31	32	0	0.0298	0.0985	0.266	98.5
46	113	31	0	0	0.1	0.086	100
47	32	113	0	0.0615	0.203	0.06	203
48	32	114	0	0.0135	0.0612	0.092	61.2
49	33	37	0	0.0415	0.142	0.177	142
50	34	36	0	0.0087	0.0268	0.302	26.8

51	34	37	0	0.0026	0.0094	0.976	9.4
52	34	43	0	0.0413	0.1681	0.027	168.1
53	35	36	0	0.0022	0.0102	0.009	10.2
54	35	37	0	0.011	0.0497	0.341	49.7
55	38	37	0	0	0.0375	2.264	37.5
56	37	39	0	0.0321	0.106	0.437	106
57	37	40	0	0.0593	0.168	0.332	168
58	38	65	0	0.009	0.0986	1.664	98.6
59	39	40	0	0.0184	0.0605	0.161	60.5
60	40	41	0	0.0145	0.0487	0.05	48.7
61	40	42	0	0.0555	0.183	0.227	183
62	41	42	0	0.041	0.135	0.325	135
63	42	49	0	0.0715	0.323	0.523	323
64	42	49	0	0.0715	0.323	0.523	323
65	42	49	0	0.0715	0.323	0.523	323
66	43	44	0	0.0608	0.2454	0.155	245.4
67	44	45	0	0.0224	0.0901	0.317	90.1
68	45	46	0	0.04	0.1356	0.36	135.6
69	45	49	0	0.0684	0.186	0.51	186
70	46	47	0	0.038	0.127	0.305	127
71	46	48	0	0.0601	0.189	0.15	189
72	47	49	0	0.0191	0.0625	0.121	62.5
73	47	69	0	0.0844	0.2778	0.548	277.8
74	48	49	0	0.0179	0.0505	0.352	50.5
75	49	50	0	0.0267	0.0752	0.497	75.2
76	49	51	0	0.0486	0.137	0.616	137
77	49	54	0	0.073	0.289	0.33	289
78	49	54	0	0.0869	0.291	0.331	291
79	49	54	0	0.073	0.289	0.33	289
80	49	66	0	0.018	0.0919	1.036	91.9
81	49	66	0	0.018	0.0919	1.036	91.9
82	49	66	0	0.018	0.0919	1.036	91.9
83	49	69	0	0.0985	0.324	0.449	324
84	50	57	0	0.0474	0.134	0.32	134
85	51	52	0	0.0203	0.0588	0.268	58.8
86	51	58	0	0.0255	0.0719	0.158	71.9
87	52	53	0	0.0405	0.1635	0.086	163.5
88	53	54	0	0.0263	0.122	0.145	122
89	54	55	0	0.0169	0.0707	0.098	70.7
90	54	56	0	0.0027	0.0096	0.276	9.6
91	54	59	0	0.0503	0.2293	0.211	229.3

92	55	56	0	0.0049	0.0151	0.28	15.1
93	55	59	0	0.0474	0.2158	0.257	215.8
94	56	57	0	0.0343	0.0966	0.194	96.6
95	56	58	0	0.0343	0.0966	0.038	96.6
96	56	59	0	0.0825	0.251	0.205	251
97	56	59	0	0.0803	0.239	0.215	239
98	56	59	0	0.0825	0.251	0.205	251
99	59	60	0	0.0317	0.145	0.403	145
100	59	61	0	0.0328	0.15	0.491	150
101	63	59	0	0	0.0386	1.432	38.6
102	60	61	0	0.0026	0.0135	1.123	13.5
103	60	62	0	0.0123	0.0561	0.063	56.1
104	61	62	0	0.0082	0.0376	0.308	37.6
105	64	61	0	0	0.0268	0.322	26.8
106	62	66	0	0.0482	0.218	0.334	218
107	62	67	0	0.0258	0.117	0.2	117
108	63	64	0	0.0017	0.02	1.437	20
109	64	65	0	0.0027	0.0302	1.768	30.2
110	65	66	0	0	0.037	0.399	37
111	65	68	0	0.0014	0.016	0.078	16
112	66	67	0	0.0224	0.1015	0.486	101.5
113	68	69	0	0	0.037	1.371	37
114	68	81	0	0.0018	0.0202	0.392	20.2
115	68	116	0	0.0003	0.0041	1.841	4.1
116	69	70	0	0.03	0.127	1.047	127
117	69	75	0	0.0405	0.122	1.067	122
118	69	77	0	0.0309	0.101	0.552	101
119	70	71	0	0.0088	0.0355	0.152	35.5
120	70	74	0	0.0401	0.1323	0.163	132.3
121	70	75	0	0.0428	0.141	0	141
122	71	72	0	0.0446	0.18	0.091	180
123	71	73	0	0.0087	0.0454	0.06	45.4
124	74	75	0	0.0123	0.0406	0.522	40.6
125	75	77	0	0.0601	0.1999	0.371	199.9
126	75	118	0	0.0145	0.0481	0.39	48.1
127	76	77	0	0.0444	0.148	0.646	148
128	76	118	0	0.0164	0.0544	0.057	54.4
129	77	78	0	0.0038	0.0124	0.577	12.4
130	77	80	0	0.017	0.0485	0.71	48.5
131	77	80	0	0.0294	0.105	0.323	105
132	77	80	0	0.017	0.0485	0.71	48.5

133	77	82	0	0.0298	0.0853	0.059	85.3
134	78	79	0	0.0055	0.0244	0.135	24.4
135	79	80	0	0.0156	0.0704	0.53	70.4
136	81	80	0	0	0.037	0.392	37
137	80	96	0	0.0356	0.182	0.158	182
138	80	97	0	0.0183	0.0934	0.233	93.4
139	80	98	0	0.0238	0.108	0.254	108
140	80	99	0	0.0454	0.206	0.16	206
141	82	83	0	0.0112	0.0366	0.359	36.6
142	82	96	0	0.0162	0.053	0.124	53
143	83	84	0	0.0625	0.132	0.203	132
144	83	85	0	0.043	0.148	0.367	148
145	84	85	0	0.0302	0.0641	0.316	64.1
146	85	86	0	0.035	0.123	0.172	123
147	85	88	0	0.02	0.102	0.448	102
148	85	89	0	0.0239	0.173	0.662	173
149	86	87	0	0.02828	0.2074	0.04	207.4
150	88	89	0	0.0139	0.0712	0.94	71.2
151	89	90	0	0.0518	0.188	0.419	188
152	89	90	0	0.0238	0.0997	0.797	99.7
153	89	90	0	0.0518	0.188	0.419	188
154	89	92	0	0.0099	0.0505	1.224	50.5
155	89	92	0	0.0393	0.1581	0.385	158.1
156	89	92	0	0.0099	0.0505	1.224	50.5
157	91	90	0	0.0254	0.0836	0.028	83.6
158	91	92	0	0.0387	0.1272	0.129	127.2
159	92	93	0	0.0258	0.0848	0.628	84.8
160	92	94	0	0.0481	0.158	0.573	158
161	92	100	0	0.0648	0.295	0.343	295
162	92	102	0	0.0123	0.0559	0.475	55.9
163	93	94	0	0.0223	0.0732	0.497	73.2
164	94	95	0	0.0132	0.0434	0.45	43.4
165	94	96	0	0.0269	0.0869	0.245	86.9
166	94	100	0	0.0178	0.058	0.053	58
167	95	96	0	0.0171	0.0547	0.027	54.7
168	96	97	0	0.0173	0.0885	0.081	88.5
169	98	100	0	0.0397	0.179	0.088	179
170	99	100	0	0.018	0.0813	0.263	81.3
171	100	101	0	0.0277	0.1262	0.197	126.2
172	100	103	0	0.016	0.0525	1.203	52.5
173	100	104	0	0.0451	0.204	0.571	204

174	100	106	0	0.0605	0.229	0.605	229
175	101	102	0	0.0246	0.112	0.422	112
176	103	104	0	0.0466	0.1584	0.324	158.4
177	103	105	0	0.0535	0.1625	0.429	162.5
178	103	110	0	0.0391	0.1813	0.597	181.3
179	104	105	0	0.0099	0.0378	0.496	37.8
180	105	106	0	0.014	0.0547	0.087	54.7
181	105	107	0	0.053	0.183	0.269	183
182	105	108	0	0.0261	0.0703	0.247	70.3
183	106	107	0	0.053	0.183	0.239	183
184	108	109	0	0.0105	0.0288	0.226	28.8
185	109	110	0	0.0278	0.0762	0.145	76.2
186	110	111	0	0.022	0.0755	0.36	75.5
187	110	112	0	0.0247	0.064	0.695	64
188	114	115	0	0.0023	0.0104	0.012	10.4
189	4	11	1	0.0209	0.0688	0.641	68.8
190	5	6	1	0.0119	0.054	0.884	54
191	8	5	1	0	0.0267	3.382	26.7
192	5	11	1	0.0203	0.0682	0.771	68.2
193	6	7	1	0.0046	0.0208	0.354	20.8
194	7	12	1	0.0086	0.034	0.164	34
195	8	9	1	0.0024	0.0305	4.452	30.5
196	8	30	1	0.0043	0.0504	0.745	50.4
197	9	10	1	0.0026	0.0322	4.5	32.2
198	11	12	1	0.0059	0.0196	0.342	19.6
199	11	13	1	0.0225	0.0731	0.349	73.1
200	12	14	1	0.0215	0.0707	0.181	70.7
201	12	16	1	0.0212	0.0834	0.076	83.4
202	12	117	1	0.0329	0.014	0.201	14
203	13	15	1	0.0744	0.2444	0.006	244.4
204	14	15	1	0.0595	0.195	0.04	195
205	15	17	1	0.0132	0.0437	1.034	43.7
206	15	19	1	0.012	0.0394	0.11	39.4
207	15	33	1	0.038	0.1244	0.054	124.4
208	16	17	1	0.0454	0.1801	0.175	180.1
209	17	18	1	0.0123	0.0505	0.792	50.5
210	30	17	1	0	0.0388	2.312	38.8
211	17	31	1	0.0474	0.1563	0.113	156.3
212	17	113	1	0.0091	0.0301	0.088	30.1
213	18	19	1	0.0112	0.0493	0.184	49.3
214	19	20	1	0.0252	0.117	0.103	117

215	19	34	1	0.0752	0.247	0.055	247
216	20	21	1	0.0183	0.0849	0.285	84.9
217	21	22	1	0.0209	0.097	0.429	97
218	22	23	1	0.0342	0.159	0.539	159
219	23	24	1	0.0135	0.0492	0.121	49.2
220	23	25	1	0.0156	0.08	1.68	80
221	23	32	1	0.0317	0.1153	0.907	115.3
222	24	70	1	0.1022	0.4115	0.039	411.5
223	24	72	1	0.0488	0.196	0.029	196
224	26	25	1	0	0.0382	0.902	38.2
225	25	27	1	0.0318	0.163	1.422	163
226	26	30	1	0.008	0.086	2.238	86
227	27	28	1	0.0191	0.0855	0.312	85.5
228	27	32	1	0.0229	0.0755	0.128	75.5
229	27	115	1	0.0164	0.0741	0.209	74.1
230	28	29	1	0.0237	0.0943	0.14	94.3
231	29	31	1	0.0108	0.0331	0.1	33.1
232	30	38	1	0.0046	0.054	0.628	54
233	31	32	1	0.0298	0.0985	0.266	98.5
234	113	31	1	0	0.1	0.086	100
235	32	113	1	0.0615	0.203	0.06	203
236	32	114	1	0.0135	0.0612	0.092	61.2
237	33	37	1	0.0415	0.142	0.177	142
238	34	36	1	0.0087	0.0268	0.302	26.8
239	34	37	1	0.0026	0.0094	0.976	9.4
240	34	43	1	0.0413	0.1681	0.027	168.1
241	35	36	1	0.0022	0.0102	0.009	10.2
242	35	37	1	0.011	0.0497	0.341	49.7
243	38	37	1	0	0.0375	2.264	37.5
244	37	39	1	0.0321	0.106	0.437	106
245	37	40	1	0.0593	0.168	0.332	168
246	38	65	1	0.009	0.0986	1.664	98.6
247	39	40	1	0.0184	0.0605	0.161	60.5
248	40	41	1	0.0145	0.0487	0.05	48.7
249	40	42	1	0.0555	0.183	0.227	183
250	41	42	1	0.041	0.135	0.325	135
251	42	49	1	0.0715	0.323	0.523	323
252	42	49	1	0.0715	0.323	0.523	323
253	42	49	1	0.0715	0.323	0.523	323
254	43	44	1	0.0608	0.2454	0.155	245.4
255	44	45	1	0.0224	0.0901	0.317	90.1

256	45	46	1	0.04	0.1356	0.36	135.6
257	45	49	1	0.0684	0.186	0.51	186
258	46	47	1	0.038	0.127	0.305	127
259	46	48	1	0.0601	0.189	0.15	189
260	47	49	1	0.0191	0.0625	0.121	62.5
261	47	69	1	0.0844	0.2778	0.548	277.8
262	48	49	1	0.0179	0.0505	0.352	50.5
263	49	50	1	0.0267	0.0752	0.497	75.2
264	49	51	1	0.0486	0.137	0.616	137
265	49	54	1	0.073	0.289	0.33	289
266	49	54	1	0.0869	0.291	0.331	291
267	49	54	1	0.073	0.289	0.33	289
268	49	66	1	0.018	0.0919	1.036	91.9
269	49	66	1	0.018	0.0919	1.036	91.9
270	49	66	1	0.018	0.0919	1.036	91.9
271	49	69	1	0.0985	0.324	0.449	324
272	50	57	1	0.0474	0.134	0.32	134
273	51	52	1	0.0203	0.0588	0.268	58.8
274	51	58	1	0.0255	0.0719	0.158	71.9
275	52	53	1	0.0405	0.1635	0.086	163.5
276	53	54	1	0.0263	0.122	0.145	122
277	54	55	1	0.0169	0.0707	0.098	70.7
278	54	56	1	0.0027	0.0096	0.276	9.6
279	54	59	1	0.0503	0.2293	0.211	229.3
280	55	56	1	0.0049	0.0151	0.28	15.1
281	55	59	1	0.0474	0.2158	0.257	215.8
282	56	57	1	0.0343	0.0966	0.194	96.6
283	56	58	1	0.0343	0.0966	0.038	96.6
284	56	59	1	0.0825	0.251	0.205	251
285	56	59	1	0.0803	0.239	0.215	239
286	56	59	1	0.0825	0.251	0.205	251
287	59	60	1	0.0317	0.145	0.403	145
288	59	61	1	0.0328	0.15	0.491	150
289	63	59	1	0	0.0386	1.432	38.6
290	60	61	1	0.0026	0.0135	1.123	13.5
291	60	62	1	0.0123	0.0561	0.063	56.1
292	61	62	1	0.0082	0.0376	0.308	37.6
293	64	61	1	0	0.0268	0.322	26.8
294	62	66	1	0.0482	0.218	0.334	218
295	62	67	1	0.0258	0.117	0.2	117
296	63	64	1	0.0017	0.02	1.437	20

297	64	65	1	0.0027	0.0302	1.768	30.2
298	65	66	1	0	0.037	0.399	37
299	65	68	1	0.0014	0.016	0.078	16
300	66	67	1	0.0224	0.1015	0.486	101.5
301	68	69	1	0	0.037	1.371	37
302	68	81	1	0.0018	0.0202	0.392	20.2
303	68	116	1	0.0003	0.0041	1.841	4.1
304	69	70	1	0.03	0.127	1.047	127
305	69	75	1	0.0405	0.122	1.067	122
306	69	77	1	0.0309	0.101	0.552	101
307	70	71	1	0.0088	0.0355	0.152	35.5
308	70	74	1	0.0401	0.1323	0.163	132.3
309	70	75	1	0.0428	0.141	0	141
310	71	72	1	0.0446	0.18	0.091	180
311	71	73	1	0.0087	0.0454	0.06	45.4
312	74	75	1	0.0123	0.0406	0.522	40.6
313	75	77	1	0.0601	0.1999	0.371	199.9
314	75	118	1	0.0145	0.0481	0.39	48.1
315	76	77	1	0.0444	0.148	0.646	148
316	76	118	1	0.0164	0.0544	0.057	54.4
317	77	78	1	0.0038	0.0124	0.577	12.4
318	77	80	1	0.017	0.0485	0.71	48.5
319	77	80	1	0.0294	0.105	0.323	105
320	77	80	1	0.017	0.0485	0.71	48.5
321	77	82	1	0.0298	0.0853	0.059	85.3
322	78	79	1	0.0055	0.0244	0.135	24.4
323	79	80	1	0.0156	0.0704	0.53	70.4
324	81	80	1	0	0.037	0.392	37
325	80	96	1	0.0356	0.182	0.158	182
326	80	97	1	0.0183	0.0934	0.233	93.4
327	80	98	1	0.0238	0.108	0.254	108
328	80	99	1	0.0454	0.206	0.16	206
329	82	83	1	0.0112	0.0366	0.359	36.6
330	82	96	1	0.0162	0.053	0.124	53
331	83	84	1	0.0625	0.132	0.203	132
332	83	85	1	0.043	0.148	0.367	148
333	84	85	1	0.0302	0.0641	0.316	64.1
334	85	86	1	0.035	0.123	0.172	123
335	85	88	1	0.02	0.102	0.448	102
336	85	89	1	0.0239	0.173	0.662	173
337	86	87	1	0.02828	0.2074	0.04	207.4

338	88	89	1	0.0139	0.0712	0.94	71.2
339	89	90	1	0.0518	0.188	0.419	188
340	89	90	1	0.0238	0.0997	0.797	99.7
341	89	90	1	0.0518	0.188	0.419	188
342	89	92	1	0.0099	0.0505	1.224	50.5
343	89	92	1	0.0393	0.1581	0.385	158.1
344	89	92	1	0.0099	0.0505	1.224	50.5
345	91	90	1	0.0254	0.0836	0.028	83.6
346	91	92	1	0.0387	0.1272	0.129	127.2
347	92	93	1	0.0258	0.0848	0.628	84.8
348	92	94	1	0.0481	0.158	0.573	158
349	92	100	1	0.0648	0.295	0.343	295
350	92	102	1	0.0123	0.0559	0.475	55.9
351	93	94	1	0.0223	0.0732	0.497	73.2
352	94	95	1	0.0132	0.0434	0.45	43.4
353	94	96	1	0.0269	0.0869	0.245	86.9
354	94	100	1	0.0178	0.058	0.053	58
355	95	96	1	0.0171	0.0547	0.027	54.7
356	96	97	1	0.0173	0.0885	0.081	88.5
357	98	100	1	0.0397	0.179	0.088	179
358	99	100	1	0.018	0.0813	0.263	81.3
359	100	101	1	0.0277	0.1262	0.197	126.2
360	100	103	1	0.016	0.0525	1.203	52.5
361	100	104	1	0.0451	0.204	0.571	204
362	100	106	1	0.0605	0.229	0.605	229
363	101	102	1	0.0246	0.112	0.422	112
364	103	104	1	0.0466	0.1584	0.324	158.4
365	103	105	1	0.0535	0.1625	0.429	162.5
366	103	110	1	0.0391	0.1813	0.597	181.3
367	104	105	1	0.0099	0.0378	0.496	37.8
368	105	106	1	0.014	0.0547	0.087	54.7
369	105	107	1	0.053	0.183	0.269	183
370	105	108	1	0.0261	0.0703	0.247	70.3
371	106	107	1	0.053	0.183	0.239	183
372	108	109	1	0.0105	0.0288	0.226	28.8
373	109	110	1	0.0278	0.0762	0.145	76.2
374	110	111	1	0.022	0.0755	0.36	75.5
375	110	112	1	0.0247	0.064	0.695	64
376	114	115	1	0.0023	0.0104	0.012	10.4

APPENDIX C

AMPL CODE

```
reset;

# Set solver
      option solver gurobi;
      option gurobi_options 'outlev=1';

# Declare BUS and BRANCH set
# Assume maximum number of buses in the system to be 10
      set BUS;
      set BRANCH;
      set HOUR := {1..168}; # 168 time periods
      set time_v within HOUR cross BUS;

# Read bus data from the .BUS data file
      param slack {BUS};
      param bus_gtype {BUS};
      param k1 {BUS};
      param k2 {BUS};   #gen cost c(p) = k1 + k2p

# Time dependent bus gen and load
      param bus_pmax {HOUR cross BUS};
      param bus_pload {HOUR cross BUS};

# Read branch data - Includes data about available right of ways
and construction costs
      param from {BRANCH};
      param to {BRANCH};
      param x0 {BRANCH};
      param branch_r {BRANCH};
      param branch_x {BRANCH};
      param branch_pmax {BRANCH};
      param branch_cost {BRANCH};


# Decision variables
      var x {BRANCH} binary;
      var f {HOUR cross BRANCH};           #Line flow
      var th {HOUR cross BUS};             #Bus voltage angle
      var bus_pgen {HOUR cross BUS} >= 0; #Gen MW

# Objective function
minimize total_cost :
(100*sum{(h,i) in HOUR cross BUS} (k1[i]+(bus_pgen[h,i]*k2[i])))
      + (sum{t in BRANCH:x0[t]=0}(x[t]*branch_cost[t]));

# Constraints
# Power balance at each node
subject to node_power_balance{(h,i) in HOUR cross BUS}:
sum{t in BRANCH: from[t]=i}f[h,t] - sum{t in BRANCH:
to[t]=i}(f[h,t])= bus_pgen[h,i] - bus_pload[h,i];

# Line flows - New Lines
subject to line_flow1{(h,t) in HOUR cross BRANCH}:
```

```
f[h,t] - ((th[h,from[t]]-th[h,to[t]])/branch_x[t])<=1000*(1-
x[t]);

subject to line_flow2{(h,t) in HOUR cross BRANCH}:
f[h,t] - ((th[h,from[t]]-th[h,to[t]])/branch_x[t])>=-1000*(1-
x[t]);

# Line MW limits - New Lines
subject to line_MW_limit1{(h,t) in HOUR cross BRANCH}:
      (f[h,t]) <= x[t]*branch_pmax[t];

subject to line_MW_limit2{(h,t) in HOUR cross BRANCH}:
      (f[h,t]) >= -x[t]*branch_pmax[t];

#Gen limits
subject to gen_limits{(h,k) in HOUR cross BUS}:
      bus_pgen[h,k] <= bus_pmax[h,k];

# Line construct
subject to xbuild{t in BRANCH}:
      x[t] - x0[t] >= 0;

# Bus angle constraint
subject to angle{(h,t) in HOUR cross BRANCH}:
      th[h,from[t]]-th[h,to[t]] <= 0.6;


subject to angle1{(h,t) in HOUR cross BRANCH}:
      th[h,from[t]]-th[h,to[t]] >= -0.6;

data;

param: BUS: slack bus_gtype k1 k2:=
include  bus.dat;

param: BRANCH: from to x0 branch_r branch_x branch_pmax
branch_cost:=
include  branch.dat;

param: time_v: bus_pmax bus_pload:=
include time.dat;

for{(h,i) in time_v}
 {
  let th[h,i]:=0;
 };

# Fix slack bus angle = 0
 fix {(h,k) in HOUR cross BUS: slack[k]=3}th[h,k]:=0;


#SOLVE
      solve;
```

```
#Output

for{t in BRANCH}
 {
  if x[t]-x0[t]=1 then display t;
 };

display _solve_elapsed_time;
display sum{(h,i) in HOUR cross BUS:
bus_gtype[i]=1}bus_pgen[h,i];
display sum{(h,i) in HOUR cross BUS:
bus_gtype[i]=1}bus_pmax[h,i];
display sum{(h,i) in HOUR cross BUS:
bus_gtype[i]=2}bus_pgen[h,i];
display sum{(h,i) in HOUR cross BUS:
bus_gtype[i]=2}bus_pmax[h,i];
display sum{(h,i) in HOUR cross BUS:
bus_gtype[i]=3}bus_pgen[h,i];
display sum{(h,i) in HOUR cross BUS:
bus_gtype[i]=3}bus_pmax[h,i];
display sum{(h,i) in HOUR cross BUS}bus_pmax[h,i];
display sum{(h,i) in HOUR cross BUS}bus_pgen[h,i];
display sum{(h,i) in HOUR cross BUS}(k1[i]+bus_pgen[h,i]*k2[i]);
display sum{t in BRANCH}((x[t]-x0[t])*branch_cost[t]);
```

APPENDIX D

GENERATION INTERCONNECTION QUEUES

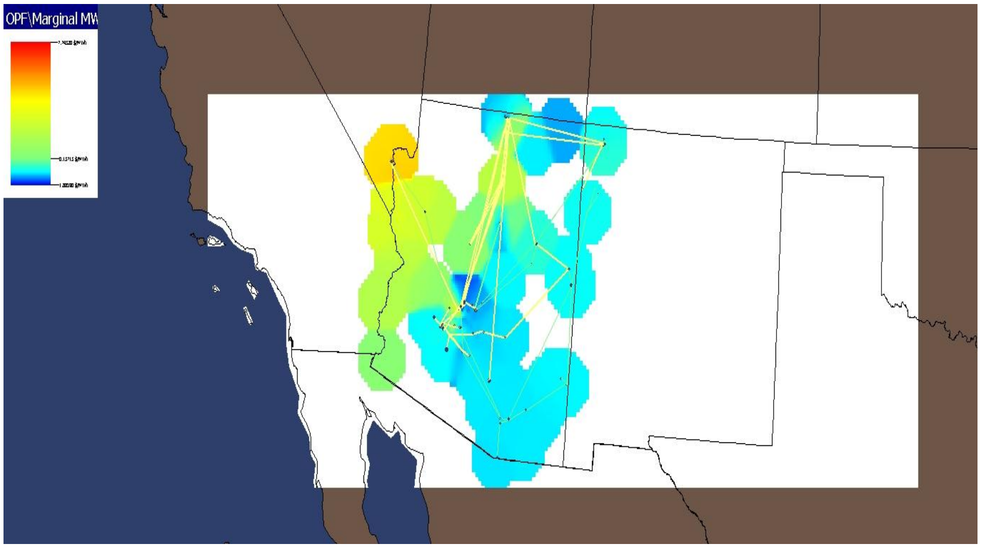
APS and SRP GENERATION INTERCONNECTION QUEUE

Bus number	**Bus name**	**Nameplate rating(MW)**	**Gen. type**
14000	Cholla 500kv	300	Wind
14002	Moenkopi 500kv	1601	Wind
14100	Cholla 345kv	740	Wind
14201	Buckeye 230kv	378	Solar pv
14204	Cholla 230kv	90	Solar PV
14204	Cholla 230kv	442.9	Wind
14209	EagleEye 230kv	40	Solar PV
14228	Surprise 230kv	40	Solar PV
14234	Yavapai 230kv	20	Solar PV
14235	GilaBend 230kv	955	Solar - PV
14235	GilaBend 230kv	1310	Solar CST
14235	GilaBend 230kv	850	Solar PV
14244	Seligman	12	Solar PV
14244	Seligman	260	Wind
14250	WillowLake	20	Solar PV
14250	WillowLake	120	Wind
15090	Hassyampa 500kv	300	Solar CST
15093	Harquahala Valley	400	Solar CLFR
15093	Harquahala Valley	300	Solar CST
15093	Harquahala Valley	60	Solar PV
15094	Harquahala Valley	800	Solar CLFR
15099	SolanaTap 500kv	198	Solar CST
15099	SolanaTap 500kv	40	Solar PV
15102	Asarco	20	Solar
19603	Blythe 161kv	40	solar PV
84832	LagunaTp 69kv	80	Solar PV
84836	NGila 69kv	400	Solar CLFR
84836	NGila 69kv	450	Solar CST

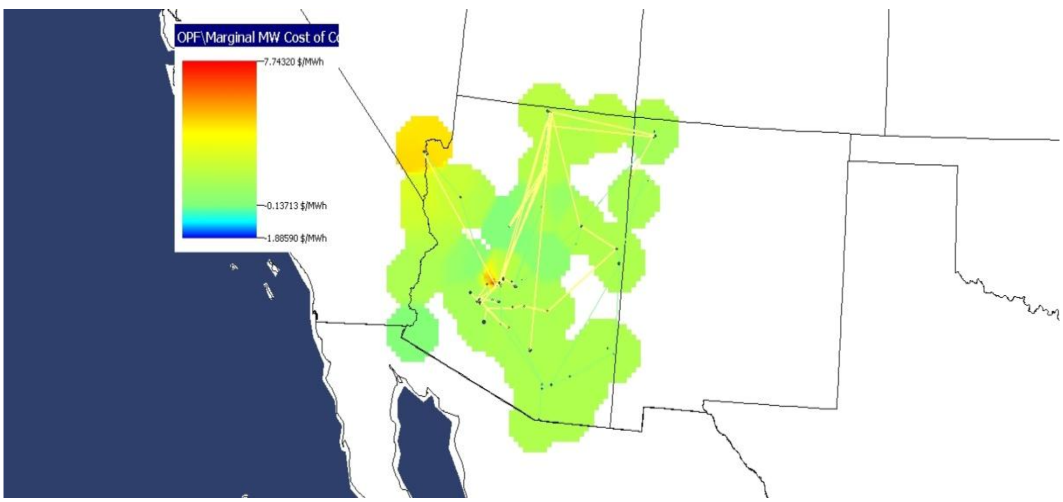
APPENDIX E

CONTOUR PLOTS OF CLMP

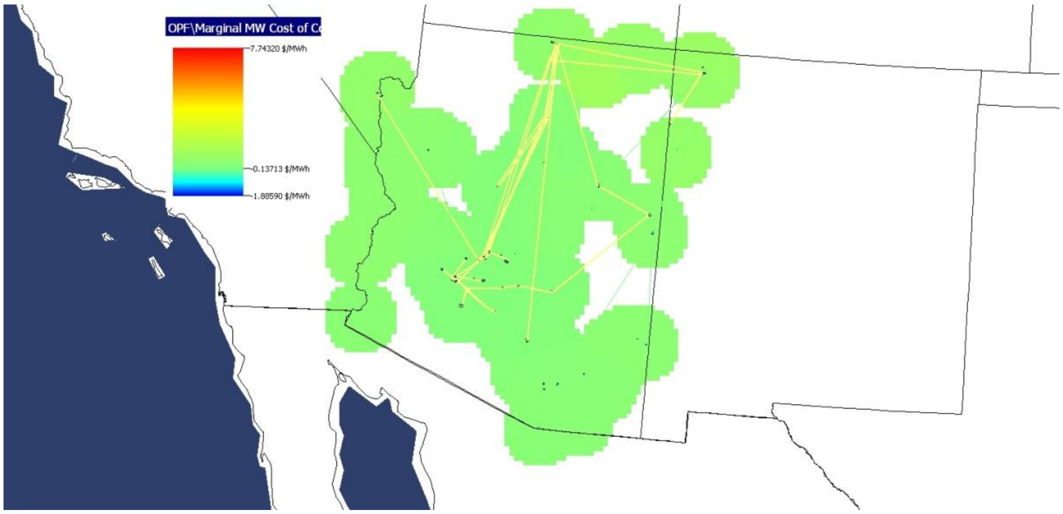
Week 1 of 2020



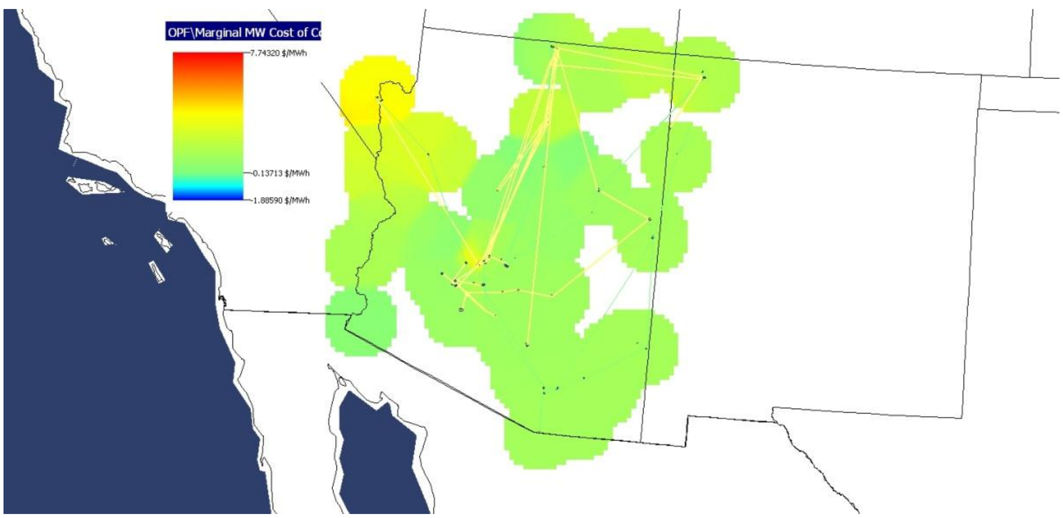
Week 8 of 2020



Week 23 of 2020



Week 46 of 2020



APPENDIX F

OPTIMIZATION MODEL INPUT DATA

Operational cost of generators based on fuel type

Type of generation	F	V_{OM}
Coal fired	0	1.642
Nuclear	0	2.485
NG (GT)	0	2.4787
NG (ST)	0	1.3077
NG (CT/CA)	0	0.94893
Hydro	0	1.287
Wind	0	0
Solar PV	0	0
Solar thermal	0	0

The transmission expansion costs per mile are shown below. The expansion costs were scaled assuming a 30 year life expectancy for the transmission lines and a 3% annual rate of interest. The scaled costs considered per scenario are also shown below.

Transmission line construction costs

Voltage level (kV)	Net present value (M$)	Scaled costs per scenario ($)
		r = 3%
500	2.5	1717.3
345	2	1288.0
230	1.5	858.7
69	1	343.5