Reduced-Order Model of ERCOT Transmission System

1 Introduction

The specific task of this project is to build a reduced order model (8-bus and then later on 200-bus) of the ERCOT Transmission System to enable power system studies like transmission planning, contingency analysis, etc. Building a reduced-order model of the transmission network could become an empirical anchor to the Integrated Transmission & Distribution Systems. Previous work by Overbye et al. [2, 3, 4, 5, 6, 7] has addressed the problem of building synthetic test cases to enable power system studies. However, these synthetic test cases are built for specific purposes like geomagnetic disturbance analysis, voltage stability, AC power flow, etc. We have approached the problem of developing synthetic test cases along the lines of Overbye et al.'s work with hybrid economic control studies as the objective.

This documentation is organized as follows: In section 2, an overview of Agent-based Modeling of Electricity Systems [1] (AMES) v3.1 is presented explaining various variables and parameters given as input by the user. Also, the integration of AMES with FNCS is briefly discussed. In section 3, the synthetic test case construction for the ERCOT region is described. Several steps such as obtaining the publicly available data, clustering the nodes, building the topology of the network and assigning physical parameters to the network are discussed in detail.

2 Agent-based Modeling of Electricity Systems (AMES)

2.1 Overview of AMES v3.1

The following is a brief overview of AMES v3.1:

- The AMES wholesale power market operates over an AC transmission grid for Max_Day (maximum no. of days) successive days, with each day D consisting of 24 successive hours H = $00, 01, \ldots, 23$.
- The AMES wholesale power market includes an Independent System Operator (ISO) and a collection of energy traders consisting of Load-Serving Entities (LSEs) and Generators distributed across the nodes of the transmission grid.
- AMES models fully operational two-settlement system that includes a daily 24-hour real-time market (RTM) as well as a daily day-ahead market (DAM), each separately settled by means of *locational marginal pricing*.

- The RTM is cleared by means of an ISO-managed SCED optimization, based on ISO load forecasts and Generation Company (GenCo) supply offers; it determines real-time dispatch levels and locational marginal prices (LMPs).

- The DAM is cleared by means of an ISO-managed SCED optimization; it determines a generation dispatch schedule and LMPs for next-day operations, based on Load Serving Entity (LSE) demand bids and GenCo supply offers.

- AMES is integrated with Framework for Network Co-Simulation (FNCS) in order to enable co-simulation of the Transactive Energy (TE) agents to establish and perform simulations within the Integrated Transmission and Distribution Test System (ITD v3.0)

Tables 1, 2, 3 and 4 refer to the exogenous and endogenous variables for the AMES Framework.

Table 1: Admissible Exogenous Variables for the AMES Framework - Structural Variables

Variable	Description	Admissibility Restrictions
K	Total number of transmission grid nodes	$K > 0$
N	Total number of distinct network branches	$N > 0$
I	Total number of Generators	$I > 0$
J	Total number of LSEs	$J > 0$
I_k	Set of Generators located at node k	$\text{Card}(\cup_{k=1}^{K} I_k) = I$
J_k	Set of LSEs located at node k	$\text{Card}(\cup_{k=1}^{K} J_k) = J$
S_o	Base apparent power (three-phase MVAs)	$S_o \geq 1$
V_o	Base voltage (line-to-line kVs)	$V_o > 0$
V_k	Voltage magnitude (kVs) at node k	$V_k = V_o,\ k = 1, \ldots, K$
p_{Lj}	Real power load (MWs) withdrawn by LSE j	$p_{Lj} \geq 0,\ j = 1, \ldots, J$
km	Branch connecting nodes k and m (if one exists)	$k \neq m$
BR	Set of all distinct branches km, $k < m$	$BR \neq \emptyset$
X_{km}	Reactance (ohms) for branch km	$X_{km} = X_{mk} > 0,\ km \in BR$
B_{km}	$[1/X_{km}]$ for branch km	$B_{km} = B_{mk} > 0,\ km \in BR$
P^U_{km}	Thermal limit (MWs) for real power flow on km	$P^U_{km} > 0,\ km \in BR$
δ_1	Reference node 1 voltage angle (radians)	$\delta_1 = 0$
π	Soft penalty weight for voltage angle differences	$\pi > 0$

Table 2: Admissible Exogenous Variables for the AMES Framework - Generator Costs

Variable	Description	Admissibility Restrictions
Money_i^o	Initial money holdings (\$) for Gen i	$\text{Money}_i^o > 0,\ i = 1, \ldots, I$
Cap_i^L	True lower production limit (MWs) for Gen i	$\text{Cap}_i^L \geq 0,\ i = 1, \ldots, I$
Cap_i^U	True upper production limit (MWs) for Gen i	$\text{Cap}_i^U > \text{Cap}_i^L,\ i = 1, \ldots, I$
a_i, b_i	True cost coefficients (\$/MWh, \$/MW^{2}h) for Gen i	$b_i > 0,\ i = 1, \ldots, I$
$\text{MC}_i(p)$	$\text{MC}_i(p) = a_i + 2b_ip$ = Gen i's true MC function	$\text{MC}_i(\text{Cap}_i^L) > 0,\ i = 1, \ldots, I$
FCost_i	Fixed costs (hourly prorated) for Gen i	$\text{FCost}_i \geq 0,\ i = 1, \ldots, I$

Table 3: Admissible Exogenous Variables for the AMES Framework - Generator Learning

Variable	Description	Admissibility Restrictions
M_i	Cardinality of the action domain AD_i for Gen i	$M_i \geq 1,\ i = 1, \ldots, I$
Mj_i	Integer-valued density-control parameter for AD_i	$\prod_{j=1}^3 Mj_i = M_i,\ i = 1, \ldots, I$
RIMax_i^L	Range-index parameter for AD_i construction	$\text{RIMax}_i^L \in [0, 1),\ i = 1, \ldots, I$
RIMax_i^U	Range-index parameter for AD_i construction	$\text{RIMax}_i^U \in [0, 1),\ i = 1, \ldots, I$
RIMin_i^C	Range-index parameter for AD_i construction	$\text{RIMin}_i^C \in (0, 1],\ i = 1, \ldots, I$
SS_i	Slope-start control parameter for AD_i construction	$SS_i > 0,\ i = 1, \ldots, I$
$q_i(0)$	Initial propensity (learning)	Any real value, $i = 1, \ldots, I$
C_i	Cooling parameter (learning)	$C_i > 0,\ i = 1, \ldots, I$
r_i	Recency parameter (learning)	$0 \leq r_i \leq 1,\ i = 1, \ldots, I$
e_i	Experimentation parameter (learning)	$0 \leq e_i < 1,\ i = 1, \ldots, I$

Table 4: Endogenous Variables for the AMES Framework

Variable	Description
p_{Gi}	Real power injection (MWs) by Gen $i = 1, \ldots, I$
δ_k	Voltage angle (radians) at node $k = 2, \ldots, K$
LMP_k	Locational marginal price (\$/MWh) at node $k = 1, \ldots, K$
P_{km}	Real power (MWs) flowing in branch $km \in$ BR
PGen_k	Total real power injection (MWs) at node $k = 1, \ldots, K$
PLoad_k	Total real power withdrawal (MWs) at node $k = 1, \ldots, K$
PNetInject_k	Total net real power injection (MWs) at node $k = 1, \ldots, K$
Profit_i	Realized profit (\$/h) for Gen $i = 1, \ldots, I$
Money_i	Cumulative money holdings (\$) for Gen $i = 1, \ldots, I$
Cap_i^{RL}	Reported lower production limit (MWs) for Gen $i = 1, \ldots, I$
Cap_i^{RU}	Reported upper production limit (MWs) for Gen $i = 1, \ldots, I$
a_i^R, b_i^R	Reported cost coefficients (\$/MWh, \$/MW^{2}h) for Gen $i = 1, \ldots, I$

2.2 Integration with FNCS

Brief Overview of FNCS

FNCS [9] API is used to develop an interface for any simulator (modeled either in Python/Java) to establish communication with other simulators. The synchronization for message passing among all the simulators is handled by FNCS. As AMES is developed using Java programming language, JNIfncs library is used to create an interface to AMES, in order to communicate with other agents. This library has the function JNIfncs.initialize to initialize the AMES with time = 0, JNIfncs.publish and JNIfncs.get_events functions to send and receive messages, JNIfncs.time_request to request time step from FNCS and stop to stop the simulator with respect to FNCS. In this way, JNIFncs library enables any java-based program/agent to establish communication with other simulators through FNCS.

Integration

The JNIfncs library functions are added at appropriate locations inside AMES source files to send/receive messages through FNCS. Specifically:

- In AMESFrame.java - to initialize and finalize the FNCS agent
- In AMESMarket.java - to synchronize with the timer within AMES i.e., the JNIfncs.time_request is synchronized with that of the hour (h) and day (d) variables in AMES
- In LSEAgent.java - to receive load forecasts for Day-Ahead Market through external load forecasting agent (loadforecast.py)

- In BUC.java - to receive load forecasts for Real-Time Market through external load forecasting agent

3 ERCOT Synthetic Test Case Construction

3.1 ERCOT Data

Generator Data

The generator data (2016) is obtained from the U.S. Energy Information Administration (EIA) [12]. The data files obtained from the EIA contains various generators, utilities and plants information in the US. This vast data is then processed to obtain the generators which are located in the ERCOT region of Texas for our purposes. The following is a brief summary of the data obtained from EIA as of 2016:

- There are 1040 generators in Texas state, of which 834 generators are located in the ERCOT region
- Each generator has a location (latitude and longitude) associated with it, along with the nameplate capacity and the fuel type
- The generation capacity proportions by fuel type in ERCOT is shown in the figure 1
- Of 834 generators, there are 630 generators with the following major fuel types (by percentage):
    1. Natural Gas Fired Combined Cycle - 37.3%
    2. Natural Gas Steam Turbine - 13.25%
    3. Natural Gas Fired Combustion Turbine - 6.8%
    4. Natural Gas Internal Combustion Engine - 0.5%
    5. Conventional Steam Coal - 20.37%
    6. Onshore Wind Turbine - 15.15%
    7. Nuclear - 4.77%
    8. Solar Photovoltaic - 0.53%
    9. Conventional Hydroelectric - 0.5%
- The thermal generation is approximately 83% of the total generation
- Non-dispatchable generation can be considered as negative load in the test case construction i.e., Net load = Load - Non-dispatchable Generation

The dispatch cost function for each generator g is modeled as follows:

$$C_{P,g} = a_g p_g + b_g [p_g]^2 \tag{1}$$

The cost coefficients a_g and b_g were derived from Dheepak et al.'s [8] work on 8-bus test system for ISO-NE.

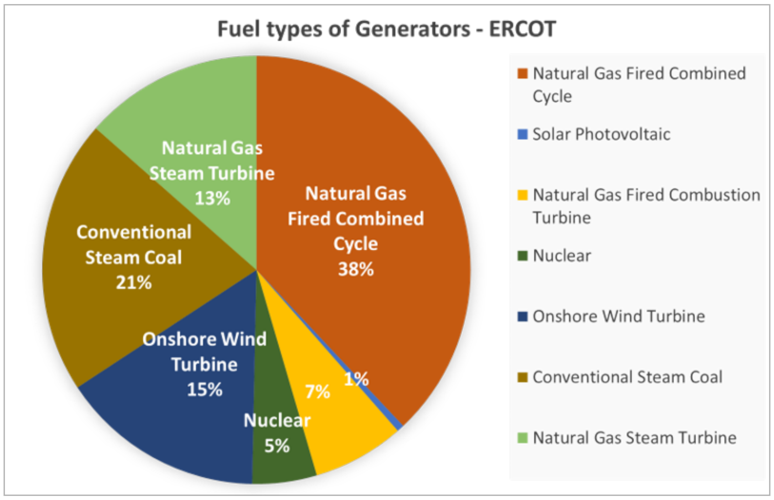

Figure 1: Generation Capacity proportions by fuel type in ERCOT

Load Data

Load data is constructed approximately based on the historical load profiles (available by weather zones) [10] and the population information obtained from the 2010 U.S. Census data [11]. An average (over the year) per capita load consumption is calculated for the eight weather zones of ERCOT as shown in Table 5. Initially, each ZIP Code is considered to be a load node. Load at each ZIP Code is therefore computed by multiplying the population of the ZIP Code with the per Capita load consumption of the corresponding weather zone.

Table 5: Power Consumption Per Capita by Weather Zone

Weather Zone	Per-capita consumption (kW)	Weather Zone	Per-capita consumption (kW)
COAST	2.362	NORTH	1.859
EAST	1.563	SCENT	2.045
FWEST	1.854	SOUTH	1.843
NCENT	2.438	WEST	2.368

The Figure 2 depicts the data collected for generator nodes and the data computed for the load type nodes. Here red circles represent the load nodes and the other color circles represent the generator nodes with different fuel types.

3.2 Clustering Algorithm

Algorithm description. A modified hierarchical clustering algorithm is used to cluster the Generation and Load Nodes into three types i.e., load cluster, generation cluster, and Hybrid Cluster.

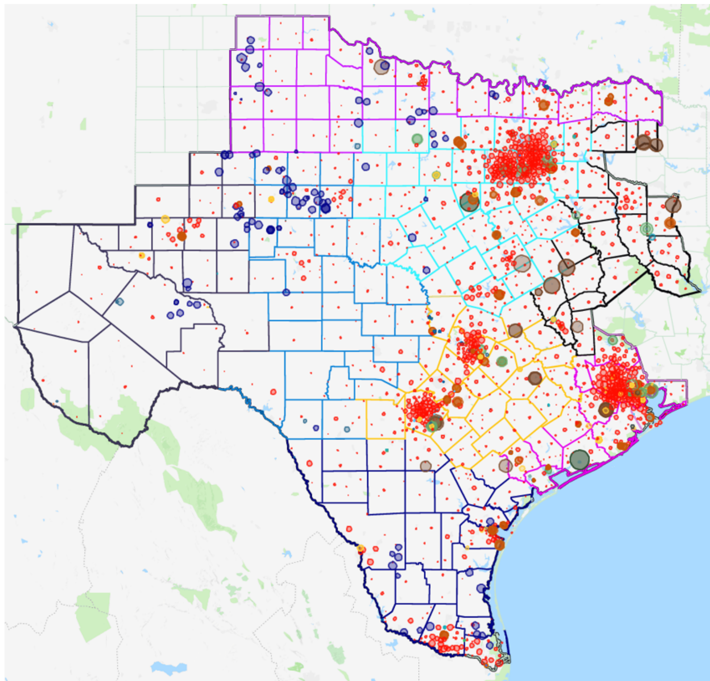

Figure 2: Load and Generation nodes in ERCOT

Algorithm 1: `Modified Hierarchical Clustering Algorithm`

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1. Start with N = N_g + N_l clusters (c_1, c_2, ... c_N) each consisting of either a single generator or a single load
2. Combine a pair of clusters c_i and c_j with minimum distance amongst all pairwise distances to form a new cluster c_{ij}
3. Update the coordinates of cluster c_{ij} as weighted (by generation capacities) average of the coordinates of its members
4. Update total generation capacity of cluster c_{ij} as sum of the generation capacities of its members
5. Remove the clusters c_i and c_j. Update the pairwise distances between the reduced number of clusters
6. Repeat 2-5 until the required number of generator clusters are formed

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In the above clustering algorithm, note that the generators and load nodes are clustered together without any constraints and therefore are allowed to form hybrid clusters (i.e., both generation and load cluster).

3.3 Transmission Line

3.3.1 Transmission Line Topology

For the 8 bus transmission system, in theory there could be 23 transmission lines to completely connect the transmission system (i.e., 23 edges to complete the 8 node graph). However, from statistical analysis of the number of transmission lines, it is found to be a constant multiple of the number of nodes/buses in the network. Therefore, not all lines are needed to build the synthetic network.

Delaunay triangulation is one of the triangulation methods known to be close to give the lines that are highly overlapped with that of the real transmission lines according to Birchfield et al. For a simple test case like 8 bus case for ERCOT, it can be adopted without using any additional algorithms from graph theory. We have therefore chosen the transmission lines from the Delaunay triangulation to build the topology of the 8-bus transmission system.

3.3.2 Transmission Line Parameters

For the 8-bus ERCOT test case, only 345 kV transmission lines are used. Therefore, the transmission line parameters are chosen according to this voltage level. The line impedance per mile is taken to be 0.584 ohm (by considering a Cardinal conductor with 2 conductor bundling with conductor spacing of 1.5 ft. per bundle).These parameters are taken from [2].

3.4 8-Bus Transmission System for ERCOT

For N = 8, the load and generator nodes are clustered using the clustered algorithm mentioned in Algorithm 1. After the nodes/buses are obtained, delaunay triangulation is applied to build the topology for the 8-bus transmission system. The resultant transmission system is depicted in the figures 3 and 4.

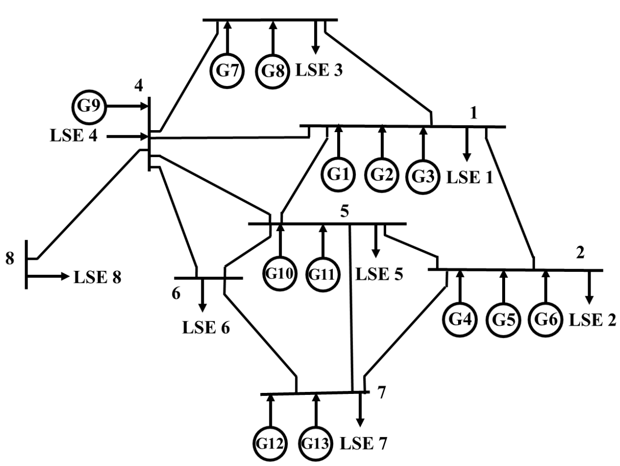

Figure 3: 8-Bus Transmission Grid

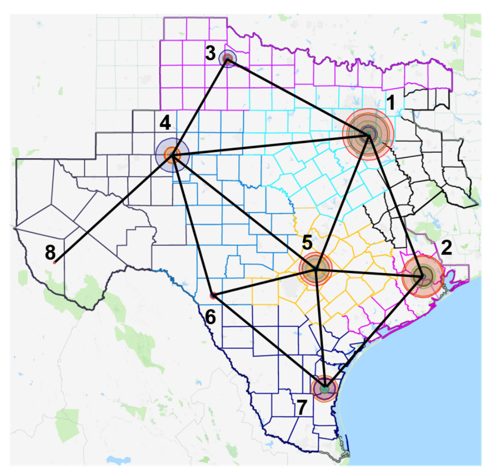

Figure 4: 8 Bus Test Case of ERCOT

3.4.1 GenCo and LSE Data

GenCo

- For the 8-bus test case, only thermal generation (83%) is considered. Although the non-dispatchable generation could be modeled as negative load, AMES is not capable of handling negative net load at the LSE's.
- The generator cost curves' coefficients are taken to be as shown in the Table 6
- In total, there are 13 GenCos in ERCOT (each with a different fuel type at a bus) with their locations, capacities and their cost coefficients as shown in Table 7

Table 6: Generator Cost-Curves for the 8-Bus Test Case

Generator Fuel Type	a ($/MWh)	b($/$MW^2h$)
Natural Gas	40	0.005
Coal	19	0.005
Nuclear	8	0.00019

Table 7: Generator Data for the 8-Bus Test Case

Name	At Bus	Generator Type	a	b	Cap^L	Cap^U
GenCo1	1	Natural Gas	40	0.005	0	19,978.8
GenCo2	1	Coal	19	0.005	0	11664.8
GenCo3	1	Nuclear	8	0.00019	0	2430.0
GenCo4	2	Natural Gas	40	0.005	0	20,761.69
GenCo5	2	Coal	19	0.005	0	3190.3
GenCo6	2	Nuclear	8	0.00019	0	2708.6
GenCo7	3	Natural Gas	40	0.005	0	80
GenCo8	3	Coal	19	0.005	0	720
GenCo9	4	Natural Gas	40	0.005	0	3438.2
GenCo10	5	Natural Gas	40	0.005	0	10589.7
GenCo11	5	Coal	19	0.005	0	5728.1
GenCo12	7	Natural Gas	40	0.005	0	7385.0
GenCo13	7	Coal	19	0.005	0	622.4

LSE Data

- Each bus in the 8-bus transmission system is considered to have an LSE entity, representing the load consumption
- Each LSE can submit a 24-hour Day-Ahead Market demand bids in either Fixed Demand bid or Price-Sensitive Demand bid or both
- For the 8-bus test case, each LSE is assumed to submit a fixed demand bid for the DAM operations
- Historical load profiles dated 04/28/2018 are considered as the load profile data for the LSEs to make a forecast on the following day i.e., on 04/29/2018

Table 8: LSE Fixed Demand Bid

Name	Bus	H-00	H-01	H-02	H-03	H-04	H-05	H-06	H-07
LSE1	1	10168.91	9560.41	9162.96	8951.62	8966.74	9243.79	9707.37	10200.05
LSE2	2	10609.49	10130.78	9823.78	9669.55	9574.93	9668.12	9928.59	10158.56
LSE3	3	252.21	243.71	239.88	240.38	242.88	249.87	256.78	266.58
LSE4	4	3067.03	3004.96	2979.83	2971.99	2956.48	2974.59	3012.23	3034.82
LSE5	5	5122.12	4779.23	4600.74	4481.19	4451.58	4510.64	4720.72	4878.95
LSE6	6	329.36	315.95	308.06	303.93	301.28	305.23	312.44	319.34
LSE7	7	4371.46	4137.38	3982.46	3906.68	3856.37	3896.78	4007.57	4081.97
LSE8	8	99.59	97.91	97.30	97.24	96.72	97.00	97.97	98.10
Name	Bus	H-08	H-09	H-10	H-11	H-12	H-13	H-14	H-15
LSE1	1	10930.74	11502.83	11990.15	12392.66	12783.36	13233.04	13799.71	14379.07
LSE2	2	10686.87	11282.58	11928.66	12497.71	13031.79	13618.55	14177.62	14643.48
LSE3	3	276.83	283.88	286.93	290.47	294.47	301.39	309.22	318.62
LSE4	4	3099.12	3155.68	3222.93	3299.02	3343.73	3409.14	3488.62	3533.64
LSE5	5	5236.73	5604.26	5947.02	6231.92	6502.99	6767.29	7065.99	7308.35
LSE6	6	332.88	345.71	360.26	372.45	382.97	393.83	405.15	415.88
LSE7	7	4286.84	4511.23	4757.32	4959.20	5116.37	5256.40	5393.67	5533.11
LSE8	8	99.65	101.14	102.94	105.27	106.26	107.95	110.14	110.95
Name	Bus	H-16	H-17	H-18	H-19	H-20	H-21	H-22	H-23
LSE1	1	14911.46	15167.50	14967.62	14421.21	14115.51	13649.33	12682.31	11671.62
LSE2	2	14874.98	14847.61	14462.77	13809.82	13539.55	13120.42	12423.70	11605.80
LSE3	3	326.55	331.57	331.62	321.10	317.11	312.21	294.56	274.56
LSE4	4	3611.84	3633.37	3634.41	3576.88	3514.78	3484.40	3382.54	3271.74
LSE5	5	7520.95	7603.62	7500.91	7233.92	7045.46	6780.70	6340.00	5820.73
LSE6	6	424.66	427.50	422.80	409.43	403.35	394.25	375.51	354.10
LSE7	7	5624.90	5645.97	5531.89	5313.97	5277.70	5142.94	4912.60	4618.83
LSE8	8	113.26	113.78	113.96	112.57	110.81	110.33	107.98	105.33

3.4.2 Input variables considered for the 8-bus test case

The following variables are considered as inputs for the 8-bus test case:

- Base Voltage, Power
- Max_Day (is set to be 3)
- Node Data, Penalty Weight
- Branch Data with max capacity, reactances
- Generator Data with FCost (ignored, initialized with 0), a, b, cap^L, cap^U, InitMoney
- LSE Fixed Demand Data
- LSE Price Sensitive Data (Not being used, added to avoid exception)
- LSE Hybrid Demand Flags - These are set to 1, which implies that only fixed demand data is considered
- Generator learning parameters are set to default. However, all M1 and M2 variables need to be set to 1 to turn off the learning

3.4.3 Transmission Line Parameters

The following Table 9 refers to the transmission line parameters of the 8-bus test case:

Table 9: 8-Bus Test Case - Branch Data

Branch From	To	lineCap	X(ohms)	Length (Miles)
1	2	1000.0	122.3124	209.4390
1	3	1000.0	125.6020	215.0720
1	4	1000.0	156.4805	267.9461
1	5	1000.0	116.1924	198.9595
2	5	1000.0	87.7518	150.2599
2	7	1000.0	123.4350	211.3613
3	4	1000.0	87.2334	149.3723
4	5	1000.0	147.8132	253.1047
4	6	1000.0	118.7483	203.3361
4	8	1000.0	126.8891	217.2758
5	6	1000.0	84.1587	144.1073
5	7	1000.0	98.6619	168.9416
6	7	1000.0	118.0990	202.2244

Refer section 3.3.2 for the transmission line parameters (per-unit values) of the 8-bus test case

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