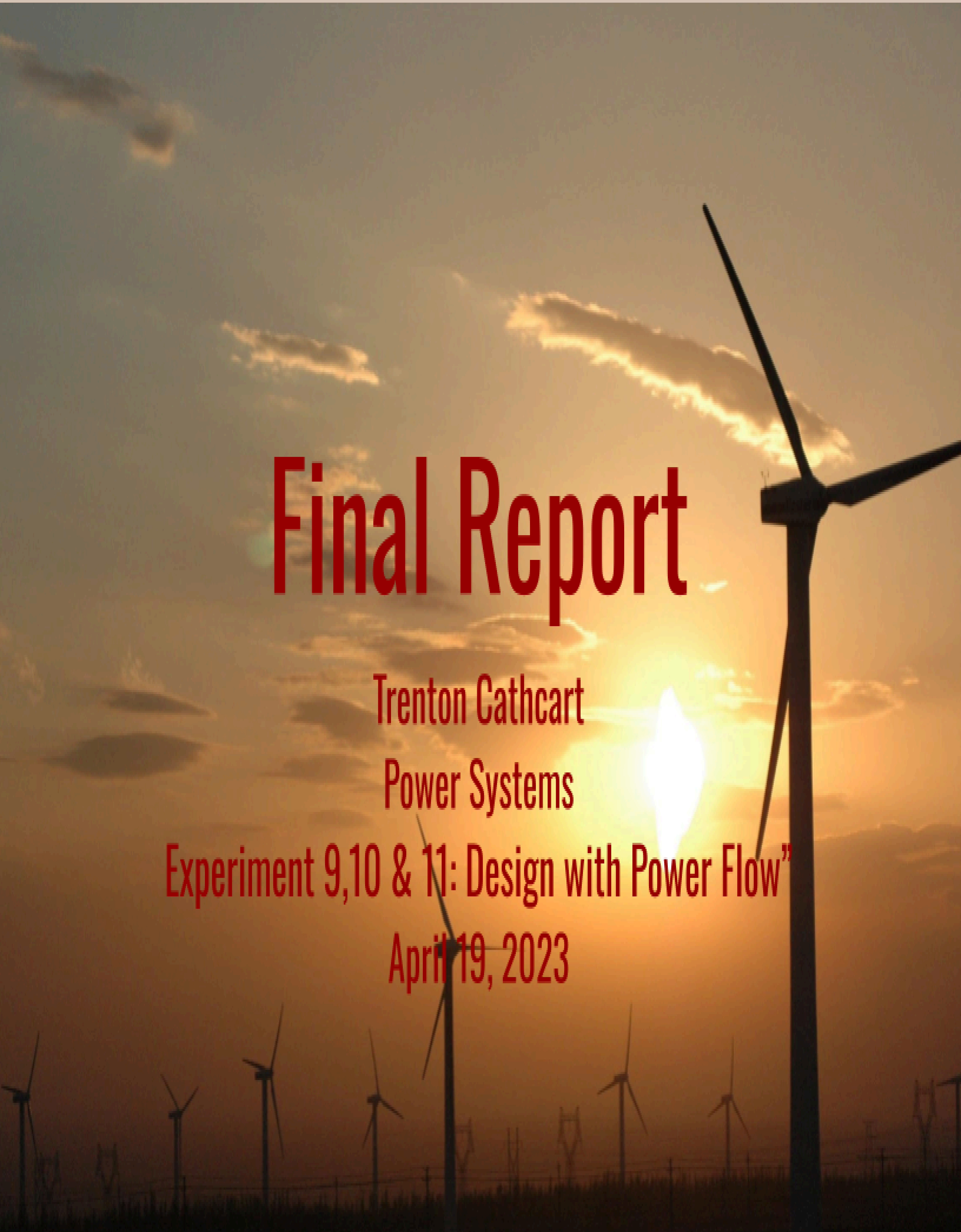

Final Report

Trenton Cathcart

Power Systems

Experiment 9,10 & 11: Design with Power Flow”

April 19, 2023

EE3541
Trenton Cathcart
Date: 04/19/2023

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III. Objectives:

The objective of this project is to perform a thorough analysis and develop an optimal design for connecting a new 200 MW wind farm to the existing power grid while minimizing cost and maintaining the reliability of the power system. To achieve this objective, the project focuses on evaluating various combinations of buses for connecting the wind farm to the existing 69 kV substations and identifying the optimal right-of-way line that minimizes energy losses and adheres to the given security constraints. By leveraging advanced features of the PowerWorld Simulator and employing a systematic approach to analyzing power flow, contingency scenarios, and system reinforcements, the project aims to arrive at a cost-effective and reliable solution for integrating the new wind farm into the power system.

IV. Equipment Used:

- PowerWorld Simulator: A software tool used for power flow analysis, contingency analysis, and system optimization in the transmission planning process.

V. Background Theory:

The power transmission system is a critical component of the electrical grid, responsible for the efficient and reliable transfer of electricity from generation plants to distribution networks that ultimately deliver power to consumers. High voltage transmission systems offer several advantages, including reduced energy losses, lower construction costs per unit of power, and efficient long-distance power transfer. However, the transmission capacity in the US has been decreasing due to factors such as aging infrastructure, regulatory and permitting challenges, and insufficient investment in transmission infrastructure. Since the mid-1990s, transmission planning has evolved to address these challenges and adapt to new priorities, such as the increased emphasis on renewable energy integration and the effects of deregulation and competition on the power industry. Power flow analysis is a crucial part of transmission planning, as it provides insights into the power transfer between buses, line loading, and voltage levels under various operating conditions. This information is essential for making informed decisions on system upgrades, reinforcements, and new capacity additions, ensuring the continued reliability and efficiency of the power grid. In this project, we aim to apply the principles of power flow analysis and transmission planning to design a cost-effective solution for integrating a new 200 MW wind farm into the existing power grid while maintaining system reliability and adhering to the given security constraints.

VI. Preliminary Calculations:

No preliminary calculations required

VII. Procedure/Result/Analysis:

I. PowerWorld Simulations:

In the PowerWorld simulations, a total of 64 different cases were analyzed to determine the best combination of buses for connecting the new 200 MW wind farm to the existing 69 kV substations. Each combination was thoroughly tested to ensure compliance with the given security constraints, such as no errors, no overloading of PU, not exceeding 100% of their limit values, and not surpassing the generators' reactive power limits. The Contingency Analysis tool was utilized to perform these tests and evaluate the performance of each combination under various operating conditions. Out of the 64 cases analyzed, only 6 met all the requirements and passed the security constraints. An example of an ideal contingency output can be observed in **Figure 1** below. To further compare these combinations, the system MWh losses for each case were determined using the 'Run' command in PowerWorld. A comprehensive list of the combinations and their corresponding losses can be found in **Table 1** below. After examining the losses and other factors, the PAI and TIM69 bus combination was identified as the most optimal choice, as it exhibited the lowest losses and zero resistance. This selection allowed for further investigation into minimizing costs while maintaining system reliability and adhering to the given security constraints.

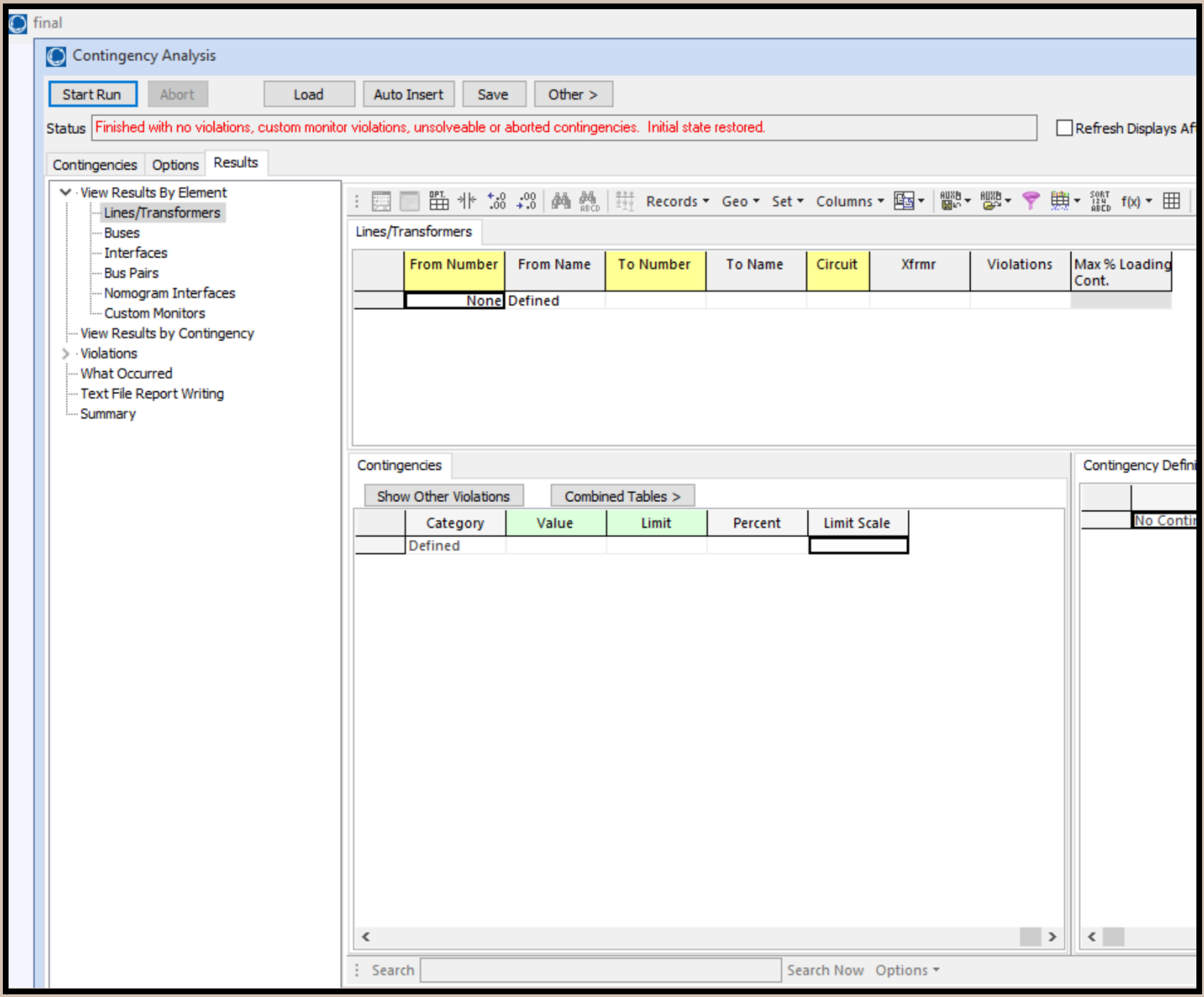

Figure 1: Ideal Contingency Analysis Output

ATTEMPTS	L1	L2	LOSS	VIOLATIONS
5	PAI	TIM69	8.35	0
7	PAI	RAY	11.08	0
8	PAI	ZEB	10.58	0
41	TIM69	PAI	8.36	0
42	TIM69	PETE	7.9	0
53	RAY	TIM69	8.4	0

Table 1: Successful Bus Combinations

II. Optimization:

In order to optimize the design and minimize costs, the inbuilt PU calculator within PowerWorld and the supplied ASCR table were utilized to determine the values of Ra and Xa per mile for each line composition (Drake, Cardinal, Pheasant, and Falcon) and their respective distances to the buses. As these were short lines, they did not have any capacitive reactances. The Ra and Xa values were retrieved from the ACSR table (**Figure 2**) and entered into the PU calculator. The final calculations for all combinations can be seen in **Table 2**.

TABLE A.4 Characteristics of aluminum cable, steel, reinforced (Aluminum Company of America)—ACSR

Code Word	Circular Mils Aluminum	Aluminum			Steel		Outside Diameter (inches)	Copper Equivalent* Circular Mils or A W G	Ultimate Strength (pounds)	Weight (pounds per mile)	Geometric Mean Radius at 60 Hz (feet)	Approx. Current Carrying Capacity† (amps)	r_a Resistance (Ohms per Conductor per Mile) 25°C (77°F) Small Currents				50°C (122°F) Current Approx 75% Capacity‡				x_a Inductive Reactance (ohms per conductor per mile at 1 ft spacing all currents)	x'_a Shunt Capacitive Reactance (megohms per conductor per mile at 1 ft spacing)
				Strand Diameter (inches)		Strand Diameter (inches)							dc	25 Hz	50 Hz	60 Hz	dc	25 Hz	50 Hz	60 Hz	60 Hz	60 Hz
Joree	2 515 000	76		0.1819	19	0.0849	1.880		61 700		0.0621									0.0450	0.337	0.0755
Thrasher	2 312 000	76		0.1744	19	0.0814	1.802		57 300		0.0595									0.0482	0.342	0.0767
Kiwi	2 167 000	72	4	0.1735	7	0.1157	1.735		49 800		0.0570									0.0511	0.348	0.0778
Bluebird	2 156 000	84	4	0.1602	19	0.0961	1.762		60 300		0.0588									0.0505	0.344	0.0774
Chukar	1 781 000	84	4	0.1456	19	0.0874	1.602		51 000		0.0534									0.0598	0.355	0.0802
Falcon	1 590 000	54	3	0.1716	19	0.1030	1.545	1 000 000	56 000	10 777	0.0520	1 380	0.0587	0.0588	0.0590	0.0591	0.0646	0.0656	0.0675	0.0684	0.359	0.0814
Parrot	1 510 500	54	3	0.1673	19	0.1004	1.506	950 000	53 200	10 237	0.0507	1 340	0.0618	0.0619	0.0621	0.0622	0.0680	0.0690	0.0710	0.0720	0.362	0.0821
Plover	1 431 000	54	3	0.1628	19	0.0977	1.465	900 000	50 400	9 699	0.0493	1 300	0.0652	0.0653	0.0655	0.0656	0.0718	0.0729	0.0749	0.0760	0.365	0.0830
Martin	1 351 000	54	3	0.1582	19	0.0949	1.424	850 000	47 600	9 160	0.0479	1 250	0.0691	0.0692	0.0694	0.0695	0.0761	0.0771	0.0792	0.0803	0.369	0.0838
Pheasant	1 272 000	54	3	0.1535	19	0.0921	1.382	800 000	44 800	8 621	0.0465	1 200	0.0734	0.0735	0.0737	0.0738	0.0808	0.0819	0.0840	0.0851	0.372	0.0847
Grackle	1 192 500	54	3	0.1486	19	0.0892	1.338	750 000	43 100	8 082	0.0450	1 160	0.0783	0.0784	0.0786	0.0788	0.0862	0.0872	0.0894	0.0906	0.376	0.0857
Finch	1 113 000	54	3	0.1436	19	0.0862	1.293	700 000	40 200	7 544	0.0435	1 110	0.0839	0.0840	0.0842	0.0844	0.0924	0.0935	0.0957	0.0969	0.380	0.0867
Curlew	1 033 500	54	3	0.1384	7	0.1384	1.246	650 000	37 100	7 019	0.0420	1 060	0.0903	0.0905	0.0907	0.0909	0.0994	0.1005	0.1025	0.1035	0.385	0.0878
Cardinal	954 000	54	3	0.1329	7	0.1329	1.196	600 000	34 200	6 479	0.0403	1 010	0.0979	0.0980	0.0981	0.0982	0.1078	0.1088	0.1118	0.1128	0.390	0.0890
Canary	900 000	54	3	0.1291	7	0.1291	1.162	566 000	32 300	6 117	0.0391	970	0.104	0.104	0.104	0.104	0.1145	0.1155	0.1175	0.1185	0.393	0.0898
Crane	874 500	54	3	0.1273	7	0.1273	1.146	550 000	31 400	5 940	0.0386	950	0.107	0.107	0.107	0.108	0.1178	0.1188	0.1218	0.1228	0.395	0.0903
Condor	795 000	54	3	0.1214	7	0.1214	1.093	500 000	28 500	5 399	0.0368	900	0.117	0.118	0.118	0.119	0.1288	0.1308	0.1358	0.1378	0.401	0.0917
Drake	795 000	26	2	0.1749	7	0.1360	1.108	500 000	31 200	5 770	0.0375	900	0.117	0.117	0.117	0.117	0.1288	0.1288	0.1288	0.1288	0.399	0.0912
Mallard	795 000	30	2	0.1628	19	0.0977	1.140	500 000	38 400	6 517	0.0393	910	0.117	0.117	0.117	0.117	0.1288	0.1288	0.1288	0.1288	0.393	0.0904
Crow	715 500	54	3	0.1151	7	0.1151	1.036	450 000	26 300	4 859	0.0349	830	0.131	0.131	0.131	0.132	0.1442	0.1452	0.1472	0.1482	0.407	0.0932
Starling	715 500	26	2	0.1659	7	0.1290	1.051	450 000	28 100	5 193	0.0355	840	0.131	0.131	0.131	0.131	0.1442	0.1442	0.1442	0.1442	0.405	0.0928
Redwing	715 500	30	2	0.1544	19	0.0926	1.081	450 000	34 600	5 865	0.0372	840	0.131	0.131	0.131	0.131	0.1442	0.1442	0.1442	0.1442	0.399	0.0920
Flamingo	666 600	54	3	0.1111	7	0.1111	1.000	419 000	24 500	4 527	0.0337	800	0.140	0.140	0.141	0.141	0.1541	0.1571	0.1591	0.1601	0.412	0.0943
Rook	636 000	54	3	0.1085	7	0.1085	0.977	400 000	23 600	4 319	0.0329	770	0.147	0.147	0.148	0.148	0.1618	0.1638	0.1678	0.1688	0.414	0.0950
Grosbeak	636 000	26	2	0.1564	7	0.1216	0.990	400 000	25 000	4 616	0.0335	780	0.147	0.147	0.147	0.147	0.1618	0.1618	0.1618	0.1618	0.412	0.0946
Egret	636 000	30	2	0.1456	19	0.0874	1.019	400 000	31 500	5 213	0.0351	780	0.147	0.147	0.147	0.147	0.1618	0.1618	0.1618	0.1618	0.406	0.0937
Peacock	605 000	54	3	0.1059	7	0.1059	0.953	380 500	22 500	4 109	0.0321	750	0.154	0.155	0.155	0.155	0.1695	0.1715	0.1755	0.1775	0.417	0.0957
Squab	605 000	26	2	0.1525	7	0.1186	0.966	380 500	24 100	4 391	0.0327	760	0.154	0.154	0.154	0.154	0.1700	0.1720	0.1720	0.1720	0.415	0.0953
Dove	556 500	26	2	0.1463	7	0.1138	0.927	350 000	22 400	4 039	0.0313	730	0.168	0.168	0.168	0.168	0.1849	0.1859	0.1859	0.1859	0.420	0.0965
Eagle	556 500	30	2	0.1362	7	0.1362	0.953	350 000	27 200	4 588	0.0328	730	0.168	0.168	0.168	0.168	0.1849	0.1859	0.1859	0.1859	0.415	0.0957
Hawk	477 000	26	2	0.1355	7	0.1054	0.858	300 000	19 430	3 462	0.0290	670	0.196	0.196	0.196	0.196	0.216				0.430	0.0988
Hen	477 000	30	2	0.1261	7	0.1261	0.883	300 000	23 300	3 933	0.0304	670	0.196	0.196	0.196	0.196	0.216				0.424	0.0980
Ibis	397 500	26	2	0.1236	7	0.0961	0.783	250 000	16 190	2 885	0.0265	590	0.235				0.259				0.441	0.1015
Lark	397 500	30	2	0.1151	7	0.1151	0.806	250 000	19 980	3 277	0.0278	600	0.235		Same as dc		0.259		Same as dc		0.435	0.1006
Linnet	336 400	26	2	0.1138	7	0.0856	0.721	4/0	14 050	2 442	0.0244	530	0.278				0.306				0.451	0.1039
Oriole	336 400	30	2	0.1059	7	0.1059	0.741	4/0	17 040	2 774	0.0255	530	0.278				0.306				0.445	0.1032
Ostrich	300 000	26	2	0.1074	7	0.0835	0.680	188 700	12 650	2 178	0.0230	490	0.311				0.342				0.458	0.1057
Piper	300 000	30	2	0.1000	7	0.1000	0.700	188 700	15 430	2 473	0.0241	500	0.311				0.342				0.462	0.1049
Partridge	266 800	26	2	0.1013	7	0.0788	0.642	3/0	11 250	1 936	0.0217	460	0.350				0.385				0.465	0.1074

Figure 2: ACSR Table

Cost	$625,000				Cost	$750,000		
Miles	Drake	PU Ra	PU Xa		Miles	Cardinal	PU Ra	PU Xa
6	PAI	0.016232	0.050284		6	PAI	0.014216	0.049149
7.4	PETE	0.020019	0.062016		7.4	PETE	0.017532	0.060618
12	DEMAR	0.032464	0.100567		12	DEMAR	0.028431	0.098299
4.5	GROSS	0.012174	0.037713		4.5	GROSS	0.010662	0.036862
11.2	HISKY	0.0303	0.093863		11.2	HISKY	0.026536	0.091745
13	Tim	0.035169	0.108948		13	Tim	0.0308	0.10649
15	RAY	0.04058	0.125709		15	RAY	0.035539	0.122873
11	ZEB	0.029758	0.092187		11	ZEB	0.026062	0.090107
Cost	$825,000				Cost	$900,000		
Miles	Pheasant	PU Ra	PU Xa		Miles	Falcon	PU Ra	PU Xa
6	PAI	0.010725	0.046881		6	PAI	0.00862	0.045243
7.4	PETE	0.013227	0.05782		7.4	PETE	0.010631	0.055799
12	DEMAR	0.021449	0.093762		12	DEMAR	0.01724	0.090485
4.5	GROSS	0.008043	0.035161		4.5	GROSS	0.006465	0.033932
11.2	HISKY	0.020019	0.087511		11.2	HISKY	0.016091	0.084453
13	Tim	0.023237	0.101575		13	Tim	0.018677	0.098026
15	RAY	0.026812	0.117202		15	RAY	0.02155	0.113106
11	ZEB	0.019662	0.085948		11	ZEB	0.015803	0.082945

Table 2: PU Bus Values

The PU values were then input into the simulation to calculate the new total power losses for the selected PAI & TIM69 combination. Examples of these PU entries for the TIM PAI combination can be observed in **Figures 3 & 4**. The PowerWorld output for the Drake line is shown in **Figure 5.**

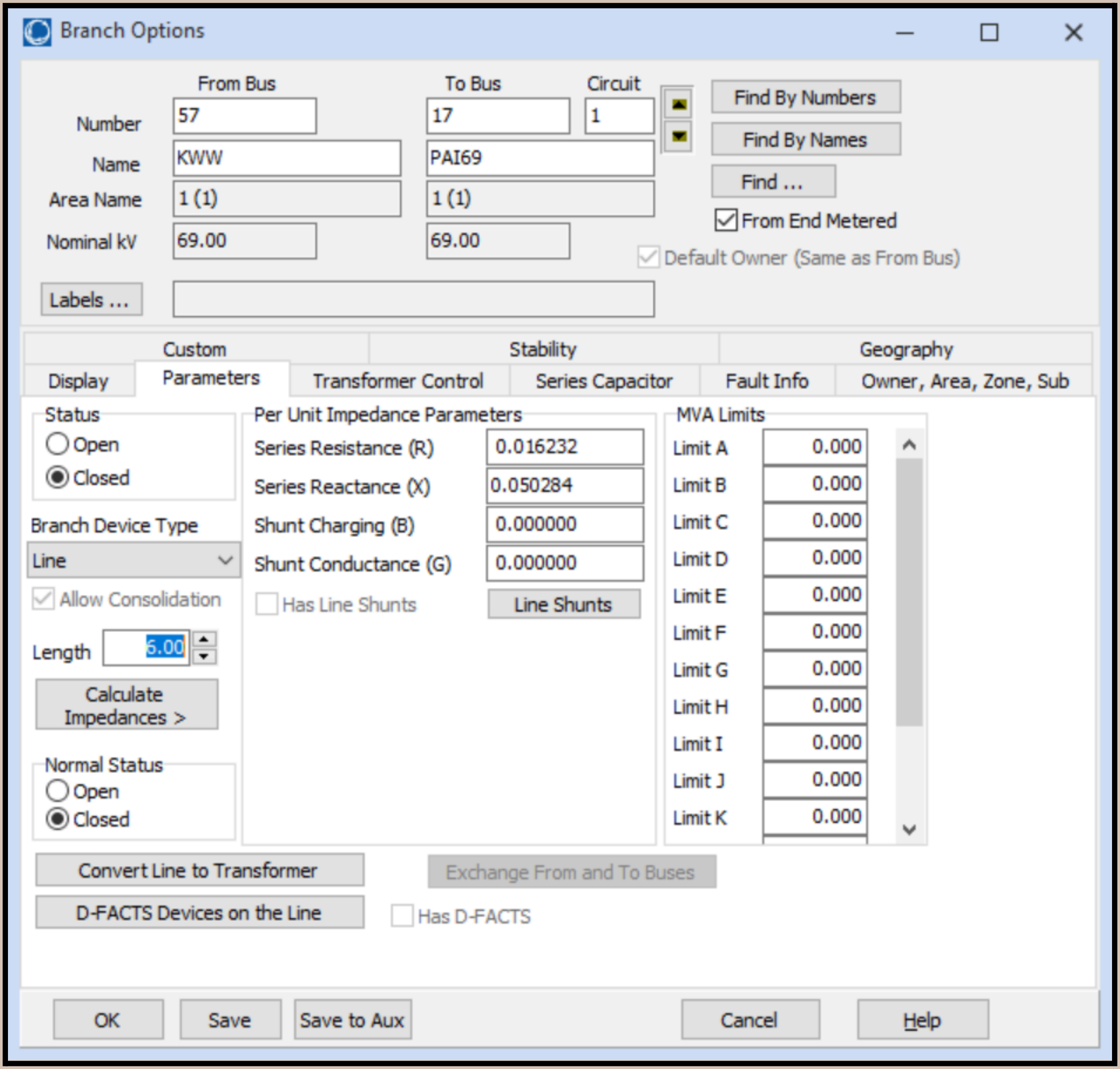

Figure 3: PAI69 PU Calculation

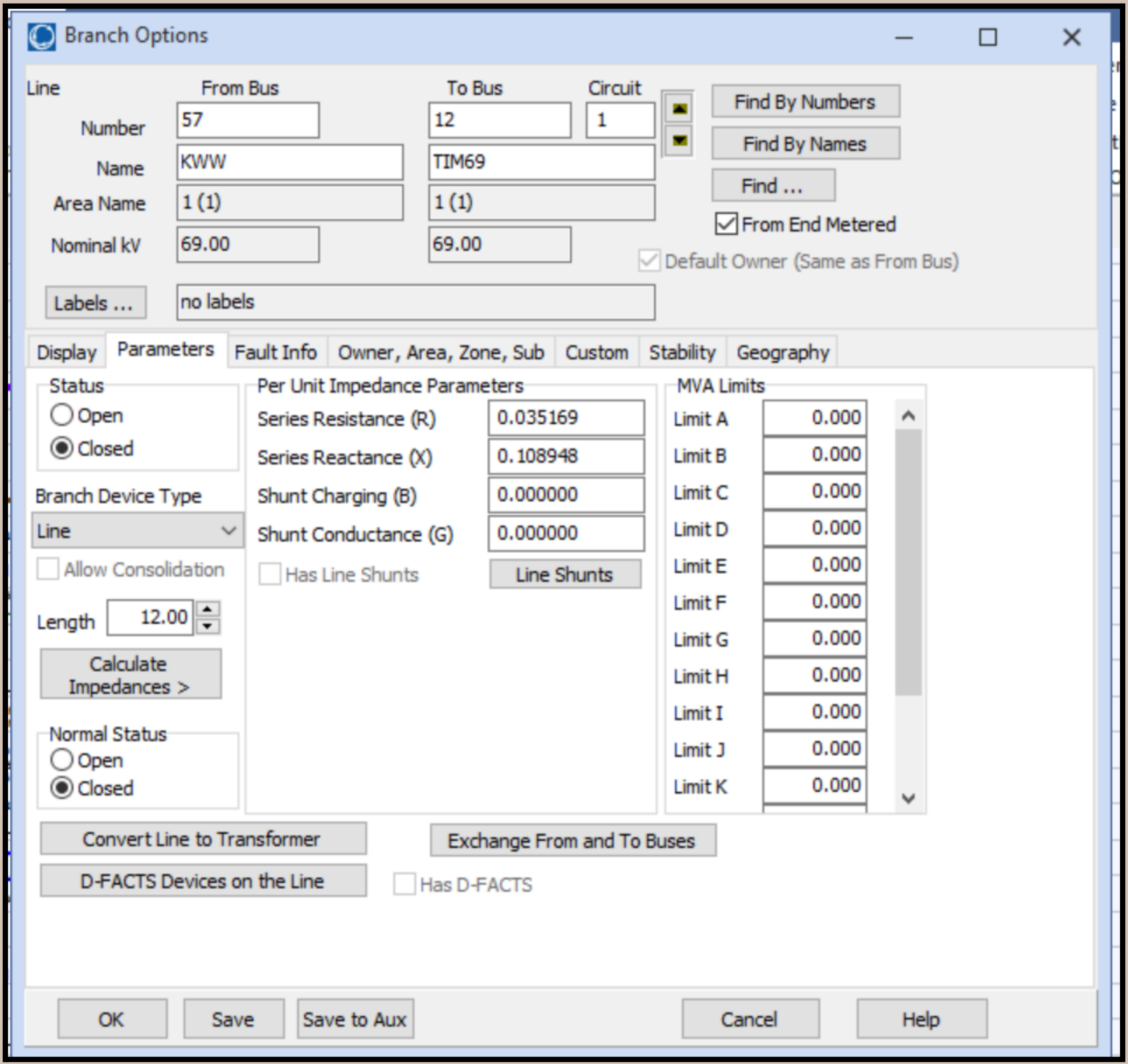

Figure 4: TIM69 PU Calculation

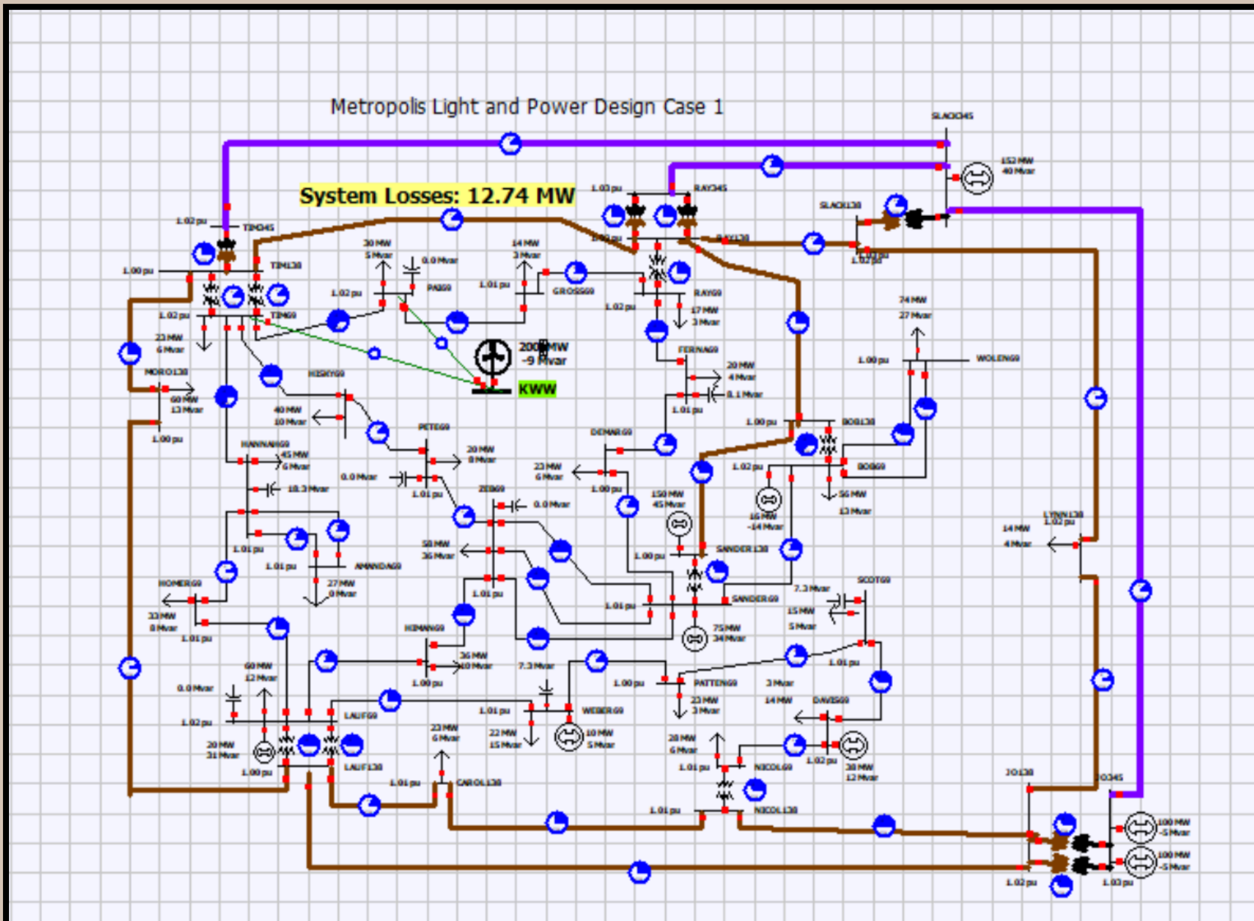

Figure 5: PowerWorld Output

With the MWh losses for each line type determined, the total power loss cost for each line was calculated, considering that each MWh costs $50 and multiplying that by the number of hours in 5 years. The MWh losses were: Drake - 12.74 MWh, Cardinal - 12.33 MWh, Pheasant - 11.58 MWh, and Falcon - 11.1 MWh. The total power loss costs associated with these losses were: Drake - $27,939,000, Cardinal - $27,020,100, Pheasant - $25,359,800, and Falcon - $24,363,000.

The construction costs per mile for each line type were: Falcon - $900,000, Pheasant - $825,000, Cardinal - $750,000, and Drake - $625,000. Given that TIM69 was 12 miles away from the wind farm and PAI was 6 miles away, the total construction costs were calculated by multiplying these costs by 18. The resulting construction costs were: Drake - $11.25 million, Cardinal - $13.5 million, Pheasant - $14.85 million, and Falcon - $16.2 million.

These construction costs were then added to the MWh losses to reach a total for each: Drake - $39.15 million, Cardinal - $40.5 million, Pheasant - $40.21 million, and Falcon - $40.5 million. Based on these calculations, the Drake line was chosen as the most cost-effective option for construction, achieving the lowest total cost over a 5-year period. These calculations can further be observed at the end within **Appendix 1.**

VIII. Conclusion:

In conclusion, this project successfully achieved its objective of designing an optimal solution for connecting a new 200 MW wind farm to the existing power grid while minimizing cost and maintaining system reliability. Through the use of PowerWorld Simulator, a systematic approach was employed to analyze 64 different cases, ultimately identifying the PAI and TIM69 bus combination as the most optimal choice. This combination had the lowest losses and zero resistance, making it ideal for further cost optimization. The project also involved a comprehensive analysis of various line compositions (Drake, Cardinal, Pheasant, and Falcon) and their respective construction costs and energy losses. By employing the PU calculator and the ASCR table, the most cost-effective line composition was determined to be the Drake line, which had the lowest total cost over a 5-year period. This project has demonstrated the importance of power flow analysis, contingency planning, and thorough evaluation of various design options in transmission planning. The results obtained provide a strong foundation for future projects involving the integration of renewable energy sources into the existing power grid. The methodology and tools utilized in this project can serve as valuable resources for power engineers and planners seeking to develop cost-effective and reliable solutions for power transmission system design and optimization.

IX. References:

None

X. Appendix:

Appendix 1:
Construction

$$Construction\ Cost = Distance \bullet Cost\ per\ mile$$

$$Falcon = 18\ miles \bullet \$900,000 \frac{\$}{mile} = \$16.2\ Million$$

$$Pheasant = 18\ miles \bullet \$825,000 \frac{\$}{mile} = \$14.85\ Million$$

$$Cardinal = 18\ miles \bullet \$750,000 \frac{\$}{mile} = \$13.5\ Million$$

$$Drake = 18\ miles \bullet \$625,000 \frac{\$}{mile} = \$11.25\ Million$$

Losses

$$MWh\ Cost = MWh(Loss) \bullet 50\$ \bullet Hours\ in\ Five\ years$$

Drake = $12.74\ MWh * \$50/MWh * 43,800\ hours = \$27,939,000$

Cardinal = $12.33\ MWh * \$50/MWh * 43,800\ hours = \$27,020,100$

Pheasant = $11.58\ MWh * \$50/MWh * 43,800\ hours = \$25,359,800$

Falcon = $11.1\ MWh * \$50/MWh * 43,800\ hours = \$24,363,000$