University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

EE4010: Electrical Power Systems
Power System Design Report

Group 4 - Design Project 2

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I) Introduction

As Ireland's energy demand continues to grow, there is further emphasis placed upon power production through clean and sustainable energy sources. In response to this Island Electric Company (IEC) has used its initiative to commence integrating a new 600 MW wind farm into its western service territory. In this report we act as the network planning team for IEC, and we have been tasked with designing the necessary power system changes that are required in order to accommodate this renewable energy project.

Due to the variability of wind patterns in the western region of Ireland, the wind farm is expected to operate with a capacity factor of roughly 40%. However, it's important to note that the intermittent nature of wind generation, particularly during times of maximum system loading, necessitates a careful and strategic approach to ensure system reliability. Simultaneously, IEC aims to make the existing 300 MW generator at the Pheasant substation redundant.

Our primary objective is to provide recommendations to accomplish the cheapest design possible while also focusing on minimising losses. To accomplish this we will be focusing on the construction of new transmission lines, transformers and bus bars if necessary. These changes must ensure the resilience of the new power system in any case, and should protect the system from any contingencies present when the new wind farm is operating at either its maximum output of 600 MW or during periods of no wind generation, with the Pheasant generator offline.

Given that the wind farm will be equipped with Type 4 Full Converter Wind Turbines our modelling approach involves treating the wind farm as a single equivalent, traditional PV bus generator. This NewWind power station will have a fixed output of either 0 or 600 MW. This report includes the strategies we used to incorporate the NewWind substation into the transmission network in an affordable and efficient manner. We have also included our analysis of the initial system and how we corrected any initial errors.

II) Initial System:

1. Basic analysis

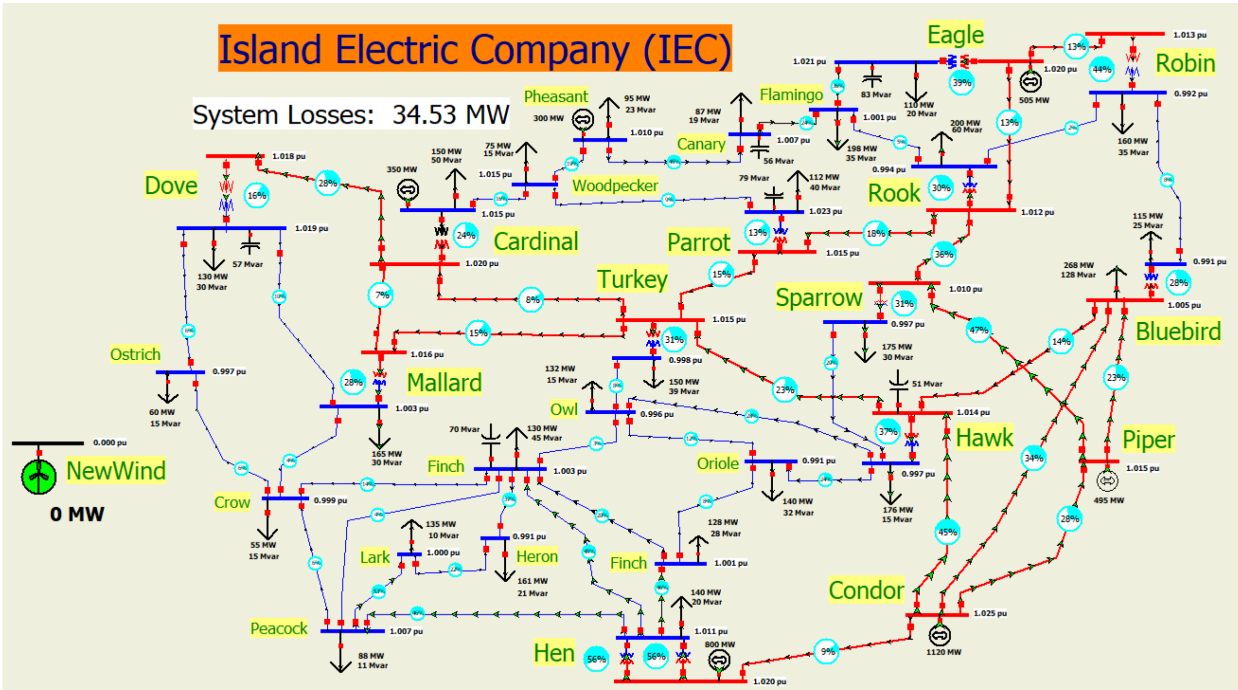

Fig.1 Initial System oneline diagram.

After conducting a contingency analysis (refer to Fig.2) in PowerWorld Simulator, it was revealed that there is a risk of overload at the Hen power station. The scenario simulated involved the disconnection of the switch between bus 35 and bus 41. This disconnection resulted in the Hen station operating at 101% of its rated capacity, indicating an overload condition. The specific contingency causing the overload was identified as the branch between Hen345 and Hen0004H, which was subjected to an 811.80 MVA flow, exceeding its 800 MVA limit by approximately 1.47%.

Contingencies

Show Other Violations | Combined Tables >

	Label	Category	Value	Limit	Percent
1	T_000035Hen345-000040H	Branch MVA	811.80	800.00	101.47

Fig. 2: Contingency analysis result.

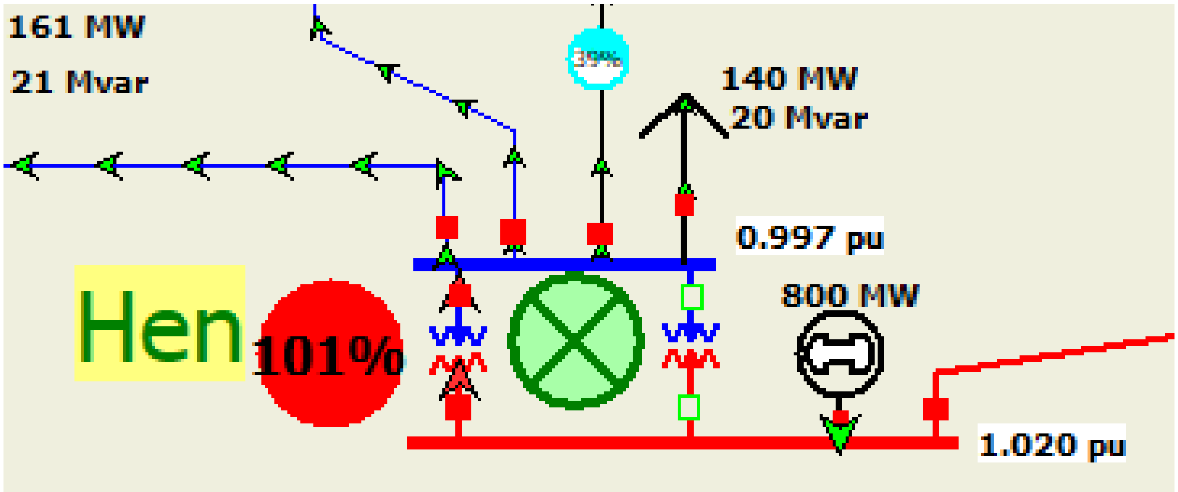

Fig. 3: Violations in oneline diagram of the initial system.

This situation presents a significant reliability concern, as prolonged operation above the rated capacity can lead to equipment failure and potential system instability. Further analysis is required to explore remedial measures such as reconfiguring the network, adjusting generation dispatch, or upgrading equipment to handle the increased load and ensure the operational integrity of the system under such contingency conditions.

System Impact Analysis Post-Pheasant Substation Disconnection

	Category	Element	Value
1	Bus Low Volts	Cardinal161 (42)	0.9197
2	Bus Low Volts	Cardinal345 (18)	0.8253
3	Bus Low Volts	Crow161 (6)	0.5429
4	Bus Low Volts	Dove161 (11)	0.7558
5	Bus Low Volts	Dove345 (8)	0.7897
6	Bus Low Volts	Finch161 (41)	0.4615
7	Branch Amp	Hawk161 (14) -> Oriole161 (13) CKT 1 at Oriol	1719.14
8	Branch Amp	Hawk161 (14) -> Owl161 (17) CKT 2 at Owl16	2015.69
9	Bus Low Volts	Hawk161 (14)	0.7178
10	Bus Low Volts	Hawk345 (3)	0.8641
11	Bus Low Volts	Hen161 (40)	0.4429
12	Bus Low Volts	Heron161 (36)	0.4253
13	Bus Low Volts	Kiwi161 (39)	0.4537
14	Bus Low Volts	Lark161 (37)	0.4353
15	Branch Amp	Mallard161 (16) -> Crow161 (6) CKT 1 at Crov	1285.83
16	Bus Low Volts	Mallard161 (16)	0.677

Finished with 85 violations, 0 custom monitor violations, 0 unsolveable, and 0 aborted contingencies. Initial state restored.

Fig. 4: Contingency analysis result.

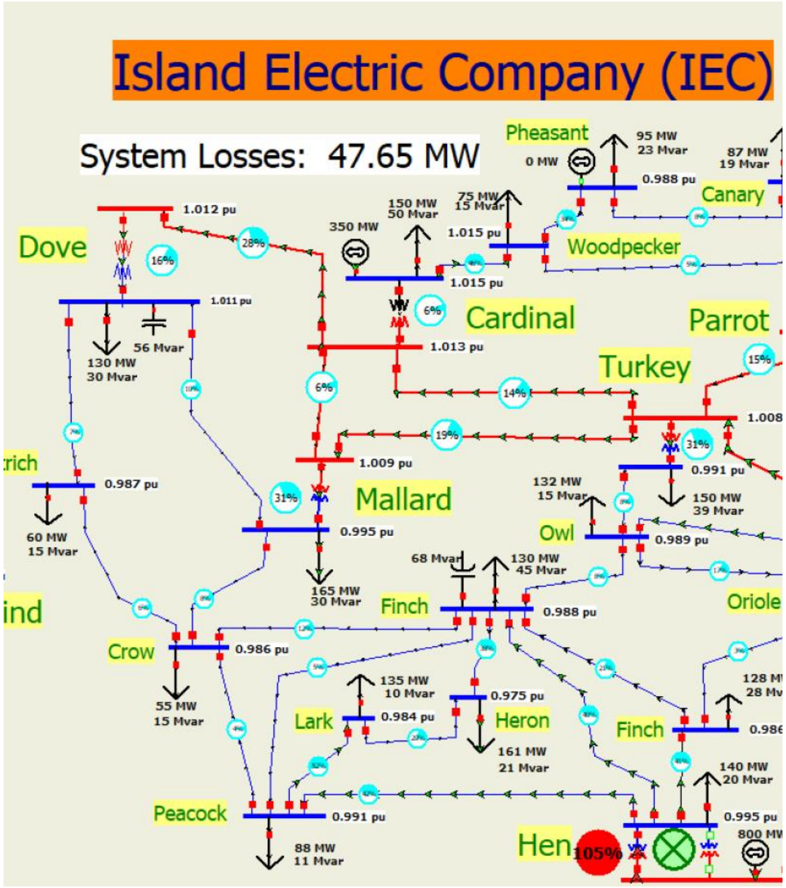

Fig. 5: Violations in oneline diagram of Post-Pheasant Substation Disconnection.

Firstly, the system is experiencing significant losses, totalling 47.65 MW, which is a substantial amount and suggests inefficiencies within the network. These losses could be due to a variety of factors such as long transmission distances, suboptimal dispatch of generation resources, or overloaded equipment.

The diagram shows multiple substations and generators with associated power flows and voltage levels. The Hen substation is marked with a ‘105%', which indicates that the generator or branch at this location is overloaded, operating above its rated capacity. This is a critical situation that requires immediate attention to prevent potential equipment damage or failure.

Other parts of the network, such as Cardinal, Turkey, Sparrow, and Hawk, are also highlighted, suggesting there may be issues at these locations, such as overloads or voltage deviations. The voltage levels across the grid vary, with most buses operating close to the nominal voltage (1.00 pu), which is a positive sign for system stability. However, there are some buses, indicated by the red circles that have higher percentages, implying voltage or loading issues that need to be addressed.

Addressing these issues is crucial for maintaining a reliable and efficient power system, especially with the integration of renewable energy sources such as the NewWind generator we introduce later.

III) Design Process

Calculations:

For the project there are six different types of lines. We were given the rated current of each type of line and calculated the capacity of the line for 161 and 345 kV using the following formula:

$$Line\ Capacity\ (VA)\ = Nominal\ line\ Voltage\ *\ Rated\ Current\ *\ \sqrt{3} \qquad \textbf{[1]}$$

This gave the following values for each type of line:

Line Type	Current (amps)	345kV Capacity (MVA)	161kV Capacity (MVA)
Wren	770		
Thrush	830		231.45
Blackbird	900		250.97
Cuckoo	1110	663.29	309.53
Osprey	1200	717.07	334.63
Falcon	1380	824.63	

Table 1. Transmission Line Capacity Comparison for 345kV and 161kV Systems

The specified values for the impedance values for the two types of lines were given as per unit per kilometre. Power world requires the values to be per unit so it was converted using the following formula:

$$Per\ unit\ impedance\ value\ =\ Per\ Unit\ per\ kilometre\ impedance\ value\ *\ Distance \qquad \textbf{[2]}$$

Impedance value	345kV Line	161kV Line
Resistance R	0.0003/km	0.0008/km
Reactance X	0.002/km	0.005/km
Shunt charging B	0.02/km	0.002/km

Table 2. Electrical Impedance Parameters for 345kV and 161kV Lines.

The following impedance values were calculated for each right of way between substations:

Substation	Distance(km)	345R	345X	345B	161R	161X	161B
NW to Ostrich	18	0.0054	0.036	0.36	0.0144	0.09	0.036
NW to Dove	55	0.0165	0.11	1.1	0.044	0.275	0.11
NW to Crow	30	0.009	0.06	0.6	0.024	0.15	0.06
NW to Peacock	55	0.0165	0.11	1.1	0.044	0.275	0.11
NW to Hen	70	0.021	0.14	1.4	0.056	0.35	0.14
Ostrich to Mallard	45	0.0135	0.09	0.9	0.036	0.225	0.09
Peacock to Hen	20	0.006	0.04	0.4	0.016	0.1	0.04
Dove to Cardinal	40	0.012	0.08	0.8	0.032	0.2	0.08

Table 3. Transmission Impedance and Admittance Values for Substation Connections.

The parameters for transformers were given as per unit values to a base of 100 MVA base. The parameters for 345:161kV operating at 560MVA were calculated as:

$$Resistance\ =\ 0.0004 * 560\ MVA/100\ MVA = 0.00224$$

$$Reactance\ =\ 0.025 *\ 560\ MVA\ /\ 100\ MVA\ =\ 0.14 \qquad \textbf{[3]}$$

Optimising the system:

With the calculations completed, we moved onto designing and optimising the system by connecting the new wind farm into the grid. Each scenario we devised was tested for the wind farm outputting 0 MW and 600 MW, as this simulates the two extremes of the system; if neither of these scenarios produce errors then the design is functional. Losses over the five years were calculated at 240 MW output to replicate the 40% capacity factor of the wind farm.

Through experimentation we found that the more expensive 345 kV lines often gave negligible improvements to the losses of the system when compared to the 161 kV lines. This ran counter to our expectations as transmitting electricity at a high voltage and lower current should lead to lower losses. This was rarely the case, and often a 345 kV line generated more losses than a 161 kV line in the same place. We assume that the increased losses stem from the voltage having to be stepped up in a transformer at the New Wind substation and then (depending on the receiving substation) step it back down to 161 kV.

The second finding we came across was that the lines connecting existing substations (Ostrich to Mallard, Dove to Cardinal and Peacock to Hen) had very little effect on the system. These lines would rarely exceed transmitting 5% of their capacity and would not reduce the system losses by more than a megawatt. These two realisations led to the decision to use 161 kV lines connecting directly to the New Wind substation.

Cost Analysis:

One of the key instructions for this integration project was to develop a transmission system at an affordable cost. Through rigorous experimentation with multiple transmission lines at different price ranges, we were successful in developing a cost effective and efficient model. The final model is a product of several failed attempts of trialling different transmission lines at different locations within the transmission system which insured a balance between cost and performance.

For this project we were provided with 6 different types of transmission lines, which can be seen below in Table.4, each with a different price point. Each of the transmission lines' cost was priced per kilometre which greatly impacted our decision on which substations to incorporate into this model. To reduce costs we focused on designing a system which focused on nearby substations such as Ostrich and Crow. We also focused on using lower voltage transmission lines which were inherently cheaper. We also used the cheapest type of transmission line such as Thrush and Blackbird wherever possible.

Line Type	345kV cost/km	161kV cost/km
Wren		
Thrush		€400,000.00
Blackbird		€425,000.00
Cuckoo	€650,000.00	€450,000.00
Osprey	€700,000.00	€475,000.00
Falcon	€750,000.00	

Table 4. Different line types and their price per kilometre.

As discussed earlier, we decided to utilise 161 kV transmission lines, directly connecting New Wind to Dove, Ostrich, Crow and Peacock which enabled us to effectively integrate the NewWind substation. A connection from New Wind to Hen was considered but given that the cheapest line between these substations was over 29 million euro, the savings in losses would have to exceed 13MW (see calculation for cost per megawatt below) which they did not. Below in Table.5, we include a screenshot of the excel tool we used to break down the cost of developing different combinations of transmission lines.

	161kV				345kV		
	Thrush	Blackbird	Cuckoo	Osprey	Cuckoo	Osprey	Falcon
NW to Ostrich	☐	☐	☑	☐	☐	☐	☐
NW to Dove	☑	☐	☐	☐	☐	☐	☐
NW to Crow	☑	☐	☐	☐	☐	☐	☐
NW to Peacock	☑	☐	☐	☐	☐	☐	☐
NW to Hen	☐	☐	☐	☐	☐	☐	☐
Ostrich to Mallard	☐	☐	☐	☐	☐	☐	☐
Peacock to Hen	☐	☐	☐	☐	☐	☐	☐
Dove to Cardinal	☐	☐	☐	☐	☐	☐	☐
	Cost per kilometre						
Distance (km)	400000	425000	450000	475000	650000	700000	750000
18	$0	$0	$9,300,000	$0	$0	$0	$0
55	$23,200,000	$0	$0	$0	$0	$0	$0
30	$13,200,000	$0	$0	$0	$0	$0	$0
55	$23,200,000	$0	$0	$0	$0	$0	$0
70	$0	$0	$0	$0	$0	$0	$0
45	$0	$0	$0	$0	$0	$0	$0
20	$0	$0	$0	$0	$0	$0	$0
40	$0	$0	$0	$0	$0	$0	$0

Table 5. Cost breakdown of the proposed strategy for incorporating the NewWind sub-station.

Another major factor contributing to the overall cost of the model is the losses suffered by the system.. The cost analysis for the system losses are conducted under the 40% generation capacity conditions. In order to estimate the losses over the 5 year period the following equations were used.

$$Cost/MW\ lost\ =\ €50/MWh * 24\ hours/day * 365\ days/year * 5\ years = €2{,}190{,}000/MW \quad \textbf{[4]}$$

$$\boldsymbol{Total\ Losses\ *\ Cost/MW\ =\ 42.3MW\ *\ €2,190,000\ =\ €92,637,000} \quad \textbf{[5]}$$

A breakdown of the total cost of integrating the NewWind Substation is included below in Table.6. In this breakdown it is clear to see that more than half of the total costs are related to the losses of the system, portraying the importance of minimising losses. This cost breakdown analysis shows the importance of a balanced system that prioritises developing an efficient system for a reasonable cost.

No. of bus bars added	0
No. of transformers added:	1
Losses at 40% (MW)	42.3
Cost of losses:	€92,637,000
Cost of infrastructure:	€76,400,000.00
total cost	€169,037,000.00

Table 6. - Infrastructure Upgrade Costs and Losses Analysis at 40% Generation Capacity.

An alternative model generated, where the transmission line was not included, was also priced. The dismissal of this transmission line significantly dropped the cost of construction but also led to a slight increase in the cost of losses to the system, which can be seen in table.7 below. However, there were significant loads on the transmission lines to Ostrich and Crow, which is further discussed below in the “Recommended Design”, when the Peacock line was dismissed.

No. of bus bars added	0
No. of transformers added:	1
Losses at 40% (MW)	42.92
Cost of losses:	€93,994,000.00
Cost of infrastructure:	€53,200,000.00
total cost	€147,194,000.00

Table.7- Infrastructure costs and Losses Analysis at 40% Generation Capacity and dismissal of Peacock line.

V) Recommended Design

Pictured below in Fig. X, is our recommended design for the given system. Four 161 kV lines connect the New Wind substation to Dove, Ostrich, Crow and Peacock. The

Thrush type power lines were used for Dove, Peacock and Crow as these were the cheapest lines available and the current in these lines didn't approach the rated values for any of the 3 New Wind output set points we tested for. The Cuckoo line type was used for Ostrich as this line transmitted a significant amount of load and if the Thrush type line was used it would be at 95% of the rated current when New Wind outputs 600 MW.

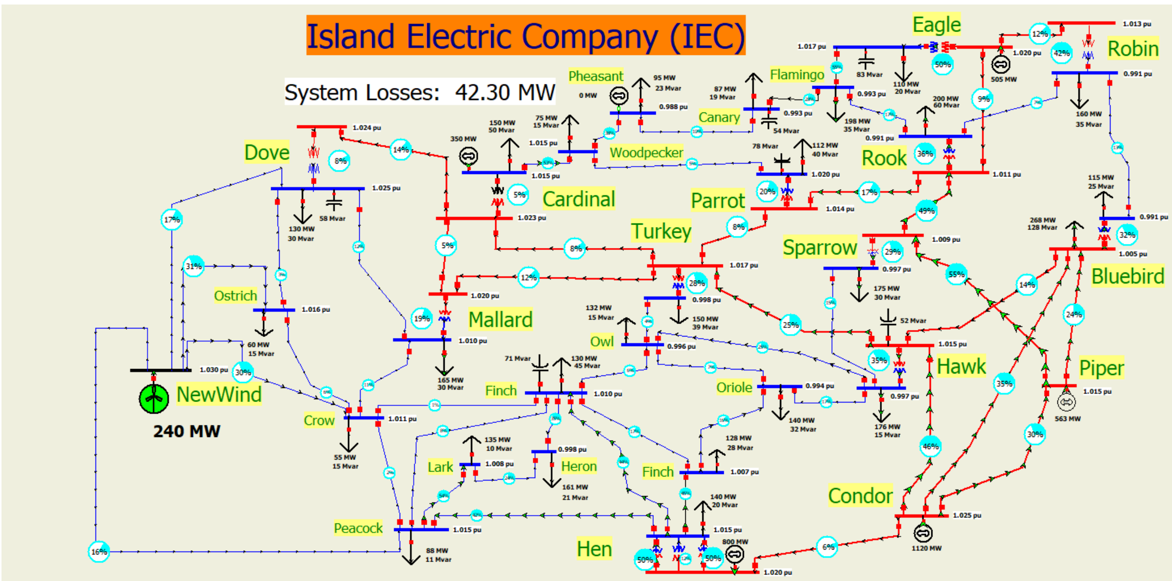

Fig. 6: The recommended design for the system at 240 MW generation.

The line going to Peacock could be removed without errors, however this would put Ostrich and Crow at 85% and 94% respectively when New Wind outputs 600MW. While these figures are within the rated values of the transmission lines, operating this close to maximum capacity means that any changes to the electrical grid in the future could cause issues. This configuration also causes violations to occur during the contingency analysis.

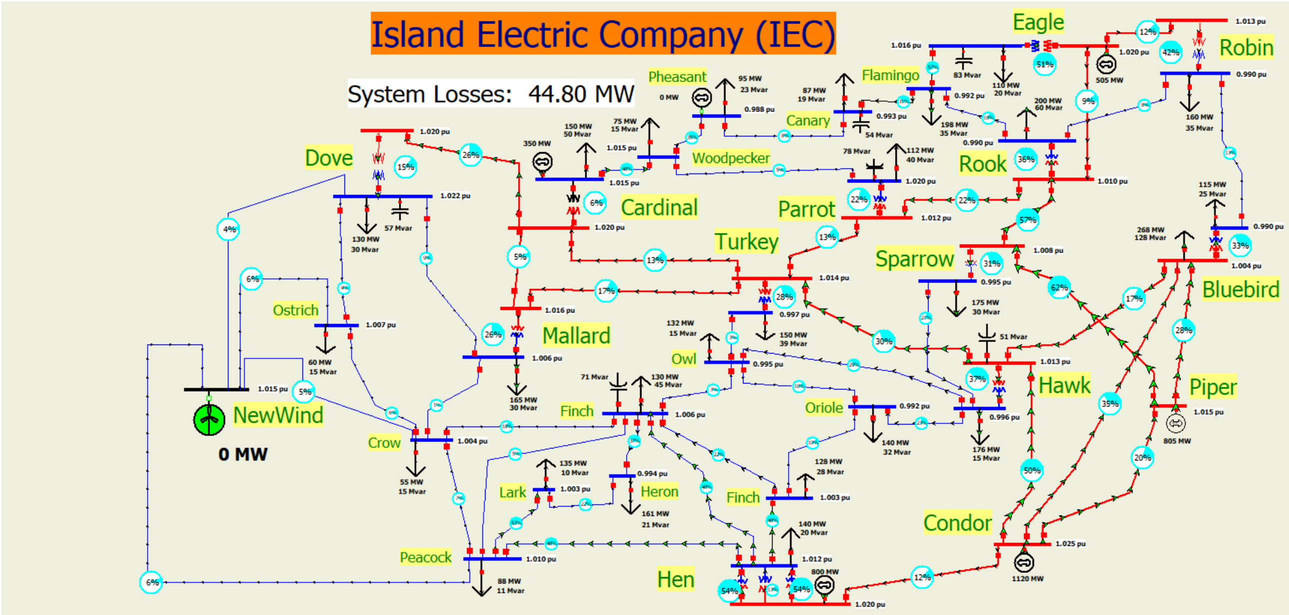

Fig. 7: The recommended design for 0 MW of generation.

<u>Sensitivity Analysis:</u>

1. Introduction

In the field of power systems engineering, leveraging computer simulations to validate grid designs prior to physical implementation is a fundamental approach. Sensitivity analysis plays a crucial role in fortifying designs by examining how variations in input parameters, such as load levels or generation capacity, influence the system's performance and stability. Enhancing these models can profoundly improve the precision with which we predict and manage aspects like network load distribution, substation capacity, and the integration of renewable energy sources. Through meticulous sensitivity analysis, engineers can identify potential operational risks and optimise the power network for both efficiency and resilience. [1]

In order to analyse the effects of various factors on optimal design of the distributed generation systems, load level is studied by PowerWorld.

2. Scenario Analysis

Scenario 1 (240 MW Generation)

In our scenario 1 analysis, we conducted a sensitivity test to ascertain the robustness of our grid upon the integration of the NewWind farm, currently set at a 40% capacity output of 240 MW (refer to Fig.8). The removal of the line leading to Peacock did not introduce immediate operational errors. However, it did result in the Ostrich and Crow buses operating at 85% and 94% of their loading capacity, respectively, when NewWind is projected to operate at full capacity.

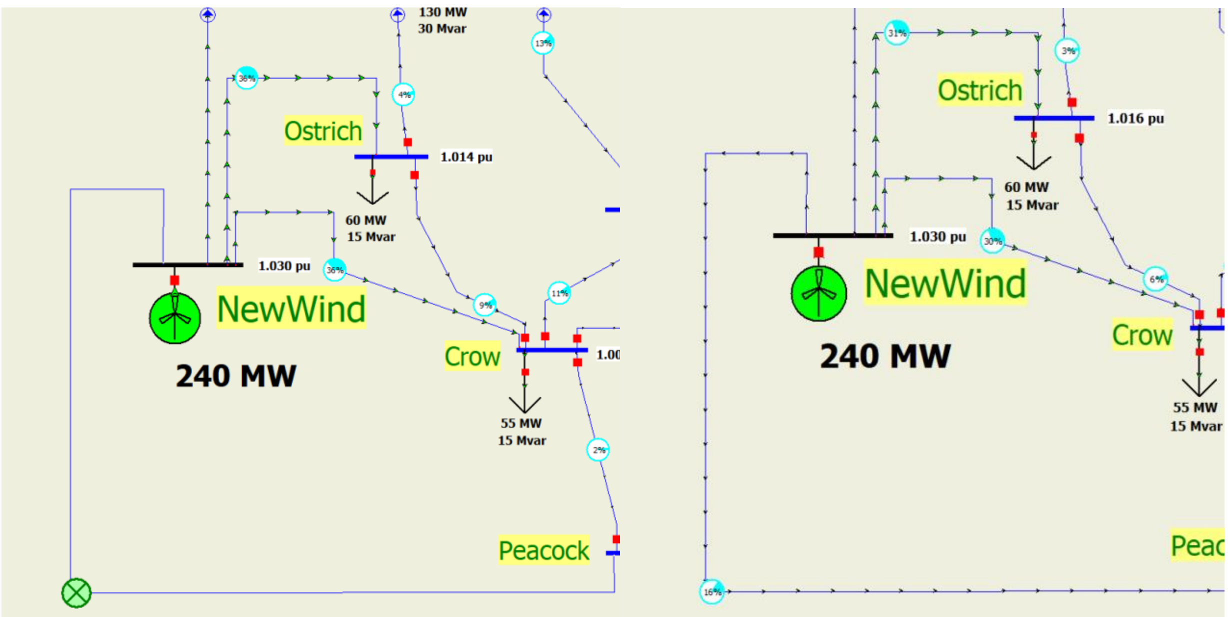

Fig.8 - Scenario 1. NewWind generating at 40% Load Level

This scenario emphasises significant cost savings, as the avoidance of new infrastructure construction saves approximately €42,450,000.00 compared to the projected expense of €209,937,000.00 for full transmission line installation.

Scenario 2 (600 MW Generation)

The system is prone to violations during contingency scenarios. This indicates potential vulnerabilities in the system's ability to cope with component failures or unanticipated shifts in power flow, emphasising the importance of maintaining operational buffers.

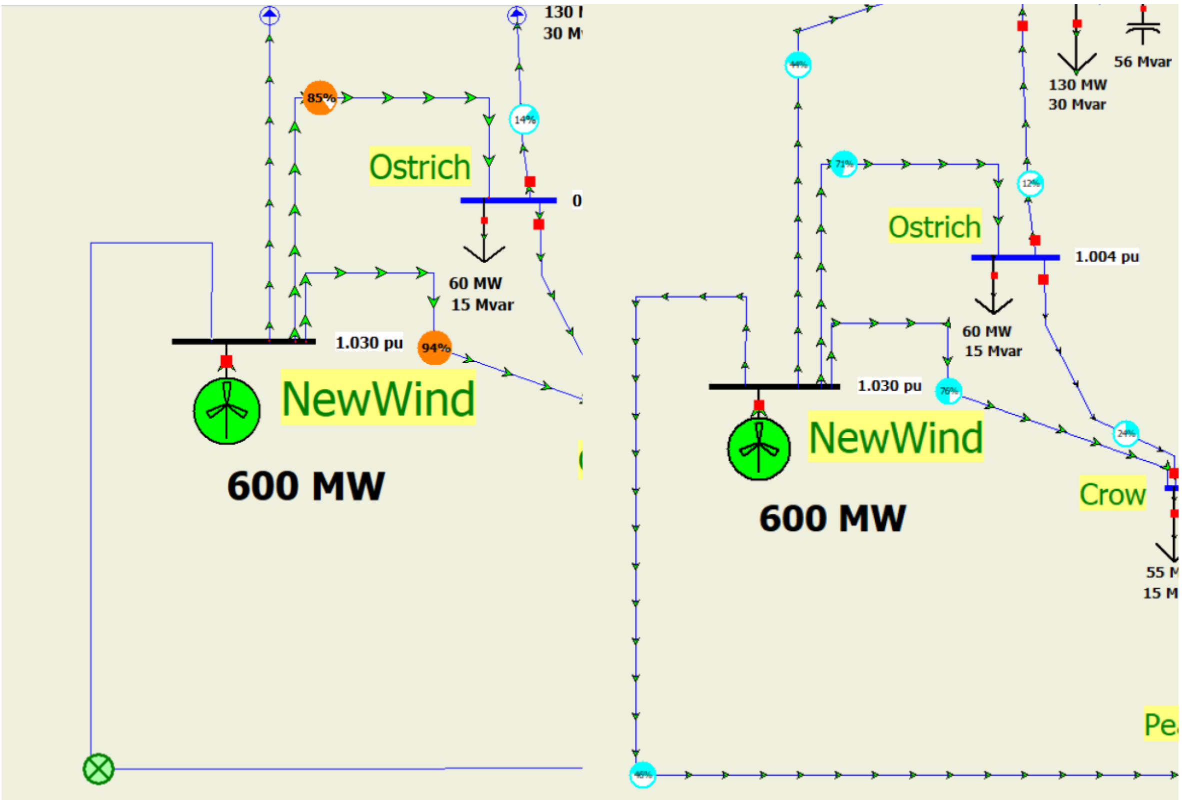

Fig.9 - Scenario 2. NewWind generating at Full Load Level

3. Summary :

If the probability of the NewWind wind farm operating frequently at full capacity is high, or if the costs associated with potential overloads are substantial, then investing in the transmission line to Peacock is recommended. This would safeguard against system overloads and ensure reliable power distribution even during peak generation periods. Otherwise, if the wind farm is expected to operate at full capacity infrequently, or if the system can be managed effectively through other measures, it may be economically prudent to defer the investment in new transmission infrastructure.

VII) Conclusion

In conclusion, our design process for the integration of a new 600 MW wind farm into the western service territory of Island Electric Company has been a meticulous journey marked by thorough calculations, optimization strategies, and cost analyses. The introduction of the NewWind substation at the 161 kV level demanded a comprehensive approach to ensure the development of a reliable power system that can handle the intermittent nature of wind generation in the western region of Ireland.

Our initial system analysis revealed the complexities and challenges of incorporating the wind farm into the transmission system, and by conducting several calculations we determined the capacities of various transmission lines and impedance values. The design process involved optimising the system by testing different scenarios, considering the wind farm's output at both extremes, and identifying unexpected findings, such as the counterintuitive behaviour of 345 kV lines in certain situations.

Cost analysis played a pivotal role in our decision-making process, with a focus on developing a transmission system that balances affordability and efficiency. We carefully selected transmission lines based on their cost per kilometre, prioritising nearby substations and utilising 161 kV lines to connect directly to the NewWind substation.

Our recommended design incorporates four 161 kV lines connecting the NewWind substation to Dove, Ostrich, Crow, and Peacock. The use of Thrush type power lines for Dove, Peacock, and Crow, along with the Cuckoo line type for Ostrich, reflects a strategic choice to minimise costs while ensuring the system's functionality and resilience.

The cost breakdown highlights the significant impact the system losses had on the overall model cost, emphasising the importance of balancing infrastructure costs and operational losses. Our final proposed design considers the 0 MW, 240 MW and 600

MW generation scenarios, providing a comprehensive solution that meets the project's objectives.

In summary, our approach to the electrical power system design for the integration of the NewWind substation aligns with the goal of creating a cost-effective, reliable, and efficient system for the IEC. The collaboration of our team members, Sean Harrington, Matthew Howe, and Leyi Huang, has resulted in a well-thought-out and carefully crafted design that addresses the challenges posed by the introduction of renewable energy sources into the existing power grid.

References:

1. (https://www.investopedia.com/ask/answers/052115/what-are-some-examples-ways-sensitivity-analysis-can-be-used.asp)