Reactive Power Study Report

TB FLATS I WIND PROJECT

ENG00024

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Acronyms

Cap	Capacitor
DETC	De-energized Tap Changer
Ft	Foot
FERC	Federal Energy Regulatory Commission
HV	High Voltage
LGIA	Large Generator Interconnection Agreement
Max	Maximum
MENG	Mortenson Engineering Services, Inc.
Min	Minimum
MPT	Main Power Transformer
MV	Medium Voltage
MVAr	Mega-Volt-Ampere reactive
MW	Mega-Watt
PAC	PacifiCorp
PF	Power Factor
POI	Point of Interconnection
pu	Per Unit
RFI	request for information
TBI	TB Flats I Wind Energy Project
Vpu	Voltage in Per Unit

1. Executive Summary

1.1. Overview

Mortenson Engineering Services, Inc. (MENG) completed a reactive power study for the TB Flats I Wind Energy Project (TBI). The project will be located in Carbon County, Wyoming. The project is to interconnect to the newly created TB Flats I substation. A short transmission line will interconnect the TB Flats I Substation to the point of interconnection (POI) at the existing Shirley Basin 230 kV Substation owned by PacifiCorp (PAC). The project consists of fourteen (14) V110 Vestas 2.0 MW turbines and sixty-five (65) V136 Vestas 4.3 MW turbines for a total nameplate of 307.5 MW. The project contains three (3) identical 3-phase, 3-winding main power transformers (MPT) each rated 75/100/125 MVA. Each MPT is equipped with a De-energized Tap Changer (DETC).

The study was performed to determine whether TBI can meet the power factor (PF) requirement at the point of interconnection (POI) using the reactive power capabilities of its turbines or if any automatic switched shunts are needed to meet this requirement. According to the Large Generator Interconnection Agreement (LGIA), TBI needs to comply with Federal Energy Regulatory Commission (FERC) order number 827. The power factor requirement is 0.95 lagging to 0.95 leading. FERC 827 does not define a voltage range in which this power factor requirement would be applicable over. The project has required that the voltage range be at the scheduled voltage of 1.03 Vpu and be as wide as possible to cover typical operating scenarios per RFI #29 attached in Appendix 4.

The reactive power study included the most up-to date collection system, MPTs, turbines and their transformers as of the issue date above.

1.2. Key Findings

The study found that TBI can meet the PF requirement at the POI for the POI voltage range from 1.05 Vpu to 0.97 Vpu.

The existence of the DETC at the MPTs limits the continuous voltage control of the collection system that is needed under daily changing wind conditions. The voltage control is limited with respect to the DETC as opposed to the operation of an load tap changer (LTC) transformer. This results in either a very low or a very high voltage throughout the collection system at certain POI voltage levels during lagging or leading PF[1] modes. The design ensures the voltage range within the collection system remains within 0.9 Vpu to 1.1 Vpu. The project can be made compliant with either the lagging or the leading PF requirement for a wide voltage range, - albeit not a full voltage range from 1.05 Vpu to 0.95 Vpu. If the tap settings of the DETCs[2] are adjusted to meet the overall leading PF requirement for a wide voltage range, then with the same tap settings and under lagging PF conditions, the voltage at some turbines becomes very high when the POI voltage is high, which results in tripping of these turbines offline. A similar issue occurs if the DETCs

[1] In this report, leading power factor means the project is absorbing reactive power, while lagging power factor means delivering reactive power.

[2] "DETCs" is used as meaning the De-energized Tap Changers of all MPTs and the turbine transformers on the project.

are set to meet the overall lagging PF requirement. If the DETCs are set to meet the lagging PF requirement for a wide voltage range, then with the same taps and under leading PF conditions, the voltage at some turbine terminals is very low when the POI voltage is low which results in tripping of these turbines offline. Thus, if the transformer settings in the project are set to meet the PF requirement at high POI voltage levels, the project will have limited PF capability at low POI voltage levels, and vice versa.

The current scheduled voltage is set at 1.03 Vpu and the project's requirement is to be able to meet the PF at that voltage. Since the scheduled voltage is relatively high, preference is given to allow the project to operate at this high voltage level. Thus, setting the MPT DETCs either up one position (1.025 pu) or up two positions (1.05 pu) was considered along with adjusting the turbine transformers DETCs. Both options are explained in Section 3. With either option of adjusting the DETCs, the reactive power capability of the project at the POI is the same. MENG recommends setting the MPT DETCs up one position to 1.025 pu, as this option provides the flexibility to tap the MPTs up one more tap in case the project experiences voltage issues in the future. The DETC settings of the Vestas provided turbine transformers were also modified to optimize project capabilities. The tap settings of the turbine transformers are listed in Table 1. The project will need to ensure that these tap settings are implemented by Vestas prior to energization.

With the recommended settings of the transformer DETCs, the project can provide 0.95 lagging PF in the voltage range from 1.05 Vpu to 0.95 Vpu at the POI, while providing 0.95 leading PF in the voltage range from 1.05 Vpu to 0.97 Vpu at the POI. Stated differently, the project can provide both the 0.95 leading and 0.95 lagging PF in the voltage range from 0.97 Vpu to 1.05 Vpu.

Additionally, MENG's analysis showed that no reactor banks are needed to meet the PF requirement. However, 30 MVArs of capacitor banks (cap banks) are needed to meet the PF requirement at the POI per the recommended settings of the DETCs. The cap banks have to divided evenly between the medium voltage (MV) buses resulting in one step of 10 MVArs per MV bus.

The findings of this report depend on the design information available as of the issue date above. Any changes to the design information and model assumptions could impact the findings and recommendations of this report.

2. Modeling Methodology

MENG built a detailed phasor-domain model of the 307.5 MW TB Flats I wind project in PSS®E version 33.11. Underground cables connecting the individual turbine transformers were modeled as pi-equivalent segments. The grid was represented as a swing source at the POI. The high voltage transmission-line to the POI was modeled as a pi-equivalent segment with impedance data based on a specific tower configuration given in Appendix 1.

Turbines were modeled as machines with reactive power capability according to their reactive power curves as shown in Appendix 5. Turbine nacelle transformers and MPTs were modeled along with their no-load losses. Downtower cables were also modeled. The DETCs were fixed at specific positions during all simulations except for the cases in Section 3 in which the DETCs were changed to achieve their optimum settings.

Several power flow cases were performed. At each POI voltage, all turbines were dispatched to meet the PF requirement at the POI by absorbing or supplying the maximum (max) possible reactive power while observing the following constraints:

1. The voltage on the Vestas 4.3 turbine terminals is kept within the range 1.13 Vpu to 0.87 Vpu.
2. The voltage on the Vestas 2.0 turbine terminals is kept within the range 1.1 Vpu to 0.9 Vpu
3. The voltage on the 34.5 kV collection system is maintained in the range 1.1 Vpu to 0.9 Vpu.

With implementing a DETC in lieu of an LTC on the MPTs the collection system voltage will operate over the range of 1.1 Vpu to 0.9 Vpu based on the various operating conditions. The collection equipment will be verified that it can handle these overvoltage conditions for up to 4 hours per day. Running the system in this manner adds additional stress to the system which may result in additional maintenance over the life of the project.

The PF requirement could not be achieved using only turbine reactive power capabilities; therefore, cap banks were added to the system to meet the PF requirement. It should be noted that the Vestas 4.3 turbine can be operated at 1.13 Vpu at its generator terminal, but such voltage is incompatible with the operating voltage of the collection system, and thus the practical max voltage at the Vestas 4.3 terminals was selected as 1.1 Vpu.

According to the LGIA, TBI needs to comply with FERC order number 827 at the high side of the MPT. Based on the PAC response to MENG regarding a request for information (RFI) on 09/12/2018, TBI will need to comply with FERC 827 at the POI instead of the high side of the MPT. Additionally, based on RFI #29 on 11/01/2018, TBI shall be capable of meeting the PF requirement at the widest possible POI voltage range.

All data used to build the model is given in Appendix 1. The collector system layout is given in Appendix 2. The PSS®E single line diagram is given in Appendix 3. RFI #29 is attached in Appendix 4. Turbine reactive power capability is attached in Appendix 5.

3. Optimum DETC Tap Setting and Capacitor Bank Size

Several power flow cases were performed to determine the optimum DETC tap settings of the MPTs and turbine transformers when the project is producing 100% output. An optimum DETC setting would allow the project to meet the PF requirement at the POI for the widest possible voltage range. The methodology for setting the DETCs is given below.

An iterative approach was used to reach optimum DETC setting. The iterative approach utilized various power flow cases until the optimum DETC setting was reached. The first such case is a power flow case with all DETCs at the nominal position (1 Vpu:1 Vpu turns ratio) while maintaining the 0.95 lagging PF requirement at a POI voltage of 1.04 Vpu. A target voltage of 1.04 Vpu was selected to ensure that the PF requirement at scheduled voltage of 1.03 Vpu can be met. To meet the 0.95 lagging PF at the POI, turbines were adjusted to supply as much reactive power as possible without violating the constraints listed in Section 2. With the turbines set to produce maximum reactive power, the remaining reactive power needed to meet the PF requirement was supplied by the cap banks. Based on the results of this case, the voltage at the collector system was inspected, and the highest voltage at the collector system is 1.152 Vpu while the lowest voltage is 1.075 Vpu.

Based on the results of the first case, it is evident that a means to bring the voltage throughout the collector system down to 1.1 Vpu is needed. It is also clear that a reduction of 0.052 Vpu is needed (which is almost 0.05 Vpu). This reduction can be carried out in two ways:

A. The first one is by adjusting the DETC settings of the MPTs at 1.05 (+2 tap) which effectively reduces the voltage by 0.05 pu throughout the collector system.
B. The second one is by adjusting the DETC settings of the MPTs at 1.025 (+1 tap). The remaining 0.025 pu voltage reduction can be obtained by tapping some turbine transformers up one position (turns ratio 1.025 Vpu:1 Vpu).

The main difference between these two options is that the first option affects a 0.05 Vpu voltage drop throughout the collector system, while the second option affects a 0.05 Vpu voltage drop only at the turbines that have higher than 1.1 Vpu voltage at their terminals. Just because a reduction of 0.05 Vpu was accomplished using the DETCs of the MPTs does not mean that no more turbines will need to be tapped. An MPT DETC tap of 1.05 Vpu will cause some loss of reactive power which will need to be compensated either by more cap banks or more turbine reactive power. In either of the two cases, this additional reactive power may cause the voltage to be above the constraints outlined in Section 2. This is explained in more detailed below in terms of adjusting the MPT DETC settings at 1.025 Vpu.

The turbines that will be affected in the second option of setting the DETCs are the ones that have higher than 1.125 Vpu voltage at their terminals after adjusting the MPT DETC to 1.025. Thus, the MPTs will be tapped at 1.025 in the second option, then a power flow solution will be used to determine what turbines have higher than 1.125 Vpu voltage at their terminals. The turbines that have higher than 1.125 Vpu voltage at their terminals will be short listed for turbine transformer tapping. A turbine that is short listed to have its transformer tapped does not necessarily mean that its transformer will be tapped, as it could be the case that adjusting the tap of one turbine could affect the voltage at a nearby turbine. This will depend on what will be done next.

The turbines that are short listed are sorted in a descending order such that the turbine that has the highest over voltage is tapped first. Optimum DETC settings are reached by tapping the turbine transformers one at a time. This means that the turbine that has the highest voltage is tapped first, the power flow is re-solved, more cap banks are added to meet the 0.95 PF requirement, the power flow is re-solved, the turbine with the highest voltage is tapped, the power flow is re-solved, more cap banks are added, the system is re-solved, the turbine that has the highest voltage is tapped, and the process continues while observing the constraints in Section 2 until there is no need to tap more turbine transformers and the PF is met at the POI. The process is summarized in Figure 1. After the tap settings of all DETCs are finalized, those tap settings are used for all power flow cases to produce the reactive power capability of the project at the POI in Section 4. MENG kept track of the turbines that were tapped to make sure that they are not different than the ones that were previously short listed. The MENG analysis showed that twelve (12) turbines need to have their turbine transformers tapped at 1.0 Vpu (nominal tap), sixty-one (61) turbines need to have their turbine transformers tapped at 1.025 Vpu (+1 tap), and six (6) turbines need to have their turbine transformers tapped at 1.05 (+2 tap). Table 1 summarizes DETC tap positions.

It was found that tapping the MPTs at 1.05 Vpu increased the capacitor bank requirements, therefore the design recommendation is to tap the MPTs at 1.025 Vpu.

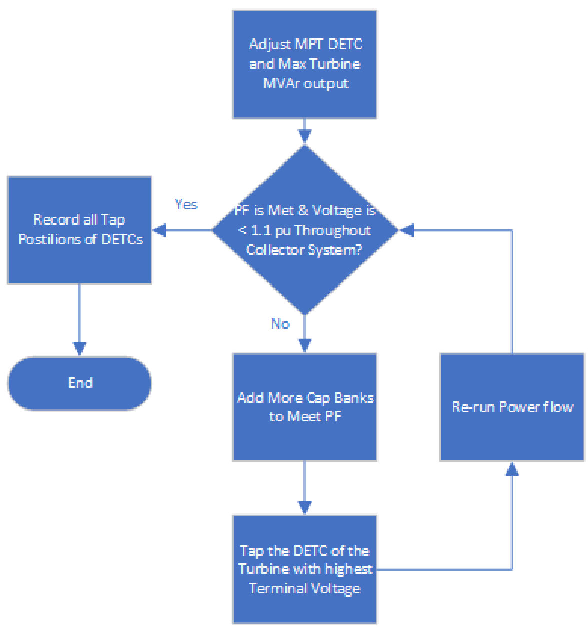

Figure 1. Iterative Process to Obtain Optimum DETC Positions

The next step involves determining the size of the cap banks. The voltage at the POI is then scheduled at 0.95 Vpu in the case with all DETCs set per the previous paragraph as given in Table 1. Capacitor banks are then added to meet the PF requirement at the POI with the turbines set to provide as much reactive power as possible without violating the constraints listed in Section 2. Half of a reactive power (0.5 MVAr) was added to each step of the cap banks as a safety margin if the reactive power at the POI was deemed too close to the limit. Table 1 summarizes cap bank requirements. Cap bank organization is given in Section 5.

In summary, MENG recommends setting the DETCs in TBI as given in Table 1. Based on that, MENG recommends installing one step of 10 MVAr cap bank at each MV bus for a total of 30 MVAr.

Table 1. Required DETC Settings

MPT	Turbine Transformer	Capacitor Banks	
		0.95 PF requirement	Safety Margin
1.025 Vpu (+1 tap)	• +1.00 Vpu (nominal tap) o TB1-N-24-01 o TB1-N-24-02 o TB1-N-24-03 o TB1-N-34-01 o TB1-N-34-02 o TB1-N-34-03 o TB1-N-34-04 o TB1-N-34-05 o TB1-N-34-06 o TB1-N-34-07 o TB1-N-34-08 o TB1-N-34-09 • +1.05 Vpu (+2 tap) o TB1-N-11-01 o TB1-N-11-02 o TB1-N-11-03 o TB1-N-11-05 o TB1-N-11-06 o TB1-N-12-06 • +1.025 Vpu (+1 tap) o All other turbines	One Step of 9.5 MVAr at each MV bus (3 x 9.5 MVAr)	One Step of 10 MVAr at each MV bus (3 x 10 MVAr)

4. Reactive Power Capability

With the DETC settings in Table 1, MENG performed various power flow cases to determine the reactive power capability, also known as power factor capability, of the project at the POI.

Various power flow cases were created at different output levels and at different POI voltage levels. At each output level and voltage level, a lagging and leading power flow case was created. The wind turbines were dispatched to supply or absorb as much reactive power as possible to meet the PF requirement at the POI. To calculate the max reactive power that the project is capable of supplying in case of lagging PF, the turbines were set to supply as much reactive power without the voltage at their terminals exceeding 1.1 Vpu with the cap banks engaged at all output levels. In leading PF cases, the MVArs of turbines were adjusted observing the constrains in Section 2 with the cap banks de-energized at all output levels. Both the Vestas 4.3 MW and 2.0 MW turbines were dispatched at the same percentage MW and MVAr with the MW and MVAr dispatched independently to produce max reactive power capability. For example, if Vestas 4.3 MW was dispatched at 10% MW output, Vestas 2.0 MW would be dispatched at the same 10% MW output. The percentage MVAr output of both turbines would be the same. That percentage MVAr output for both turbines would be set such that the constraints outlined in Section 2 are observed. Even though it is not necessary that both turbines will be dispatched at the same percentage real and reactive power in day-to-day operations, this was done in simulations to deal with a managed number of cases.

The MENG analysis revealed that TBI wind project will be able to provide 0.95 leading to 0.95 lagging PF for the voltage range of 1.05 Vpu to 0.97 Vpu at the POI. This holds up regardless of the way the DETCs are set. The full reactive power capability of the project at different voltage levels is provided in Figure 2. As can be seen from the graph, the project can meet the lagging PF requirement at certain output levels for the voltage range of 1.05 Vpu to 0.95 Vpu. Also, the project is not able to provide 0.95 leading PF at certain output levels if the voltage at the POI is less than 0.97 Vpu. The results in Figure 2 are summarized in Table 2. The max collection system voltage when the voltage is 1.03 Vpu (with power factor of 0.95) at the POI is plotted in Figure 3. A plot showing the PF capability of the project is given in Figure 4.

A detailed tabulation of the results is given in Table 3, Table 4, Table 5, and Table 6 for the POI voltages 1.05 Vpu, 1.03 Vpu, 0.97 Vpu, and 0.95 Vpu, respectively. The results in the tables include gross real and reactive power at the 34.5kV MV buses. A negative sign in the table means leading reactive power whether at the turbine terminals or the POI.

The project can meet the lagging PF requirement at 1.05 Vpu at the POI even though the DETCs were set to allow the project to operate at a max voltage of 1.04 Vpu. The reason for the project being able to meet the PF at 1.05 Vpu at the POI is that, at that POI voltage, with full project output and all cap banks engaged in full, the turbines are able to be dispatched to provide the remaining reactive power needed to meet the PF requirement. Dispatching the turbines this way causes the voltage at the turbine terminals to be less than the case in which the turbines are initially dispatched in full and the cap banks are set to provide the remaining reactive power needed. In other words, the voltage at the turbine terminals is more sensitive to the capacitive current injection at the turbine terminals than it is sensitive to the capacitive current injected by the cap banks at the substation.

Table 2. Summary of Reactive Power Results

	0.95 PF Leading	0.95 PF Lagging	0.95 PF (both ways)
Max POI Voltage (pu)	1.05	1.05	1.05
Min POI Voltage (pu)	0.97	0.95	0.97

In summary, the project can meet the lagging PF requirement for the POI voltage range from 1.05 Vpu to 0.95 Vpu, and it can meet the leading PF requirement if the POI voltage is more than 0.97 Vpu. Overall, the project can meet the PF requirement if the voltage at the POI is in between 0.97 Vpu to 1.05 Vpu.

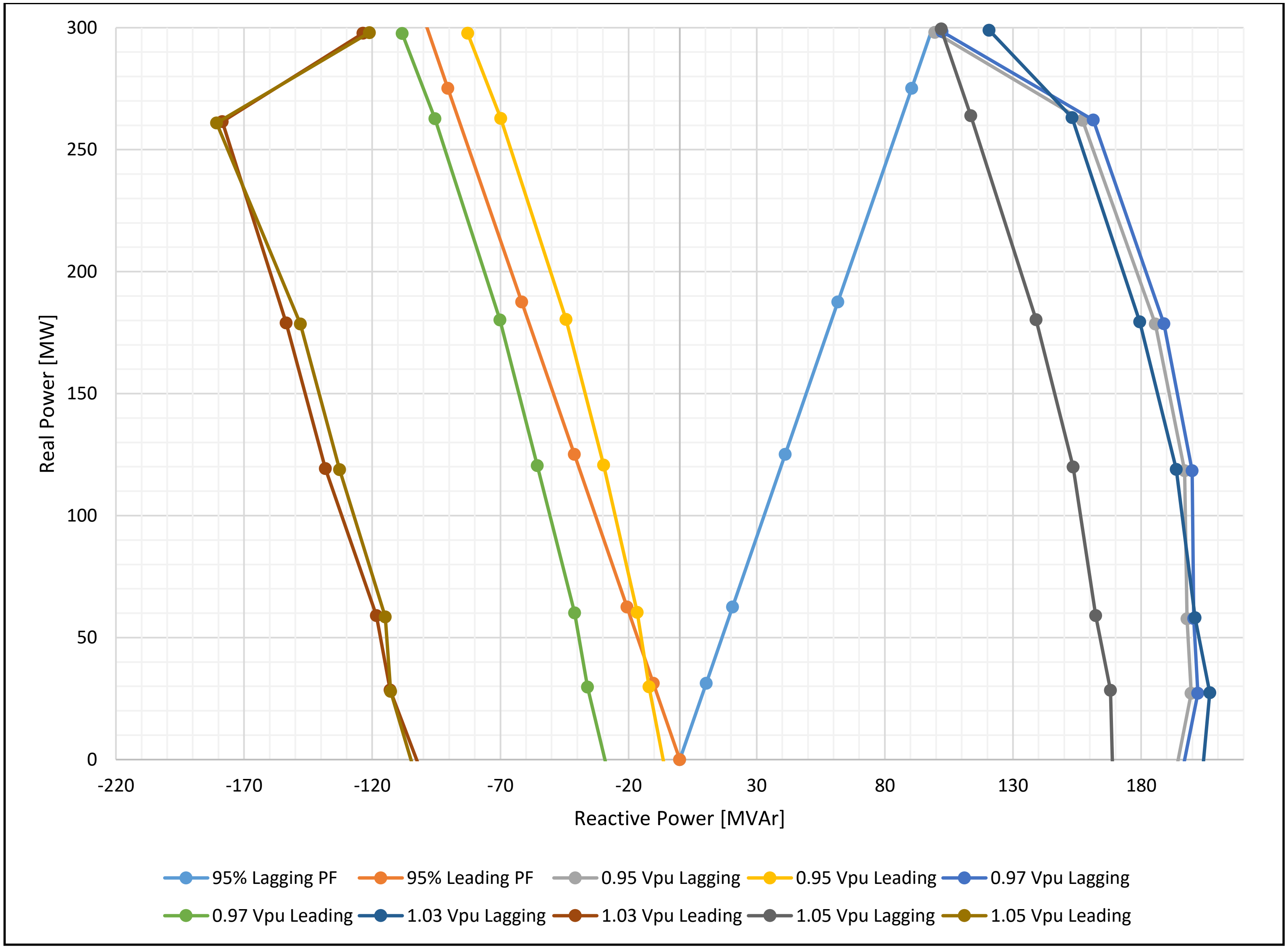

Figure 2. P-Q Capability of the Project at Different POI Voltages with Cap Banks Engaged

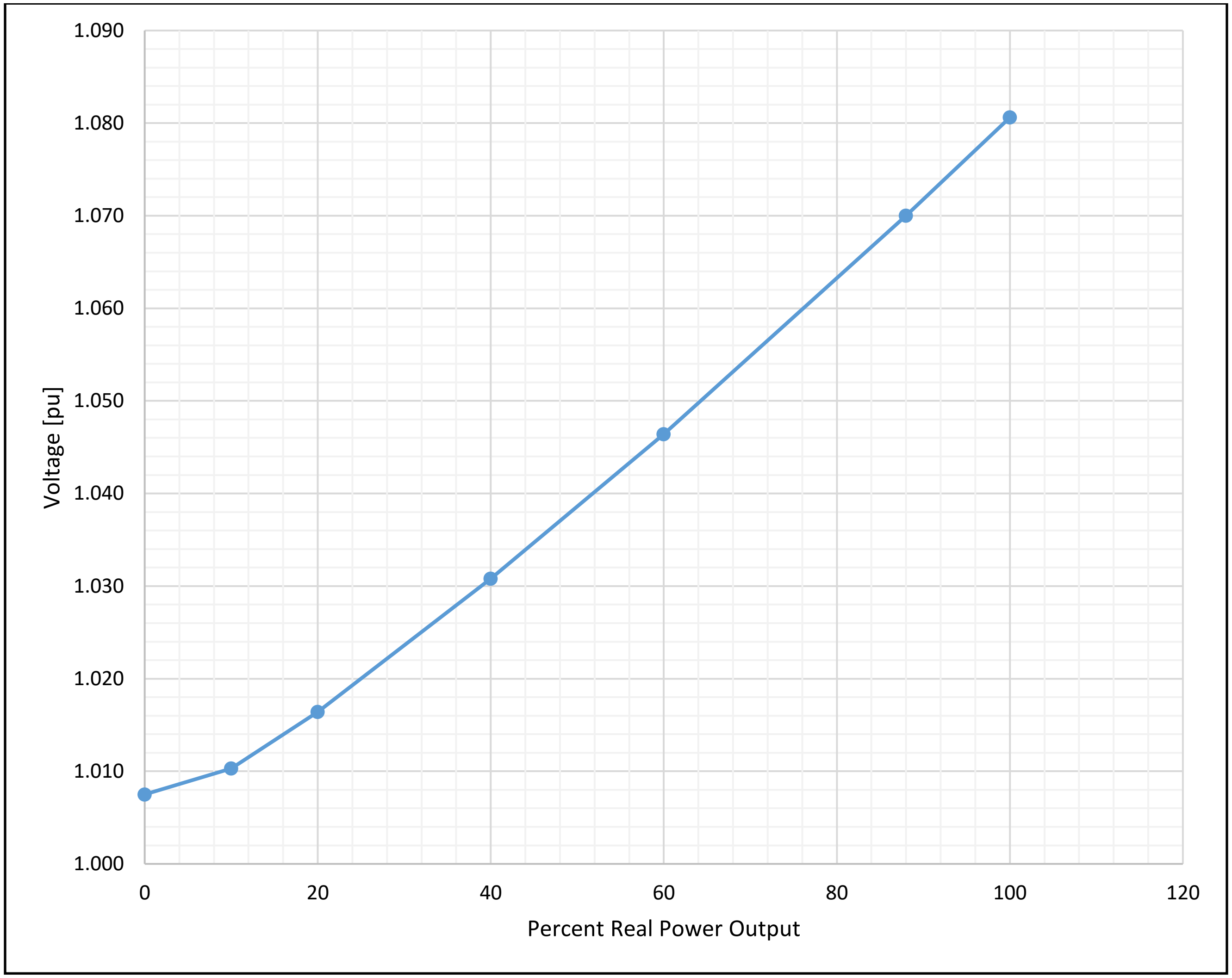

Figure 3. Maximum Collection System Voltage when POI Voltage is 1.03 Vpu while Meeting 0.95 PF

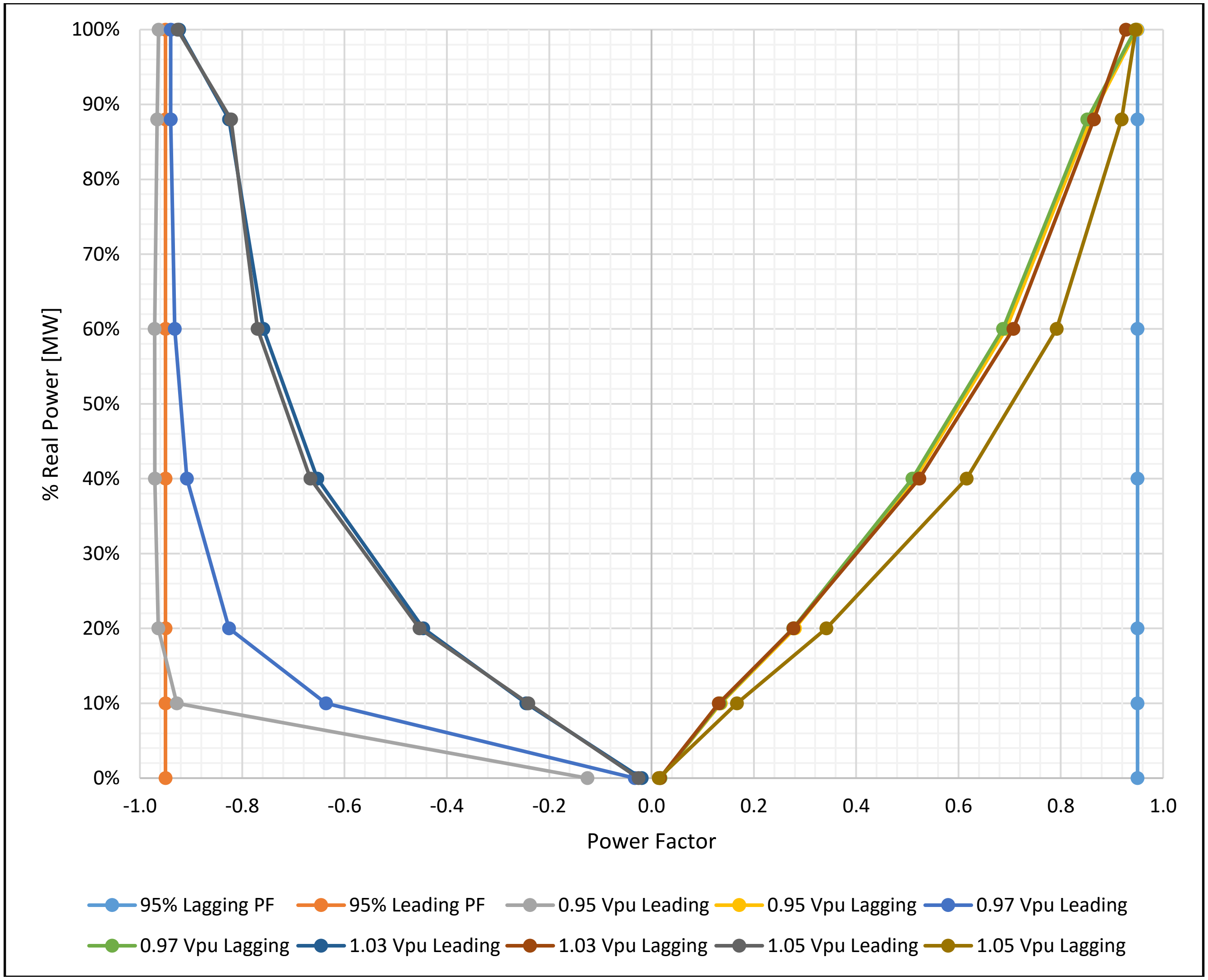

Figure 4. Power Factor Capability of the Project at Different POI Voltages

Table 3. Reactive Power Capability at V = 1.05 pu at the POI

	Leading						Lagging					
	Max Absorption MVAr						Max Supplying MVAr					
% Turbine MW	POI MW	POI MVAr	% Turbine MVAr	Bus 1 MVAr	Bus 2 MVAr	Bus 3 MVAr	POI MW	POI MVAr	% Turbine MVAr	Bus 1 MVAr	Bus 2 MVAr	Bus 3 MVAr
0	-2.6	-104.2	142.7	-38.6	-36.7	-25.5	-2.3	168.8	72.9	64.7	61.8	51.4
10	28.0	-112.8	118.4	-38.7	-38.4	-31.5	28.4	168.1	69.6	62.6	60.9	53.7
20	58.5	-114.9	118.4	-39.1	-38.8	-31.9	59.1	162.3	66.8	60.7	59.0	52.0
40	118.8	-132.7	117.5	-40.7	-42.1	-39.9	119.9	153.5	62.4	57.0	56.3	52.2
60	178.6	-148.1	117.5	-43.5	-44.9	-42.5	180.3	139.0	59.9	53.6	52.9	49.0
90	261.0	-180.7	137.5	-49.4	-50.6	-48.2	264.0	113.5	59.4	49.4	48.1	42.5
100	298.0	-121.0	100.0	-29.3	-30.1	-28.3	299.5	102.0	79.8	47.7	46.3	40.1

Table 4. Reactive Power Capability at V = 1.03 pu at the POI

	Leading						Lagging					
	Max Absorption MVAr						Max Supplying MVAr					
% Turbine MW	POI MW	POI MVAr	% Turbine MVAr	Bus 1 MVAr	Bus 2 MVAr	Bus 3 MVAr	POI MW	POI MVAr	% Turbine MVAr	Bus 1 MVAr	Bus 2 MVAr	Bus 3 MVAr
0	-2.0	-102.0	79.6	-36.5	-35.3	-26.8	-3.3	204.1	100.0	79.4	76.1	62.4
10	28.6	-113.0	81.9	-38.0	-38.0	-32.7	27.4	206.8	97.7	78.1	76.3	66.8
20	59.0	-118.4	83.6	-39.4	-39.4	-33.9	58.1	201.1	94.7	76.1	74.3	65.1
40	119.2	-138.3	85.4	-42.2	-43.5	-41.7	119.0	193.8	90.1	72.4	72.0	66.6
60	179.0	-153.5	85.1	-44.8	-46.0	-44.2	179.4	179.4	87.4	68.9	68.6	63.3
90	261.5	-178.5	81.1	-48.2	-49.3	-47.5	263.2	153.0	86.7	64.7	63.4	55.8
100	297.7	-123.6	100.0	-29.6	-30.4	-28.8	299.0	120.7	100.0	55.2	53.8	46.5

Table 5. Reactive Power Capability at V = 0.97 pu at the POI

	Leading						Lagging					
	Max Absorption MVAr						Max Supplying MVAr					
% Turbine MW	POI MW	POI MVAr	% Turbine MVAr	Bus 1 MVAr	Bus 2 MVAr	Bus 3 MVAr	POI MW	POI MVAr	% Turbine MVAr	Bus 1 MVAr	Bus 2 MVAr	Bus 3 MVAr
0	-1.0	-29.0	33.3	-10.7	-10.6	-7.6	-3.4	196.4	100.0	76.9	73.7	60.2
10	29.7	-36.0	35.6	-12.1	-12.5	-10.7	27.2	202.1	100.0	76.9	75.2	65.7
20	60.1	-41.0	37.3	-13.5	-13.8	-11.9	57.8	200.6	100.0	76.6	74.9	65.4
40	120.5	-55.6	38.6	-15.9	-16.8	-16.4	118.4	199.9	100.0	75.4	75.2	69.5
60	180.2	-70.1	37.9	-18.3	-19.1	-18.7	178.7	188.9	100.0	73.5	73.3	67.6
90	262.7	-95.5	33.6	-21.7	-22.4	-22.0	262.2	161.3	100.0	69.3	68.1	59.7
100	297.6	-108.3	54.3	-23.1	-23.8	-23.6	298.4	102.3	100.0	49.6	48.5	41.7

Table 6. Reactive Power Capability at V = 0.95 pu at the POI

	Leading						Lagging					
	Max Absorption MVAr						Max Supplying MVAr					
% Turbine MW	POI MW	POI MVAr	% Turbine MVAr	Bus 1 MVAr	Bus 2 MVAr	Bus 3 MVAr	POI MW	POI MVAr	% Turbine MVAr	Bus 1 MVAr	Bus 2 MVAr	Bus 3 MVAr
0	-0.8	-6.3	17.8	-2.4	-2.7	-1.5	-3.4	193.8	100.0	76.1	73.0	59.5
10	29.8	-12.0	20.1	-3.8	-4.3	-3.7	27.2	199.5	100.0	76.0	74.4	64.9
20	60.3	-16.6	21.6	-5.0	-5.5	-4.7	57.8	197.9	100.0	75.8	74.1	64.6
40	120.7	-29.7	22.9	-7.4	-8.2	-8.3	118.4	197.0	100.0	74.6	74.4	68.7
60	180.4	-44.3	22.2	-9.8	-10.5	-10.6	178.6	185.6	100.0	72.5	72.4	66.7
90	262.8	-69.8	17.8	-13.2	-13.7	-13.9	262.0	157.2	100.0	68.2	67.1	58.7
100	297.7	-82.8	27.1	-14.6	-15.1	-15.4	298.1	99.5	100.0	47.8	46.7	40.1

5. Capacitor Bank Arrangement

Table 1 provides the total cap bank reactive power needed per real power bus to comply with the 0.95 PF requirement at the POI. The cap bank steps per MV bus depend on the flicker requirement, which is 3% at the POI. Per the IEEE std. 1036-2010, the voltage change in percentage at the POI due to CAP switching is given by the following equation:

$$\Delta V = \frac{Q_{capacitor}}{S_{sc}} \times 100\%$$

Where S_{sc} is the three-phase short circuit at the POI. Based on RFI #8, the present three-phase short circuit currents at the HV buses are given in Table 7. Based on the table, the cap bank step size that would cause a 3% voltage change at the POI is 78.8 MVAr. Thus, one step of 10 MVAr of cap banks per real power bus is acceptable.

Table 7. Three-Phase Short Circuit at HV Bus

	Three-Phase Short Circuit
MPT HV Bus	6.6 kA

Based on Figure 2, the need for cap banks is dependent on the POI voltage and the MW output. In general, cap banks are needed if the project is operating in lagging PF mode and the output is 260 MW or more. Alternatively, the cap banks can be left engaged at lagging PF mode at all output levels while depending on the turbines dynamic reactive power capability to adjust the reactive power required at the POI.

The findings of this report depend on the design information available as of the issue date above. Any changes to the design information and model assumptions could impact the findings and recommendations of this report.

Appendix 1. Modeling Assumptions

- High Voltage Transmission-line Specifications

  The preliminary overhead transmission line structure was provided via email on 02/25/2019. The parameters per mile are given in the table below. The line has a length of 0.6 miles. The positive, negative and zero sequence data of the line was calculated using ETAP:

Conductor type (Phase and Ground):	795 Drake (Single)
Positive/negative sequence resistance:	0.0599 Ω/mile
Positive/negative sequence reactance:	0.5665 Ω/mile
Positive/negative sequence capacitance:	7.52×10^{-6} Siemens/mile
Zero sequence resistance:	0.5496 Ω/mile
Zero sequence reactance:	2.2129 Ω/mile
Shield wire height:	85 ft
Number of shield wires:	2
Spacing between shield wires:	25 ft
Phase conductor height:	60 ft
Phase conductor spacing	$D_{AB} = 15\ ft$
	$D_{BC} = 15\ ft$
	$D_{CA} = 30\ ft$

- Underground Cable Specification

  The collector system design is provided in Appendix 2. Impedance data from WTEC cables were considered based on a temperature of 105 °C. Their positive and zero sequence data is provided below.

Table 8. Cable Positive Sequence Impedance

MV cable	R (μΩ/ft)	X_L (μΩ/ft)	Capacitance (μF/kft)
1250 MCM	21	36	0.12009
1000 MCM	26	37	0.09174
750 MCM	35	39	0.0823
500 MCM	50	42	0.07041
4/0 AWG	118	46	0.05273
1/0 AWG	251	52	0.04237

Table 9. Cable Zero Sequence Impedance

MV cable	R (μΩ/ft)	X_L (μΩ/ft)	Capacitance (μF/kft)
1250 MCM	238	122	0.12009
1000 MCM	277	173	0.09174
750 MCM	233	102	0.0823
500 MCM	300	169	0.07041
4/0 AWG	330	119	0.05273
1/0 AWG	501	169	0.04237

- Vestas V110 2.0 MW Specifications Based on 0051-0155 V01 - V100 110-2.0 2.2MW 50 60Hz GenSpec.pdf and Transformer Specifications Based on 29064903 TRAFO 2.2VCS 34.5 D 60 A4 JST data.pdf. Reactive power capability is attached in Appendix 5.

Rating:		2.0 MW	
Max leading MVArs:		0.406	
Max lagging MVArs:		0.583	
Turbine Transformer Voltage:		34.5kV/0.69 kV	
Turbine Transformer Winding configuration:		Dyn5	
Turbine Transformer No load losses:		7.5 kW @ V= 1.1 pu	
Hub Height:		80 meters	
Downtower cable:	Vendor:	Nexan	
	Positive sequence resistance:	0.347 Ohm/km	
	Positive sequence reactance:	0.272 Ohm/km	
	Positive sequence capacitance:	0.25 microF/km	
DETC:		Regulated bus	Low voltage bus
		Min/Max tap	±5%
		Number of taps	5
Positive Sequence Impedance [BASE=2.08 MVA]:		Z%	11.66
		X/R	14.468

- Vestas V136 4.3 MW Specifications Based on TB Flats TSA Ex. B.1.1.2.b Performance Specification (V136).pdf and Transformer Specifications Based on 180813 5150kVA 345kV TPS 0068 6644 60Hz Dyn5 A4 Siemens NEO ECO PRELIMI.pdf. Reactive power capability is attached in Appendix 5.

Rating:		4.3 MW	
Voltage:		0.72 kV	
Max leading MVArs:		1.08 @ 0.9 pu and 1.52 @ 1.1 pu	
Max lagging MVArs:		1.71 @ 0.9 pu and 1.99 @ 1.1 pu	
Turbine Transformer Winding configuration:		Dyn5	
Turbine Transformer No load losses:		10.2 kW @ V= 1.1 pu	
Hub Height:		82 meters	
Downtower cables:	Vendor:	Nexan	
	Positive sequence resistance:	0.347 Ohm/km	
	Positive sequence reactance:	0.272 Ohm/km	
	Positive sequence capacitance:	0.25 microF/km	
DETC		Regulated bus	Low voltage bus
		Min/Max tap	±5%
		Number of taps	5
Positive sequence impedance [BASE=5.15 MVA]:		Z%	9.54
		X/R	15.35

- MPT specifications based on exhibit N.

Rating:	75/100/125 MVA	
Voltage:	230kV/34.5 kV/13.8 kV	
Cooling Class:	ONAN/ONAF1/ONAF2	
Winding configuration:	Ynyn0	
No load losses:	41 kW	
DETC	Regulated bus	MV bus
	Min/Max tap	±5%
	Number of taps	5
Positive sequence impedance [BASE=75 MVA]:	Z%	7.5%
	X/R	40

Appendix 2. Collection System Design

The study was based on the collector system at the time of performing the study:

Feeder	From Node	To Node	Length (ft)	Cable Size
11	JB11-1	sub11	8185.039	'1250'
11	JB11-2	JB11-1	8151.1	'1250'
11	JB11-3	JB11-2	6739.767	'1250'
11	JB11-4	JB11-3	8237.558	'1250'
11	TB1-N-11-01	JB11-4	5073.156	'1250'
11	TB1-N-11-02	TB1-N-11-01	1458.591	'1000'
11	TB1-N-11-03	TB1-N-11-02	6398.559	'750'
11	TB1-N-11-04	TB1-N-11-03	1349.352	'500'
11	TB1-N-11-05	TB1-N-11-04	1462.444	'4/0'
11	TB1-N-11-06	TB1-N-11-05	1387.876	'1/0'
12	JB12-1	sub12	8142.284	'1250'
12	TB1-N-12-03	TB1-N-12-02	1477.932	'750'
12	TB1-N-12-04	TB1-N-12-03	1594.181	'500'
12	TB1-N-12-05	TB1-N-12-04	1423.982	'4/0'
12	TB1-N-12-06	TB1-N-12-05	1480.449	'1/0'
12	TB1-N-12-02	TB1-N-12-01	1537.267	'1000'
12	JB12-2	JB12-1	8096.63	'1250'
12	JB12-3	JB12-2	6754.327	'1250'
12	JB12-4	JB12-3	8340.042	'1250'
12	TB1-N-12-01	JB12-4	7931.039	'1250'
13	JB13-1	sub13	8132.095	'1250'
13	TB1-N-13-05	TB1-N-13-04	1427.984	'4/0'
13	TB1-N-13-06	TB1-N-13-05	1427.783	'1/0'
13	TB1-N-13-03	TB1-N-13-02	1499.047	'750'
13	TB1-N-13-04	TB1-N-13-03	1408.632	'500'
13	TB1-N-13-02	TB1-N-13-01	1475.362	'1000'
13	JB13-2	JB13-1	8034.469	'1250'
13	JB13-3	JB13-2	6779.795	'1250'
13	TB1-N-13-01	JB13-3	4901.124	'1250'
14	JB14-1	sub14	8127.457	'1250'
14	TB1-N-14-06	TB1-N-14-05	1477.553	'1/0'
14	TB1-N-14-04	TB1-N-14-03	1494.496	'500'
14	TB1-N-14-05	TB1-N-14-04	1428.626	'4/0'
14	JB14-2	JB14-1	7999.961	'1250'
14	JB14-3	JB14-2	6817.186	'1250'
14	TB1-N-14-01	JB14-3	1918.942	'1250'
14	TB1-N-14-02	TB1-N-14-01	1427.446	'1000'
14	TB1-N-14-03	TB1-N-14-02	4839.831	'750'
21	TB2-N-21-02	TB2-N-21-01	1515.555	'1/0'
21	TB2-N-21-01	JB21-3	7257.54	'4/0'
21	JB21-1	sub21	7813.34	'4/0'
21	JB21-2	JB21-1	7863.814	'4/0'
21	JB21-3	JB21-2	7296.552	'4/0'
22	JB22-1	sub22	7818.269	'1250'
22	TB2-N-22-05	TB2-N-22-04	1463.189	'4/0'
22	TB2-N-22-06	TB2-N-22-05	1453.848	'1/0'
22	TB2-N-22-04	TB2-N-22-03	1428.87	'500'

Feeder	From Node	To Node	Length (ft)	Cable Size
22	TB2-N-22-02	TB2-N-22-01	1439.852	'1000'
22	TB2-N-22-03	TB2-N-22-02	1562.008	'750'
22	JB22-2	JB22-1	7845.789	'1250'
22	TB2-N-22-01	JB22-3	7719.883	'1250'
22	JB22-3	JB22-2	7304.696	'1250'
23	TB1-N-23-06	TB1-N-23-05	1312.909	'1/0'
23	TB1-N-23-05	TB1-N-23-04	1351.291	'4/0'
23	TB1-N-23-04	TB1-N-23-03	1418.645	'500'
23	TB1-N-23-03	TB1-N-23-02	1417.231	'750'
23	TB1-N-23-02	TB1-N-23-01	1498.622	'1000'
23	JB23-3	JB23-2	7312.451	'1250'
23	JB23-1	sub23	7836.33	'1250'
23	JB23-2	JB23-1	7844.172	'1250'
23	TB1-N-23-01	JB23-3	3049.967	'1250'
24	TB1-N-24-02	TB1-N-24-01	3560.716	'750'
24	TB1-N-24-03	TB1-N-24-02	1194.289	'500'
24	TB1-N-24-04	TB1-N-24-03	6058.864	'500'
24	TB1-N-24-01	JB24-1	5615.97	'750'
24	TB1-N-24-05	TB1-N-24-04	1397.849	'4/0'
24	TB1-N-24-06	TB1-N-24-05	1433.679	'1/0'
24	JB24-1	sub24	7834.377	'750'
25	JB25-2	JB25-1	7666.426	'1250'
25	JB25-3	JB25-2	8245.549	'1250'
25	TB2-N-25-01	JB25-4	5642.348	'1250'
25	TB2-N-25-02	TB2-N-25-01	2824.793	'1000'
25	TB2-N-25-03	TB2-N-25-02	1710.677	'750'
25	TB2-N-25-04	TB2-N-25-03	1210.975	'500'
25	TB2-N-25-05	TB2-N-25-04	1367.881	'4/0'
25	TB2-N-25-06	TB2-N-25-05	1416.919	'1/0'
25	JB25-4	JB25-3	5526.339	'1250'
25	JB25-1	sub25	7673.72	'1250'
31	JB31-1	sub31	7698.864	'1250'
31	TB1-N-31-03	TB1-N-31-02	1329.581	'750'
31	TB1-N-31-04	TB1-N-31-03	5156.406	'500'
31	TB1-N-31-05	TB1-N-31-04	1361.708	'4/0'
31	TB1-N-31-06	TB1-N-31-05	1286.734	'1/0'
31	TB1-N-31-02	TB1-N-31-01	1313.529	'1000'
31	JB31-2	JB31-1	7716.72	'1250'
31	JB31-3	JB31-2	8265.379	'1250'
31	TB1-N-31-01	JB31-3	6040.545	'1250'
32	TB1-N-32-04	TB1-N-32-03	1355.817	'500'
32	TB1-N-32-05	TB1-N-32-04	1384.874	'4/0'
32	TB1-N-32-06	TB1-N-32-05	1127.222	'1/0'
32	TB1-N-32-02	TB1-N-32-01	1357.432	'1000'
32	JB32-1	sub32	7662.22	'1250'
32	TB1-N-32-03	TB1-N-32-02	1346.081	'750'
32	JB32-2	JB32-1	7715.054	'1250'
32	TB1-N-32-01	JB32-2	8365.255	'1250'
33	TB1-N-33-03	TB1-N-33-02	4730.804	'750'
33	TB1-N-33-04	TB1-N-33-03	1258.454	'500'

Feeder	From Node	To Node	Length (ft)	Cable Size
33	TB1-N-33-05	TB1-N-33-04	1276.29	'4/0'
33	TB1-N-33-06	TB1-N-33-05	1317.377	'1/0'
33	TB1-N-33-02	TB1-N-33-01	1292.817	'1000'
33	JB33-3	JB33-2	5399.057	'1250'
33	TB1-N-33-01	JB33-3	8215.404	'1250'
33	JB33-1	sub33	7607.207	'1250'
33	JB33-2	JB33-1	7760.405	'1250'
34	TB1-N-34-02	TB1-N-34-01	1224.65	'1000'
34	TB1-N-34-03	TB1-N-34-02	5150.104	'750'
34	TB1-N-34-04	TB1-N-34-03	2051.575	'500'
34	TB1-N-34-05	TB1-N-34-04	1072.231	'500'
34	TB1-N-34-06	TB1-N-34-05	1067.071	'500'
34	TB1-N-34-07	TB1-N-34-06	1088.588	'4/0'
34	TB1-N-34-08	TB1-N-34-07	4032.535	'4/0'
34	TB1-N-34-09	TB1-N-34-08	1011.889	'1/0'
34	TB1-N-34-10	TB1-N-34-09	1044.771	'1/0'
34	JB34-1	sub34	3762.532	'1000'
34	TB1-N-34-01	JB34-1	8335.207	'1000'
34	TB1-N-34-11	TB1-N-34-10	1083.903	'1/0'

Appendix 3. PSSE Single Line Diagram

(Click to Open attachment)

Appendix 4. RFI #29

(Click to Open attachment)

Appendix 5. Turbine Reactive Power Capability

(Click to Open attachment)