REACTIVE POWER STUDY REPORT

KINGS POINT WIND PROJECT

100.440000

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PREPARED BY:	**CURTIS ROE**	**05/22/2020** DATE
REVIEWED BY:	**AHMAD ABDULLAH**	**05/26/2020** DATE
REVIEWED BY:	**STEVE LAY**	**06/01/2020** DATE
APPROVED BY:	**MICHAEL EBERT**	**05/27/2020** DATE

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Acronyms

DETC	De-Energized Tap Changer
Ft	Foot
FERC	Federal Energy Regulatory Commission
HV	High Voltage
KP	Kings Point Wind Project
LGIA	Large Generator Interconnection Agreement
MPT	Main Power Transformer
MV	Medium Voltage
MVAr	Mega-Volt-Ampere reactive
MW	Mega-Watt
Mortenson	Mortenson Engineering Services, Inc.
OLTC	On Load Tap Changer
PF	Power Factor
POI	Point of Interconnection
pu	Per Unit
Vpu	Voltage in Per Unit

1. Executive Summary

1.1. Overview

Mortenson Engineering Services, Inc. (Mortenson) completed a reactive power study for the Kings Point Wind Project (KP). The main purpose of the study is to report on the reactive power capabilities of KP assessing if the system can meet the power factor (PF) requirement at the high side of the Main Power Transformer (MPT) using the reactive power capabilities of its turbines or if any automatic capacitive switched shunts are needed to meet this requirement.

According to the Large Generator Interconnection Agreement (LGIA), KP needs to comply with Federal Energy Regulatory Commission (FERC) order number 827. The power factor requirement is 0.95 lagging to 0.95 leading, measured at the high voltage side of the MPT, per RFI#4 (response on 6/28/2019 from Tenaska). Additionally, the project is required to offset any reactive power the high voltage side of the MPT at standstill (zero wind) per the same RFI. It should be noted that the project is not required to meet the PF requirement in the transition from standstill to cut-off wind speed generation per the same RFI. Specifically, the project is required to offset the charging reactive power at the high side of the MPT in case of zero generation. The voltage range for the power factor requirement is 0.95 Vpu to 1.05 Vpu at high voltage side of the MPT.

Kings Point Wind Project is located in Jasper, Barton, Dade and Lawrence Counties, of the state of Missouri. It consists of fifty-seven (57) Vestas V120-2.2 and twelve (12) Vestas V110-2.0 wind turbine generators (WTG) totaling 149.4 MW. The project contains a single 3-phase, 3-winding MPT rated 99/132/165 MVA. The MPT is equipped with both a de-energized tap changer (DETC) and an on load tap changer (OLTC), both of which are located on the high voltage windings. A 15.04-mile transmission line will interconnect the proposed Kings Point Wind Project Substation to the point of interconnection (POI) at the La Russell 161 kV Substation, which is owned by Empire District Electric Company.

This study includes the most up-to date collection system, MPTs, turbines and their nacelle mounted transformers as of 05/18/2020.

1.2. Key Findings

The study found that Kings Point can meet the PF requirement at the high voltage side of the MPT for the POI voltage range from 0.95 Vpu to 1.05 Vpu if 48.6 MVAr of switched capacitor banks are installed at the low side of the MPT. The capacitor banks should be divided into three steps of 16.2 MVAr each. The OLTC has to be set to schedule the voltage at the low side at 1.046 Vpu at all generation conditions except for zero generation. The OLTC programming needs to be used along with setting all the WTT DETCs per Table 1 for the project to meet the PF requirement. The project will need to ensure that these tap settings are implemented prior to energization.

Additionally, the analysis showed that no reactor banks are needed to offset collection system charging reactive power under zero generation as long as the OLTC is scheduled to control the voltage at the low side of the MPT to 1.0046 Vpu. The OLTC programming can be done using the power plant controller and SCADA.

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

2. Modeling Methodology

Mortenson built a detailed phasor-domain model of the 149.4 MW KP 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 tie-line to the POI was modeled as a pi-equivalent segment with impedance data based on a specific tower configuration as is given in Appendix 1. This data was communicated via RFI #2 (from Tenaska dated 05/20/2019).

Per RFI#4, (from Tenaska dated 6/26/2019), there are no limitations on the operation of the OLTC. The OLTC has the capability to control the substation voltage ±10% through 33 discrete steps. Mortenson allowed the OLTC to move unconditionally to produce a reactive power capability on the project. As this was done, the results were used to select a set point for the OLTC that produced the corresponding reactive power capability of the project.

Turbines were modeled as machines with a reactive power capability according to their reactive power curves. The V120 2.2 machines have standstill reactive power capability (real power 0.0 MW reactive power 0.15 MVAr). Whereas, the V110 2.0 machines have zero output at standstill (zero wind). Mortenson also modeled the standstill reactive power capability of the project per RFI #4 (from Tenaska dated 05/01/2019). Wind turbine transformer (WTT) impedances and the MPT impedance was modeled along with their no-load losses. The down-tower cables in the wind turbines were also modeled. Several impedance values for the WTTs were provided and Mortenson selected the worst-case impedance for this report.

To create the unfettered reactive power capability of the project, several power flow cases were created. At each POI voltage level, all turbines were dispatched to meet the PF requirement at the high voltage side of the MPT by absorbing or supplying the maximum possible reactive power while observing the following constraints:

1. The voltage on the turbine terminals is kept within the range 0.95 Vpu to 1.05 Vpu.
2. The voltage on the 34.5 kV collection system is maintained in the range 1.1 Vpu to 0.9 Vpu.

If the PF requirement could not be achieved using only turbine reactive power capabilities, then a capacitor or reactor bank would be added to the system to meet the PF requirement.

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. Collection cable impedance data is included in Appendix 4. Turbine reactive power capability is attached in Appendix 5.

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

3. Capacitor Bank Size and DETC Tap Settings

Several power flow cases were performed to determine the capacitor bank size and DETC tap settings of the substation MPT and the WTTs. An ideal capacitor bank and DETC setting would allow the project to meet the PF requirement at the high voltage side of the MPT for the widest possible voltage range while keeping the voltage at the Vestas 2.2 MW turbine terminal within 5% to maximize turbine reactive power production.

The voltage at the POI is scheduled over a range of voltages from 0.95 Vpu 1.05 Vpu, with the turbines set to provide maximum reactive power. To be able to select the DETC setting for either the WTTs or the MPT, the highest turbine terminal voltage must be determined. The highest turbine terminal voltage would occur under the following conditions:

- POI voltage is 1.05 Vpu
- Turbines are producing maximum reactive power
- 48.6 MVAr of capacitor banks are engaged
- Project is producing full real power

Under the conditions above, the project would meet the PF requirement at the high side of the MPT. The highest terminal voltage would be 1.24 Vpu. Therefore, a voltage drop of greater than 10% is needed to bring the voltage down to the 1.05 Vpu limit needed at the Vestas 2.2 MW turbine terminals for the turbines to be able to provide maximum reactive power output. Thus, a decision was made to tap all the DETCs of the Vestas 2.2 MW turbine WTTs two positions, except KP 58 (bus number 211075). The WTT DETC tap settings are listed in Table 1.

Table 1. WTTs DETC tap settings

Turbine Name	Type	Tap	Turbine Name	Type	Tap
KP 133	2.2	2	KP 18	2.2	2
KP 128	2.2	2	KP 17	2.2	2
KP 120	2.2	2	KP 22	2.2	2
KP 134	2.2	2	KP 27	2.2	2
KP 126	2.2	2	KP 16	2.2	2
KP 114	2.2	2	KP 14	2.2	2
KP 129	2.2	2	KP 11	2.2	2
KP 106	2.2	2	KP 20	2.2	2
KP 119	2.2	2	KP 19	2.2	2
KP 65	2.2	2	T-8	2.2	2
KP 67	2	0	T-9	2.2	2
KP 62	2	0	T-10	2.2	2
KP 56	2.2	2	KP 91	2.2	2
KP 53	2	0	KP 98	2.2	2
KP 51	2	0	KP 99	2.2	2
KP 58	2.2	1	KP 85	2.2	2
KP 47	2	0	KP 94	2.2	2
KP 44	2	0	KP 124	2.2	2
KP 39	2	0	KP 118	2.2	2
KP 28	2	0	KP 96	2.2	2
KP 25	2	0	KP 90	2.2	2
T-32	2.2	2	KP 100	2.2	2
KP 36	2.2	2	KP 105	2.2	2
T-34	2.2	2	KP 113	2.2	2
KP 31	2.2	2	KP 69	2.2	2
KP 35	2.2	2	KP 63	2.2	2
KP 46	2	0	KP 60	2.2	2
KP 30	2.2	2	KP 74	2.2	2
KP 52	2.2	2	KP 72	2.2	2
KP 55	2	0	KP 68	2.2	2
KP 50	2	0	KP 59	2.2	2
KP 33	2.2	2	T-78	2.2	2
KP 29	2.2	2	T-71	2.2	2
KP 26	2.2	2	KP 73	2.2	2
			KP 80	2.2	2

Based on tapping the 2.2 MW WTTs, another case was run with the project producing full output with a leading power factor to test to make sure that the wind turbine terminal voltage would not fall below 0.95 Vpu. The case confirmed the terminal voltage and that tapping the WTTs as stated above was confirmed as a valid option.

In summary, the project needs 48.6 MVAr of shunt capacitor banks in service to meet the PF requirement at the high side of the MPT. That the capacitor banks need to be used along with tapping the WTTs up to bring the turbine terminal voltage to acceptable levels.

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

4. Reactive Power Capability

Mortenson performed various power flow cases to determine the reactive power capability, also known as power factor capability, of the project at the high voltage side of the MPT.

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 high voltage side of the MPT. To calculate the maximum reactive power that the project is capable of supplying with a lagging PF, the turbines were set to supply as much reactive power without the voltage at their terminals exceeding 1.1 Vpu with the capacitor banks engaged at all output levels. In leading PF cases, the reactive power of the turbines was adjusted using the constraints in Section 2 and with the capacitor banks de-energized at all output levels. Both the Vestas 2.2 and 2.0 turbines were dispatched at the same percentage of real and reactive power output. The real and reactive power was dispatched independently to produce maximum reactive power capability. For example, if the Vestas 2.2 was dispatched at 10% real power output, then the Vestas 2.0 would be dispatched at the same 10% real power output. The percentage of reactive power output of both turbines would be the same. That percentage of reactive power output for both turbines would be set such that the constraints outlined in Section 2 were observed. Even though it is not necessary that both turbines will be dispatched at the same percentage of real and reactive power in day-to-day operations, this was done in simulations as a simplifying assumption.

Mortenson ran special cases with the standstill reactive power capability as given in RFI#4 to assess whether reactor banks were needed at zero MW generation.

The analysis revealed that KP will be able to provide 0.95 leading to 0.95 lagging PF for the voltage range of 0.95 Vpu to 1.05 Vpu at the POI. The full unfettered reactive power capability of the project at different voltage levels is provided in Figure 1.

A detailed tabulation of the results are given in Table 2, Table 3, Table 4, and Table 5 for 0.95, 0.98, 1.04, and 1.05 Vpu POI voltage. The results in the tables include real power dispatch for the Vestas 2.0 and the Vestas 2.2 machines; reactive test (Lagging or Leading); POI real and reactive power; percent of test system reactive output (% Q Output), MPT tap, switched shunt output, medium voltage (34.5kV) bus voltage; and minimum and maximum terminal bus voltage.

Based on Table 2, Table 3, Table 4, and Table 5, the medium voltage bus can be scheduled at 1.045 Vpu so that the project can meet the PF at the high side of the MPT. Thus, another set of power flow cases was performed with the OLTC targeting the 1.035 Vpu at the low side of the MPT. Figure 2 shows the KP reactive power capability for 1.0387 Vpu at the substation medium voltage bus. Table 6 is the data graphed in Figure 2. An analysis of whether this OLTC setting ensures minimum OLTC operations per year was not performed.

In summary, KP can meet the PF requirement at the high voltage side of the MPT for the POI voltage range from 0.95 Vpu to 1.05 Vpu. The OLTC can be set to target 1.0387 Vpu at the low side of the MPT.

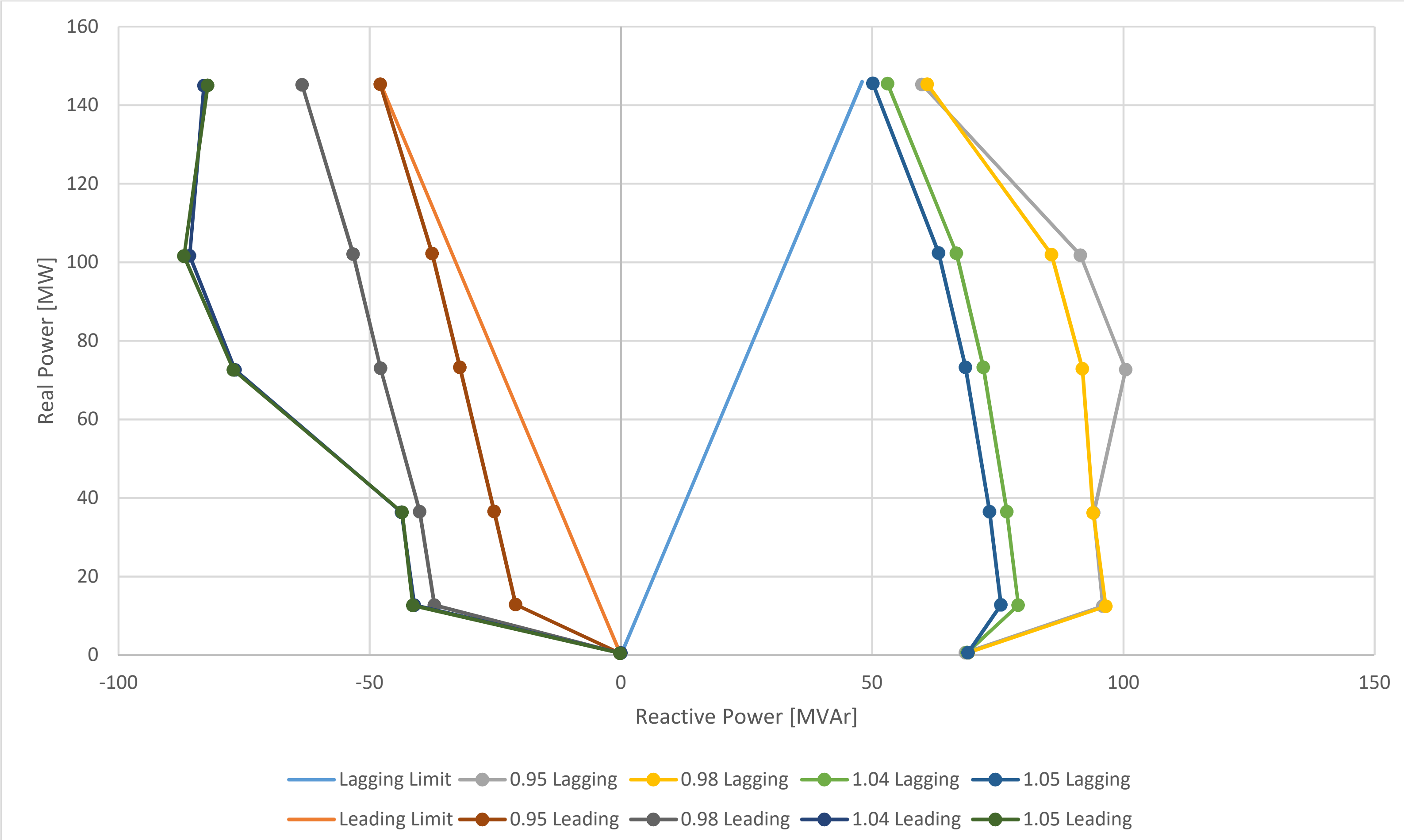

Figure 1. P-Q Capability of the Project at Different POI Voltages Including Capacitor Banks

Table 2. Reactive Power Capability at V = 0.95 pu at the POI

POI Voltage [pu]	Dispatch [%]	Reactive Test	MPT HV Real Power [MW]	MPT HV Reactive Power [MVAr]	MPT Tap Position	Capacitor Banks [MVAr]	Substation Voltage [pu]	Minimum Terminal Voltage [pu]	Maximum Terminal Voltage [pu]	Minimum Collection Voltage [pu]	Maximum Collection Voltage [pu]
0.95	0	Leading	0.443	-0.179	-5	0	0.9808	0.9256	0.9809	0.9801	0.9809
0.95	0	Lagging	0.584	68.596	-2	48.6	1.0643	1.0207	1.065	1.0643	1.0674
0.95	9	Leading	12.833	-20.955	-16	0	1.0259	0.9535	1.0124	1.0235	1.026
0.95	9	Lagging	12.497	95.938	11	48.6	1.0358	1.0219	1.0623	1.0358	1.048
0.95	25	Leading	36.542	-25.216	-16	0	1.0222	0.9521	1.0099	1.0216	1.025
0.95	25	Lagging	36.224	94.112	11	48.6	1.0354	1.0229	1.0649	1.0354	1.0518
0.95	50	Leading	73.216	-32.045	-16	0	1.0167	0.95	1	1.0167	1.026
0.95	50	Lagging	72.634	100.469	16	48.6	1.0261	1.0269	1.0812	1.0261	1.0514
0.95	70	Leading	102.251	-37.587	-16	0	1.0128	0.95	1	1.0128	1.0276
0.95	70	Lagging	101.759	91.446	16	48.6	1.0177	1.0198	1.078	1.0177	1.0477
0.95	100	Leading	145.302	-47.883	-16	0	1.005	0.9501	1	1.005	1.0281
0.95	100	Lagging	145.288	59.895	7	48.6	1.0233	1.0142	1.0595	1.0233	1.0571

Table 3. Reactive Power Capability at POI Voltage 0.98 pu

POI Voltage [pu]	Dispatch [%]	Reactive Test	MPT HV Real Power [MW]	MPT HV Reactive Power [MVAr]	MPT Tap Position	Capacitor Banks [MVAr]	Substation Voltage [pu]	Minimum Terminal Voltage [pu]	Maximum Terminal Voltage [pu]	Minimum Collection Voltage [pu]	Maximum Collection Voltage [pu]
0.98	0	Leading	0.442	-0.155	0	0	0.9802	0.9251	0.9803	0.9795	0.9803
0.98	0	Lagging	0.599	69.138	2	48.6	1.069	1.0252	1.0697	1.069	1.0721
0.98	9	Leading	12.676	-37.122	-16	0	1.0363	0.95	1.0128	1.0314	1.0363
0.98	9	Lagging	12.422	96.505	15	48.6	1.0411	1.0268	1.0674	1.0411	1.0533
0.98	25	Leading	36.507	-40.075	-16	0	1.0345	0.9506	1.014	1.0317	1.0361
0.98	25	Lagging	36.168	94.01	16	48.6	1.035	1.0225	1.0645	1.035	1.0514
0.98	50	Leading	73.047	-47.829	-16	0	1.0278	0.95	1	1.0277	1.0346
0.98	50	Lagging	72.871	91.877	16	48.6	1.0365	1.0272	1.082	1.0365	1.0594
0.98	70	Leading	102.08	-53.272	-16	0	1.0241	0.95	1	1.0241	1.0362
0.98	70	Lagging	101.968	85.715	16	48.6	1.0323	1.0266	1.0844	1.0323	1.0603
0.98	100	Leading	145.176	-63.445	-16	0	1.0165	0.95	1.0025	1.0165	1.0368
0.98	100	Lagging	145.323	61.005	11	48.6	1.0295	1.02	1.0655	1.0295	1.0632

Table 4. Reactive Power Capability at POI Voltage 1.04 pu

POI Voltage [pu]	Dispatch [%]	Reactive Test	MPT HV Real Power [MW]	MPT HV Reactive Power [MVAr]	MPT Tap Position	Capacitor Banks [MVAr]	Substation Voltage [pu]	Minimum Terminal Voltage [pu]	Maximum Terminal Voltage [pu]	Minimum Collection Voltage [pu]	Maximum Collection Voltage [pu]
1.04	0	Leading	0.472	-0.003	8	0	0.9909	0.9354	0.991	0.9902	0.991
1.04	0	Lagging	0.649	68.903	12	48.6	1.0652	1.0216	1.0659	1.0652	1.0683
1.04	9	Leading	12.704	-41.1	-9	0	1.0461	0.9555	1.0227	1.0405	1.0461
1.04	9	Lagging	12.717	79.089	16	48.6	1.0594	1.0259	1.0726	1.0594	1.067
1.04	25	Leading	36.307	-43.682	-8	0	1.0375	0.9503	1.0169	1.034	1.0388
1.04	25	Lagging	36.461	76.831	16	48.6	1.0584	1.026	1.0744	1.0584	1.0701
1.04	50	Leading	72.628	-76.795	-16	0	1.0568	0.9559	1.015	1.0531	1.061
1.04	50	Lagging	73.216	72.116	16	48.6	1.0561	1.0262	1.0818	1.0561	1.0741
1.04	70	Leading	101.628	-85.831	-16	0	1.048	0.9501	1.0087	1.0461	1.0555
1.04	70	Lagging	102.322	66.773	16	48.6	1.053	1.0264	1.0849	1.053	1.0761
1.04	100	Leading	144.96	-82.959	-13	0	1.0352	0.9529	1.0213	1.0352	1.0519
1.04	100	Lagging	145.473	53.07	16	48.6	1.042	1.0225	1.0724	1.042	1.0732

Table 5. Reactive Power Capability at Voltage 1.05 pu

POI Voltage [pu]	Dispatch [%]	Reactive Test	MPT HV Real Power [MW]	MPT HV Reactive Power [MVAr]	MPT Tap Position	Capacitor Banks [MVAr]	Substation Voltage [pu]	Minimum Terminal Voltage [pu]	Maximum Terminal Voltage [pu]	Minimum Collection Voltage [pu]	Maximum Collection Voltage [pu]
1.05	0	Leading	0.468	-0.147	11	0	0.9827	0.9274	0.9827	0.9819	0.9827
1.05	0	Lagging	0.615	69.088	13	48.6	1.0685	1.0248	1.0693	1.0685	1.0716
1.05	9	Leading	12.6	-41.381	-7	0	1.042	0.9514	1.0186	1.0363	1.042
1.05	9	Lagging	12.756	75.637	16	48.6	1.0627	1.0257	1.0736	1.0627	1.0696
1.05	25	Leading	36.311	-43.551	-7	0	1.0414	0.9542	1.0209	1.038	1.0427
1.05	25	Lagging	36.487	73.392	16	48.6	1.0617	1.0259	1.0754	1.0617	1.0726
1.05	50	Leading	72.577	-77.144	-14	0	1.052	0.951	1.0099	1.0483	1.0561
1.05	50	Lagging	73.239	68.609	16	48.6	1.0594	1.0261	1.0818	1.0594	1.0765
1.05	70	Leading	101.598	-86.962	-15	0	1.0502	0.9513	1.0111	1.0482	1.0577
1.05	70	Lagging	102.366	63.256	16	48.6	1.0563	1.0262	1.0847	1.0563	1.0786
1.05	100	Leading	145.017	-82.269	-12	0	1.0401	0.9578	1.0263	1.0401	1.0568
1.05	100	Lagging	145.526	50.148	16	48.6	1.0461	1.0231	1.0746	1.0461	1.0764

Figure 2. P-Q Capability of the Project at 1.046 Vpu at the MV Bus Including Capacitor Banks

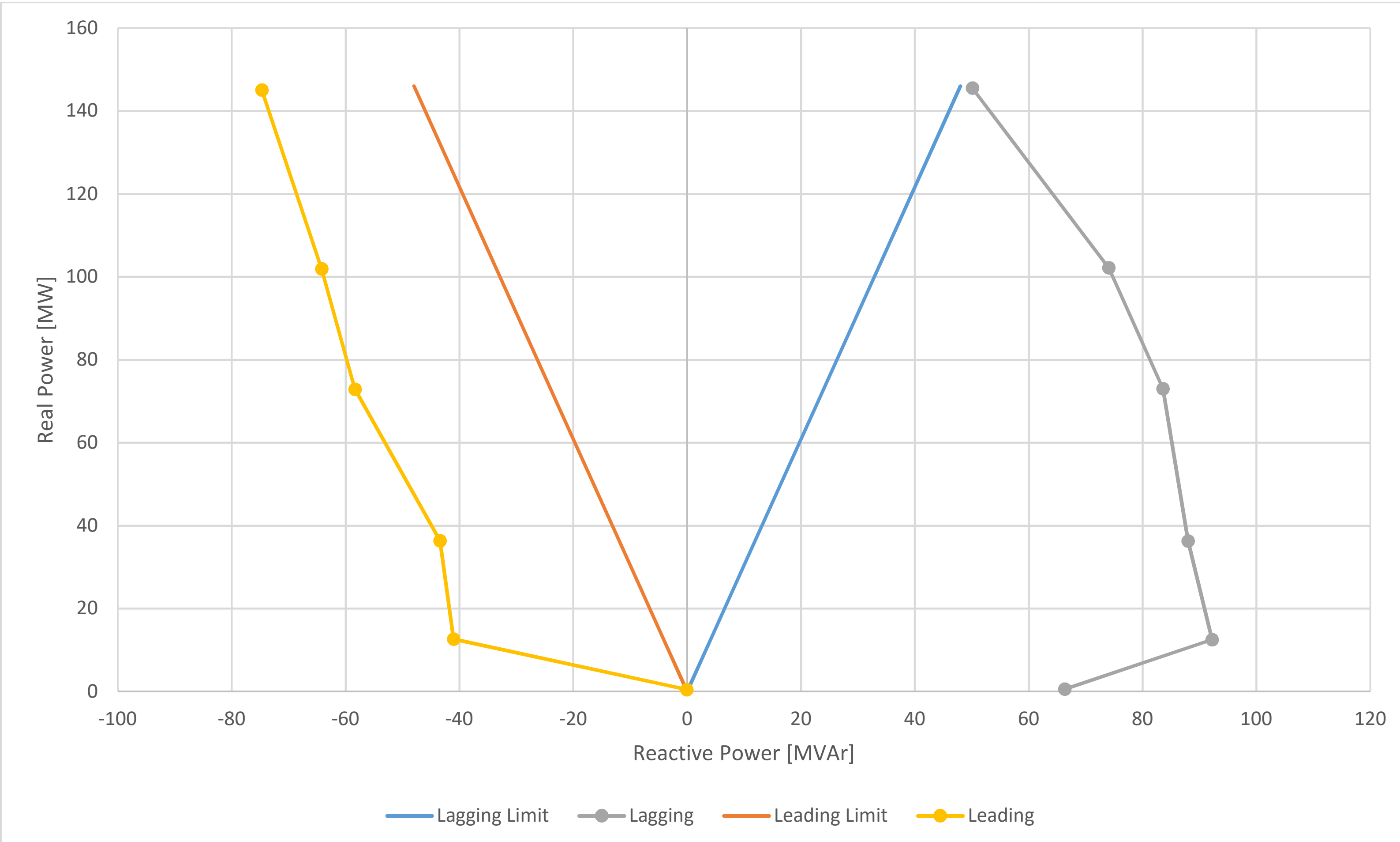

Table 6. Reactive Power Capability at POI Voltage Approaching 1.046 pu

POI Voltage [pu]	Dispatch [%]	Reactive Test	MPT HV Real Power [MW]	MPT HV Reactive Power [MVAr]	MPT Tap Position	Capacitor Banks [MVAr]	Substation Voltage [pu]	Minimum Terminal Voltage [pu]	Maximum Terminal Voltage [pu]	Minimum Collection Voltage [pu]	Maximum Collection Voltage [pu]
1	0	Leading	0.45	-0.09	3	0	0.9819	0.9267	0.982	0.9812	0.982
1	0	Lagging	0.564	66.311	9	48.6	1.0437	1.0013	1.0445	1.0437	1.0468
1	9	Leading	12.667	-41.048	-15	0	1.0461	0.9556	1.0228	1.0405	1.0461
1	9	Lagging	12.525	92.195	16	48.6	1.0459	1.0266	1.0688	1.0459	1.0569
1	25	Leading	36.326	-43.414	-15	0	1.0452	0.958	1.0249	1.0419	1.0465
1	25	Lagging	36.306	87.99	15	48.6	1.0469	1.0265	1.0711	1.0469	1.0615
1	50	Leading	72.896	-58.326	-16	0	1.0358	0.9501	1	1.0346	1.0413
1	50	Lagging	73.047	83.55	15	48.6	1.0451	1.0268	1.0819	1.0451	1.0658
1	70	Leading	101.956	-64.184	-16	0	1.0315	0.95	1	1.0315	1.042
1	70	Lagging	102.211	74.054	13	48.6	1.046	1.0268	1.0853	1.046	1.0709
1	100	Leading	145.072	-74.726	-16	0	1.0233	0.9505	1.0093	1.0233	1.0417
1	100	Lagging	145.537	50.08	8	48.6	1.0462	1.0231	1.0746	1.0462	1.0765

5. Capacitor Bank Arrangement

The Mortenson analysis showed that a 48.6 MVAr capacitor bank is needed to meet the PF requirement at the POI. The capacitor banks are recommended to be split evenly into three steps of 16.2 MVAr each. Per the IEEE std. 1036-2010, the voltage change, ΔV, in percentage at the POI due to capacitor switching is given by the following equation:

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

Where $Q_{capacitor}$ is the capacitor step size [MVAr] and S_{sc} is the three-phase short circuit [MVA]. The PSSE modeled three-phase short circuit currents at the POI (substation HV bus) and MV collector system substation bus and the calculated voltage change are given in Table 7.

Table 7. IEEE 1036 Voltage Change

	$I_{sc}[kA]$	$S_{sc}[MVA]$	$Q_{capacitor}[MVAr]$	$\Delta V[\%]$
POI	16.783	4680	16.2	0.35
High Side of the MPT	6.723	1875	16.2	0.86
MV Collector System	20.489	1224	16.2	1.32

The voltage change results in Table 7 are below the threshold (1.5% ΔV) for the flicker limit.

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

6. Results

The study found that KP can meet the PF requirement at the POI for the POI voltage range from 0.95 Vpu to 1.05 Vpu. This can be done using a combination of the reactive capability of the wind turbines along with switched static capacitor banks installed on the medium voltage bus in the substation.

Additionally, the Mortenson analysis showed that no reactor banks are needed to meet the PF requirement of KP. However, 48.6 MVAr of capacitor banks are needed to be installed on the MV side of the MPT to meet the PF requirement at the high voltage side of the MPT. The capacitor banks are recommended to be split evenly into three steps 16.2 MVAr each.

Appendix 1. Modeling Assumptions

- High Voltage Tie-line Specifications

  The overhead line structure that connects the project to the POI was based on the data in Table 8. This data was communicated via RFI #2 (from Tenaska dated 05/20/2019). The line has a length of 15.04 miles (design length – no sag included). The positive sequence data of the line was calculated using ETAP (version 19.0.1).

Table 8. High Voltage Tie-Line Specification

Conductor Type (Phase and Ground):	795 Drake (Multiple)
Positive/Negative Sequence Resistance [Ω/mile]	0.1194
Positive/Negative Sequence Reactance [Ω/mile]	0.75485
Positive/Negative Sequence Capacitance [µSiemens/mile]	5.67251
Zero Sequence Resistance [Ω/mile]	0.60905
Zero Sequence Reactance [Ω/mile]	2.40106
Zero Sequence Capacitance [µSiemens/mile]	3.22697
Shield Wire Height [ft]:	85
Number of Shield Wires:	2
Spacing Between Shield Wires [ft]:	50
Phase Conductor Height [ft]:	60
Phase Conductor Spacing [ft]:	$D_{AB} = 15$
	$D_{BC} = 15$
	$D_{CA} = 30$

- Utility Contribution

  Utility fault current data is summarized in Table 9. The utility fault data was obtained via RFI #2, (from Tenaska response dated 5/20/2019).

Table 9. Utility Fault Current Data

	Fault Apparent Power [MVA]	**Fault Current [kA]**	**X/R**
Three Phase to Ground	4,350.09	15.6	8.54
Single Line to Ground	4,322.19	15.5	8.70

- Underground Cable Specification

  Cable impedance model data is based on the data sheets in Appendix 5, these data sheets were received from WTEC dated 08/21/2019 (submittal #W25-3.0). Impedance data based on an operating temperature of 105°C (RHO =181 rho =3002) was used for this assessment as this is worst case. The positive sequence parameters are shown in Table 10. The zero sequence parameters are shown in Table 11.

Table 10. Cable Positive Sequence Impedance

MV Cable Size	R [μΩ/ft]	X_L [μΩ/ft]	Capacitance [μF/kft]
1250 MCM	21	37	0.12009
1000 MCM	26	38	0.09174
750 MCM	35	40	0.08230
500 MCM	50	43	0.07041
4/0 AWG	118	48	0.05273
1/0 AWG	251	54	0.04237

Table 11. Cable Zero Sequence Impedance

MV Cable Size	R [μΩ/ft]	X_L [μΩ/ft]	Capacitance [μF/kft]
1250 MCM	266	137	0.12009
1000 MCM	309	196	0.09174
750 MCM	252	108	0.08230
500 MCM	330	189	0.07041
4/0 AWG	353	129	0.05273
1/0 AWG	545	214	0.04237

- Vestas 2.2 MW Specifications are based on information within 0056-7860 V02 - 2.2MW Transformer Datasheets.pdf. This data was communicated via KP RFI #4 (from Tenaska dated 06/25/2019). Additionally, transformer details within Trafo SGB Test Report - 729429 Test Report 5003010.pdf, communicated via KP RFI #38 (from Solas Energy Consulting dated 04/22/2020) were used. Applicable data for the Vestas 2.2 MW machines is summarized in Table 12.

Table 12. Vestas 2.2 MW Model Data

Machine Rating [MVA]		2.326	
[pu base= 2.326 MVA]	**Synchronous Xdi**	3.282	
	Transient X'di	0.1975	
	Subtransient X''di	0.1256	
	Negative Sequence X2v	0.1975	
	Zero Sequence X0i	0.3976	
	Leakage Reactance	0.07718	
Leading Reactive Power at Peak Output [MVAr]		0.723	
Lagging Reactive Power at Peak Output [MVAr]		0.723	
Transformer Voltage [kV]		34.5/0.69	
Transformer Winding Configuration		Dyn5	
Number of Taps		5	
Transformer No load losses [kW]		5.031	
Hub height [m]		100	
Impedance [base=100 MVA]		Z	4.804
		X/R	11.61
Downtower cables	**Vendor**	Nexan	
	Positive sequence resistance [Ω/km]	0.272	
	Positive sequence reactance [Ω/km]	0.272	
	Positive sequence capacitance [μF/km]	0.250	
	Zero sequence resistance [Ω/km]	0.554	
	Zero sequence reactance [Ω/km]	0.272	
	Zero sequence capacitance [μF/km]	0.250	

- Vestas 2.0 MW Specifications are based on information within 0039-2022_V01 - 2MW-MK7 Transformer Datasheets.pdf. This data was communicated via KP RFI #4 (from Tenaska dated 06/25/2019). Additionally, transformer details within Trafo SGB Test Report - 729429 Test Report 5003010.pdf, communicated via KP RFI #38 (from Solas Energy Consulting dated 04/22/2020) were used. Applicable data for the Vestas 2.0 MW machines is summarized in Table 13.

Table 13. Vestas 2.0 MW Model Data

Machine Rating [MVA]		2.093	
[pu base= 2.093 MVA]	**Synchronous Xdi**	3.282	
	Transient X'di	0.1975	
	Subtransient X''di	0.1256	
	Negative Sequence X2v	0.1975	
	Zero Sequence X0i	0.3976	
	Leakage Reactance	0.07718	
Leading Reactive Power at Peak Output [MVAr]		0.583	
Lagging Reactive Power at Peak Output [MVAr]		0.406	
Transformer Voltage [kV]		34.5/0.69	
Transformer Winding Configuration		Dyn5	
Transformer No load losses [kW]		5.031	
Hub height [m]		100	
Impedance [base=100 MVA]		Z	4.804
		X/R	11.61
Downtower cables	**Vendor**	Nexan	
	Positive sequence resistance [Ω/km]	0.272	
	Positive sequence reactance [Ω/km]	0.272	
	Positive sequence capacitance [μF/km]	0.250	
	Zero sequence resistance [Ω/km]	0.554	
	Zero sequence reactance [Ω/km]	0.272	
	Zero sequence capacitance [μF/km]	0.250	

- MPT specifications based on the transformer test report (received from Liberty Utilities dated 04/15/2020 - submittal #8). Applicable MPT data is included in Table 14.

Table 14. MPT Model Data

Rating [MVA]:	99/132/165	
Voltage [kV]:	161/34.5/14.1	
Cooling Class:	ONAN/ONAF/ONAF	
Winding configuration:	YNyn0	
No Load Losses [kW]:	112	
OLTC:	Regulated Bus	medium voltage bus
	Min/Max Tap	±10%
	Number of Taps	33
DETC:	Regulated Bus	medium voltage bus
	Min/Max Tap	±5%
	Number of Taps	5
Positive sequence impedance [base=99 MVA]:	Z%	10.26
	X/R	80.932
Zero sequence impedance [base=99 MVA]:	Z%	10.26
	X/R	80.932

Appendix 2. Collection System Design

The study was based on the collector system design as of 05/18/2020:

Feeder	From Node	To Node	Length [ft]	Cable Size
11A	fdr11A	sub11	1	'1250'
11A	JB11A-1	KP 67	143.8349	'1000'
11A	JB11A-2	JB11A-1	9739.009	'750'
11A	JB11A-3	JB11A-2	3174.217	'1/0'
11A	KP 106	JB11A-3	655.0645	'1/0'
11A	KP 114	JB11A-3	2955.082	'1/0'
11A	KP 119	JB11A-2	20817.54	'500'
11A	KP 120	KP 119	3236.004	'500'
11A	KP 126	KP 133	1347.638	'1/0'
11A	KP 128	KP 120	1448.092	'4/0'
11A	KP 129	KP 106	4670.23	'1/0'
11A	KP 133	KP 134	2425.853	'1/0'
11A	KP 134	KP 128	1177.772	'1/0'
11A	KP 62	JB11A-1	1001.818	'4/0'
11A	KP 65	fdr11A	3899.182	'1250'
11A	KP 67	KP 65	3373.738	'1000'
11B	fdr11B	sub11	1	'1000'
11B	JB11B-1	KP 53	214.5608	'500'
11B	KP 25	KP 28	1116.757	'1/0'
11B	KP 28	T-32	1194.155	'1/0'
11B	KP 39	KP 44	1522.309	'4/0'
11B	KP 44	KP 47	1231.476	'4/0'
11B	KP 47	JB11B-1	2589.295	'500'
11B	KP 51	JB11B-1	3096.392	'4/0'
11B	KP 53	KP 56	3426.08	'500'
11B	KP 56	KP 58	1208.551	'750'
11B	KP 58	fdr11B	2063.04	'1000'
11B	T-32	KP 39	2971.645	'1/0'
12A	fdr12A	sub12	1	'1250'
12A	JB12A-1	fdr12A	26542.3	'1250'
12A	KP 11	KP14	2603.534	'4/0'
12A	KP 16	KP 17	1333.317	'500'
12A	KP 17	KP 18	1146.537	'500'
12A	KP 18	KP 19	1602.617	'750'
12A	KP 19	JB12A-1	70.21489	'750'
12A	KP 20	JB12A-1	3721.726	'1/0'
12A	KP 22	KP 20	1021.05	'1/0'
12A	KP 27	KP 22	2312.056	'1/0'
12A	KP14	KP 16	1372.36	'500'
12A	T-10	KP 11	6628.822	'1/0'
12A	T-8	T-9	1212.089	'1/0'

Feeder	From Node	To Node	Length [ft]	Cable Size
12A	T-9	T-10	1144.502	'1/0'
12B	fdr12B	sub12	1	'1250'
12B	JB12B-1	KP 46	4583.112	'750'
12B	KP 26	KP 30	4492.317	'1/0'
12B	KP 29	KP 26	1195.933	'1/0'
12B	KP 30	T-34	1247.531	'4/0'
12B	KP 31	KP 35	1272.952	'1/0'
12B	KP 33	KP 29	1243.924	'1/0'
12B	KP 35	JB12B-1	578.5732	'1/0'
12B	KP 36	JB12B-1	2531.011	'500'
12B	KP 46	KP50	1756.525	'750'
12B	KP 52	fdr12B	3188.687	'1250'
12B	KP 55	KP 52	2294.078	'1000'
12B	KP50	KP 55	1136.976	'1000'
12B	T-34	KP 36	1297.875	'500'
13A	fdr13A	sub13	1	'1250'
13A	JB13A-1	fdr13A	8056.926	'1250'
13A	KP 59	JB13A-1	8802.444	'4/0'
13A	KP 60	KP 59	2348.608	'1/0'
13A	KP 63	KP 60	4783.681	'1/0'
13A	KP 68	JB13A-1	4015.536	'500'
13A	KP 69	KP 63	1172.244	'1/0'
13A	KP 72	KP 68	1100.634	'500'
13A	KP 73	KP 80	2436.916	'1/0'
13A	KP 74	KP 72	1189.244	'500'
13A	KP 80	T-78	2744.466	'1/0'
13A	T-71	KP 73	1407.935	'1/0'
13A	T-78	KP 74	1378.538	'4/0'
13B	fdr13B	sub13	1	'1250'
13B	JB13B-1	fdr13B	17003.86	'1250'
13B	KP 100	KP 94	1389.4	'1/0'
13B	KP 105	KP 100	1419.796	'1/0'
13B	KP 113	KP 105	2514.478	'1/0'
13B	KP 118	KP 96	4407.832	'1/0'
13B	KP 124	KP 118	1371.074	'1/0'
13B	KP 85	JB13B-1	1493.541	'750'
13B	KP 90	KP98	7189.598	'4/0'
13B	KP 91	KP 85	1490.822	'500'
13B	KP 94	JB13B-1	1486.72	'4/0'
13B	KP 96	KP 90	1100.423	'1/0'
13B	KP 99	KP 91	1423.707	'500'
13B	KP98	KP 99	3183.012	'500'

Appendix 3. PSSE Single Line Diagram

(Click to open attachment)

Appendix 4. Cable Impedance Data

(Click to open attachment)

Appendix 5. Turbine Reactive Power Capability

(Click to open attachment)