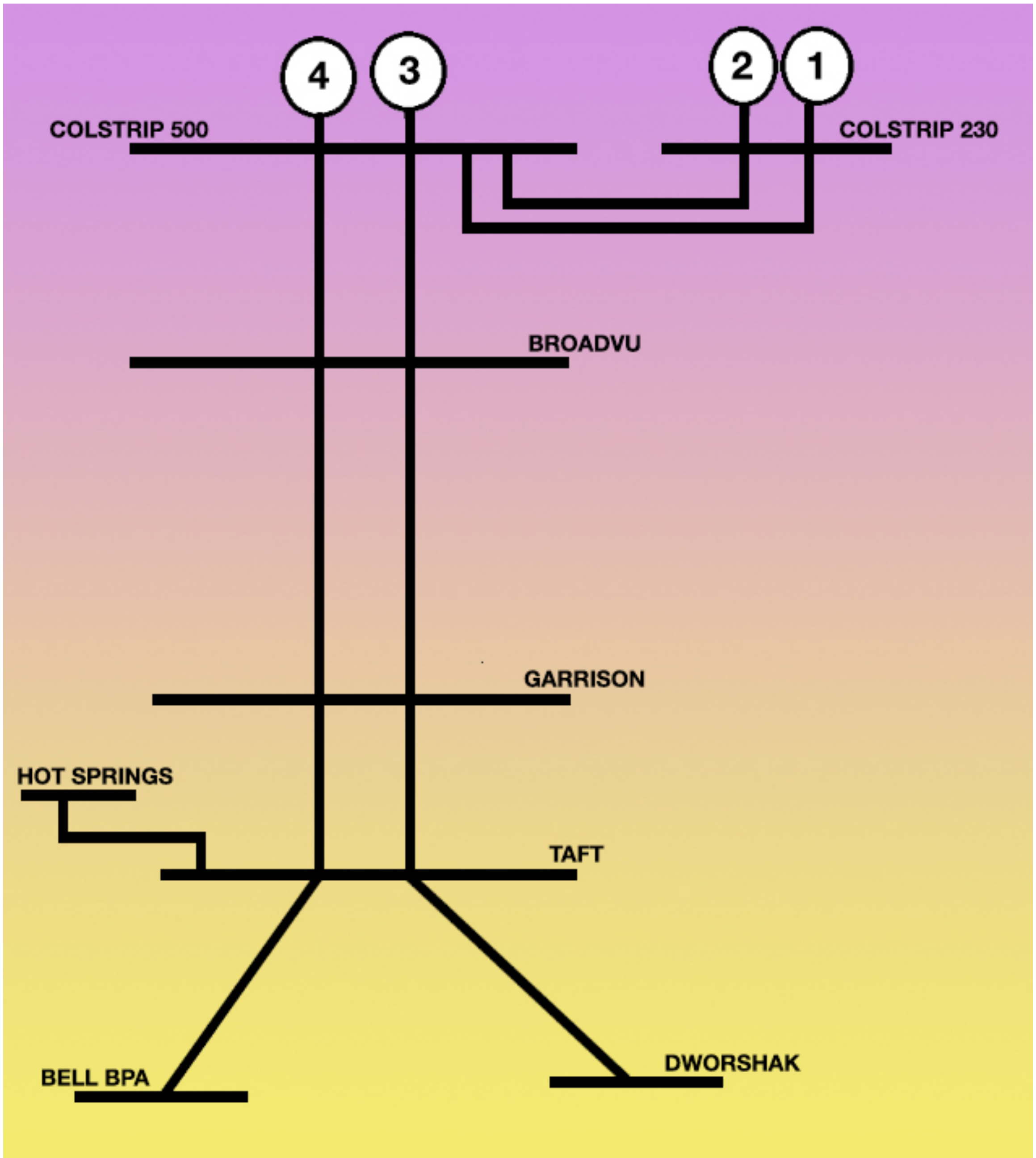
Repurposing the Colstrip Transmission System

A white paper explaining the transmission questions that arise when considering the retirement of coal fired generation facilities and the addition of new renewable resources on the Colstrip Transmission System.



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Forward

This white paper explains the transmission questions that arise when considering the retirement of coal fired generation facilities and the addition of new renewable resources on the Colstrip Transmission System (CTS). The white paper also contains a discussion of several potential mitigations to address these questions and the range of costs associated with making this transition. Four scenarios are examined, each with a different amount of Colstrip Generation (Units 1 through 4) retiring and a similar amount of wind energy added to the system.

No new engineering analysis was done specifically for the preparation of this white paper. Rather, the paper is based primarily on my knowledge of high-voltage transmission systems and my extensive experience with the Colstrip Transmission System (CTS), including participation in numerous other transmission studies of that system over the past 44 years. I also rely on my deep involvement in the design and implementation of the existing Remedial Action Scheme (RAS) at Colstrip, which is an important component surrounding much of this discussion (see Acceleration Trend Relay (ATR) in note 3 at the end of this paper).

Several engineering studies that touch on this topic have been completed by various groups recently. While each of these studies (listed below in this paper) endeavored to answer some basic questions about the feasibility of retiring the coal-fired generation at Colstrip and adding wind generation, none of them have answered the basic question of the adequacy or feasibility of any proposed RAS (see note 3) intended to properly replace the ATR. The purpose of the ATR is to protect the Montana transmission from critical contingencies on the CTS (see note 2).

Most of these questions will ultimately have to be answered through additional transmission studies and engineering efforts well beyond those that have been done so far. This white paper identifies this future study work and also some of the other financial and policy questions that will ultimately have to be decided by the various commercial entities involved.

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Note About the Author: As an employee of Montana Power Company (MPC) and Northwestern Energy Corporation (NWE), for over 38 years Chuck Stigers was directly involved in the engineering design studies and the planning and operational studies of the Colstrip Transmission System (CTS). During that time Dr. Stigers performed a variety of studies[1] on the CTS and was tasked with leading the team that designed the Remedial Action Scheme currently functioning at Colstrip. Dr. Stigers earned his MS and PhD degrees in physics from The University of Arkansas in 1968 and 1970. He is currently employed by Utility System Efficiencies, Inc. as a Principal Power Systems Engineer. Since 2011 he has continued to perform transmission study work. Much of this study work involved applying his knowledge of the CTS, and working with a model of the ATR to properly represent that device in dynamic simulations.

Renewable Northwest

This paper was commissioned by Renewable Northwest, a non-profit renewable energy advocacy organization based in Portland, Oregon.

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[1] Power flow analysis (steady state network performance), Fault duty analysis, Dynamic stability analysis (transient stability performance), Sub-synchronous Resonance analysis, Transient Switching Analysis., RAS design analysis and engineering design.

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Executive Summary

This paper explains the transmission questions that arise when considering the retirement of coal fired generation facilities at Colstrip and the addition of new renewable resources on the Colstrip Transmission System (CTS). Several potential mitigations to address these questions, and the range of costs associated with making this transition, are discussed. Four scenarios are examined, each with a different amount of Colstrip Generation (Units 1 through 4) retiring and a similar amount of wind energy added to the system.

Scenario 1: Colstrip 1 and 2 retire; 610 MW of wind energy is added to the CTS.

Under this scenario there should be no important power flow issues (see Note 1) associated with this fairly modest change in the resources at Colstrip. However, there would be a need to design a Remedial Action Scheme (RAS)[2] capable of providing wind generator tripping for certain critical transmission outages on the CTS to assure transient stability is maintained (see Note 2). The design study for this "Wind RAS" should take about 3-6 months. It would be essential for this RAS to coordinate well with the Acceleration Trend Relay (ATR)—the current RAS for the Colstrip Units—and the other existing RAS protection schemes on the CTS. To achieve this coordination between the "Wind RAS" and the ATR, timing is critical. The "Wind RAS" would be required to trip the appropriate amount of wind generation after the ATR has reached its trip decision, but before it is too late to properly protect the system.

The "Wind RAS" would be subject to review by the various WECC reliability committees (particularly the Remedial Action Scheme Reliability Subcommittee, or RASRS) that are tasked with the protection of the reliability of the Western Interconnection. While there are no significant technical barriers to designing such a RAS, one should anticipate a lengthy review process. This should be expected to be a very thorough and detailed review of the physical design of the RAS, and could require 1-2 years after the design study effort is complete.

[2] Remedial Action Scheme (RAS – also sometimes called an Special Protection Scheme (SPS) is a protection scheme that performs operations on a system in response to certain events that go beyond the actions of simple fault protection that is provided for every transmission line. Simple fault protection detects a fault anywhere on the line and opens breakers at either end of the faulted line to "clear" the fault. A RAS may be designed to initiate actions such as generation tripping or other switching actions to prevent a system from collapsing due to a switching event. Every RAS has its own unique features.

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Scenario 2: Colstrip 1, 2 and 3 retire; 1,355 MW of wind energy is added to the CTS.

Because this scenario represents the retirement of a much greater fraction of the total capacity of the Colstrip generation, one should expect the need for more engineering analysis and design. The range of variation of the flow over Path 8 (Montana-to-Northwest) would be much greater under this scenario. This increases the demand for shunt VAr resources (see note 1) to keep the voltage well regulated as the flow varies. This variance will somewhat depend on whether any of the regulating generation (used to compensate for the variable nature of the wind) is local or remote (west of the CTS).[3]

Assuming that there is no local regulating generation the range of variation in flow on the CTS due simply to the variability of the wind power in Montana would be greater than 1,500 MW (part of this would be due to variation of other wind projects that are already in place in Montana that can be expected to be partially correlated with the "new" 1,355 MW of wind. Besides this variation, the load in eastern Montana can be expected to vary over a range of about 300 MW. This has the effect of requiring a larger number of variable VAr resources that are flexible (see note 1) to maintain the voltages in Montana within an acceptable range. Under this scenario it is necessary to study the Montana transmission system under a wider range of operation, with the expectation that any level of wind generation could last for a significant period of time, and must therefore be treated as a normal system condition.

The required "Wind RAS" for this scenario would take on a completely different character from that for Scenario 1. It would be required to operate independent of the ATR when Colstrip unit 4 is off-line for maintenance, since the ATR can only operate when at least one of the Colstrip units is present. There are two options for designing a RAS for this scenario: 1) Continue to operate the ATR for the purpose of making the tripping decision of the remaining Colstrip unit (number 4); 2) Retire the ATR and use a single RAS device to provide tripping both for Colstrip 4 and for the new wind generators.

Scenario 3: All Colstrip units are retired; 2,100 MW of wind energy is added to the CTS.

This scenario would result in the maximum possible variation of the flow on the CTS. For this reason there could be some steady-state system operational difficulties. With the very limited amount of conventional generation in eastern Montana there will likely be

[3] This paper will assume that the regulating generation is remote (worst case choice). An energy storage plant such as that proposed for the Harlowton area would be a possible way to build local regulating generation. Also, a gas-fired combustion turbine (aero-derivative, not combined cycle) located in the Billings area could also be used for local regulating generation.

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significant voltage concerns that will have to be mitigated with resources such as Voltage Source Converters (VSCs, STATCOMS), Static VAr Compensators (SVCs), switched shunt devices, or other such VAR sources. The necessary RAS under this scenario may be simplified in some ways because it won't be required to coordinate with the ATR. This RAS could be simplified further by using a continuous acting VAR source such as a VSC or an SVC to minimize transient voltage deviations caused by some contingencies. Providing reliable load service under extreme calm wind conditions will also be a concern, though the CTS can certainly carry in enough power from West Coast markets, assuming that power is available. System restoration after a major outage could also be problematic. Restarting a large AC power network when most of the resources are wind powered machines with inverters that rely on a stable system with a well-regulated frequency will require a stable voltage source. Conventional generators in eastern Montana can provide some start-up. NorthWestern Energy will need to conduct a "black start study" to confirm this is enough.

Scenario 4: This scenario considers any system benefits from different locations of wind generators when all Colstrip units are retired and 2,100 MW of wind energy is added to the CTS.

With the contemplation of such a large concentration of wind generation in eastern Montana, utilizing the strong transmission connection that the CTS can provide would be very beneficial for moving power across the area, supporting the load when the wind is down, and exporting the surplus when the wind output is at maximum. From a transmission engineering perspective, there is no obvious advantage to moving the wind machines or their points of interconnection farther away from the CTS. At full capacity each of the above scenarios requires a significant amount of power to be exported from the Montana area since it far exceeds the indigenous load. The CTS provides the best currently available means to export the surplus power from eastern Montana into the western interconnection.

There are line outage conditions along the CTS that can cause thermal overloading on certain elements of the CTS (at maximum flow conditions). The most important example of this is the outage of one Colstrip—Broadview 500 kV line. Under maximum flow conditions (with the existing coal-fired generators) the outage of one of these lines can cause the flow in the adjacent line to exceed the current rating of its series capacitor bank. A series capacitor typically has an emergency rating, but flow must be curtailed before a certain time has passed. The protective relaying will automatically bypass the capacitor at this time limit. However, bypassing a series capacitor may not be a desirable outcome, from a systems perspective, since voltages would drop. Also, during such an outage, generation that is connected at Colstrip is at some risk of being tripped. In general the CTS is capable of

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operating at or near its maximum capacity with any single line out of service on a temporary basis (in steady state operation). Placing some of the wind-powered generators so that they are connected at Broadview instead of Colstrip should mitigate the issue of a single Colstrip—Broadview 500 kV line outage as described above.

In general, none of the above scenarios pose a problem that is known to be insurmountable, but all of them require some amount of additional study work and engineering to design the necessary system reinforcements to achieve completely reliable operations. The additional studies that need to be completed include: 1) examining all single and double contingencies on the CTS with power flow, post-transient power flow and dynamic studies; 2) RAS design and approval (1-3 years) 3) Path Rating approval through the standard WECC process (1-2 years). A reasonable expectation for the amount of time it will take to conduct these studies and receive the necessary regulatory approvals is 1-3 years depending upon the available man power to complete the work.

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Introduction

This white paper is an effort to delineate in broad terms the transmission issues that are involved in retiring existing coal-fired generation at Colstrip and adding new renewable resources such as wind and solar to the Colstrip Transmission System (CTS). The specific question of retiring varying amounts of generation at the Colstrip power plants in eastern Montana and adding a similar amount of wind-powered generation connected to the Colstrip 500 kV system at Colstrip and Broadview is examined in detail. A casual observer may be tempted to suggest that if similar generation capacity is connected to the Colstrip switching station, the transmission capacity should simply remain the same. However, this idea ignores numerous transmission issues that are not apparent if one is not familiar with the electric transmission design issues of the Colstrip project. The unique features of the CTS present complicating factors that must be addressed.

This paper does not attempt to specify the design of any necessary system changes to achieve a megawatt-for-megawatt replacement of coal-fired generators with wind-powered generation. That work will need to be completed as part of the required generator interconnection studies for specific wind projects. Instead it is a general discussion of the engineering issues that would arise due to the unique features of the CTS and provides context for the solutions and associated costs. The focus will be on how the change from coal-fired generation to wind-powered generation would lead to a different set of operating concerns for the Colstrip Transmission System (CTS) and what the solutions and range of costs associated with those solutions may be.

In this paper the design issues of the CTS are discussed without engaging in a lot of technical language or mathematical expressions that might require the reader to be versed in engineering subjects. The goal is not to completely avoid technical subjects, but rather present these subjects on a very basic level to give the average reader a better understanding of the issues and solutions that exist. The CTS presently relies on a sophisticated combination of technical features that have greatly enhanced both its reliability, and its capacity.

To replace the coal-fired generators with wind-powered generators and retain a similar capacity with similar reliability will require specific and targeted engineering solutions to make sure that the system can meet performance requirements.

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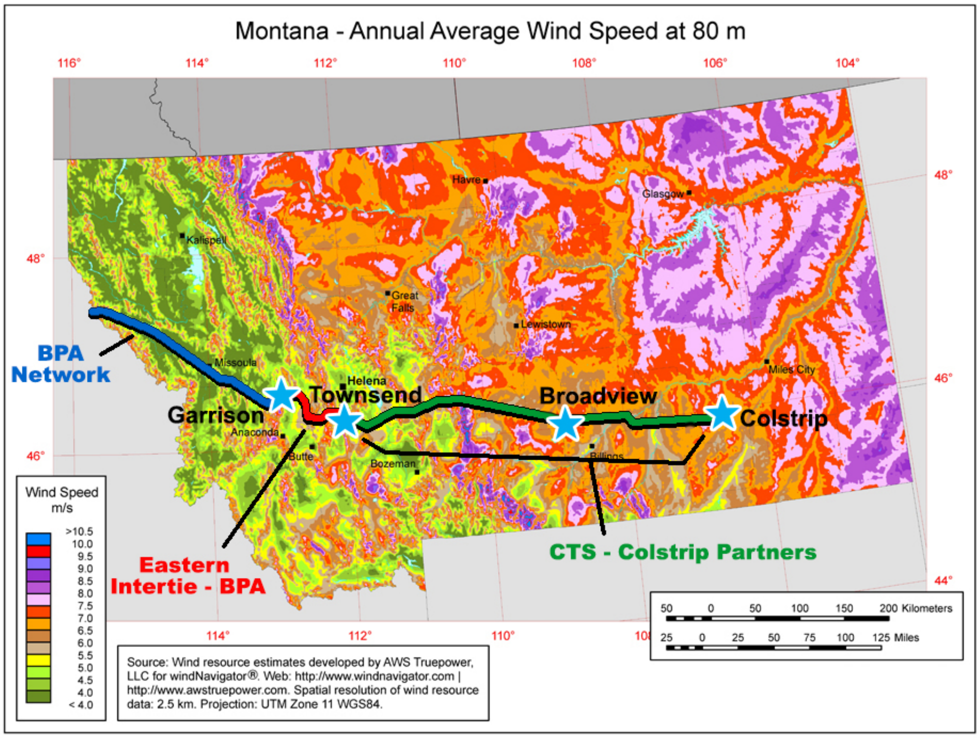
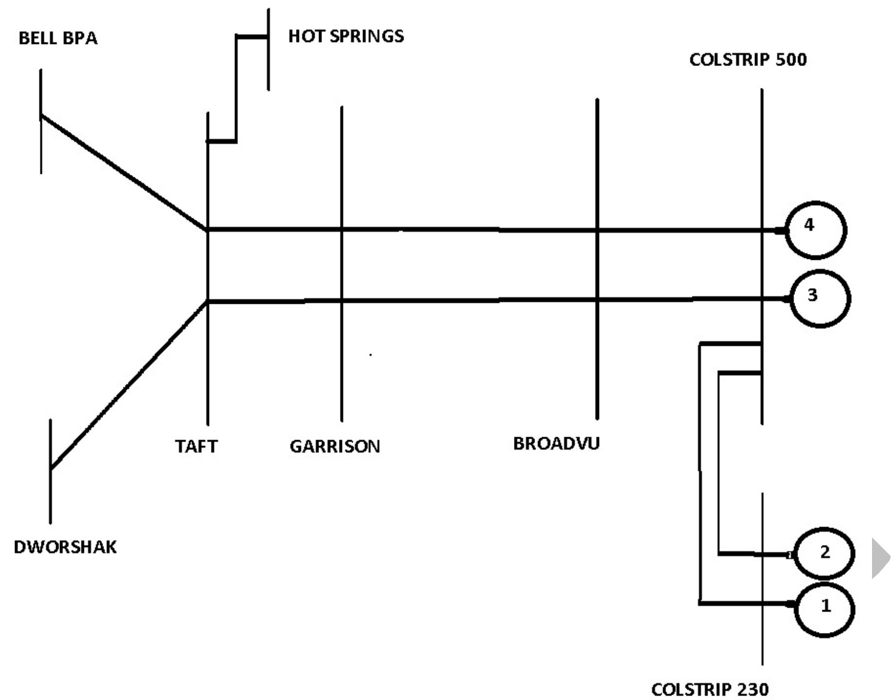
The Colstrip Transmission System (CTS)



This image is based on an underlying image that was created by the National Renewable Energy Laboratory for the U.S. Department of Energy using wind data provided by AWSTruepower™.

The CTS stretches for roughly 500 miles across the State of Montana and northern Idaho from Colstrip in the southeastern quadrant of the state to interconnection points in the eastern part of Washington State. The portion of the CTS owned by the Colstrip Consortium (CPM) extends approximately 240 miles from Colstrip to the ownership change location near Townsend, Montana. The BPA-owned portion of CTS extends from Townsend to a switching station called "Taft" which is approximately 215 miles west near the Montana – Idaho state line north of I-90. There are two BPA lines that interconnect CTS to points west of Taft. One connects Taft to a switching station called "Bell" near Spokane, WA (about 85 miles west); the other connects Taft to a switching station called "Dworshak" (near the dam with the same name about 75 miles southwest of Taft).



There are eight important 500 kV (EHV) line segments that represent major elements of the CTS system.[4] Every line section in the CTS is and must be series compensated to achieve the present rating of the CTS throughout the length of the CTS. (Series capacitor banks are multi-million dollar investments with unique insulation and protection issues that represent significant engineering considerations in their own right.)

Besides these eight lines that each represent a major contingency, there is another 500 kV line connecting the Taft switching station to a station called Hot Springs in Northwest Montana. This connects four Northwest Montana Hydro (NWMH) large hydro-electric plants (Hungry Horse, Libby, Cabinet Gorge and Noxon) into BPA's 500 kV system at Taft. There are also several 230 kV lines that knit these four plants together, and some that connect them into the greater Spokane area. At high transfer levels on the transmission path between the Montana Area, and the Northwest Area (Path 8), there is some interaction between the level of the total generation produced by the NWMH plants and the flow on Path 8 that is allowed. Generally, these four hydro plants only operate at peak output during peak load hours in the spring months. Path 8 usually operates at maximum

[4] Colstrip – Broadview 500 kV line A (Broadview is about 110 miles west of Colstrip); Colstrip – Broadview 500 kV line B; Broadview – Townsend – Garrison 500 kV line 1 (Garrison is in western Montana); Broadview – Townsend – Garrison 500 kV line 2; Garrison – Taft 500 kV line 1 (Taft is near the boundary between Montana and Idaho); Garrison – Taft 500 kV line 2; Taft – Bell 500 kV line (Bell is near Spokane, WA); Taft – Dworshak 500 kV line

flow during off-peak hours. The thermal plants at Colstrip are often scheduled for maintenance during the spring to avoid a situation where the demands are high on Path 8 during this season. During the spring runoff season, curtailment of the flow over the CTS may be required occasionally. The change from coal-fired generation, which requires scheduled maintenance outages that can conveniently be used to avoid congestion on Path 8, to wind power that has no such maintenance scheduling characteristic, may cause the need to work out some other arrangement to avoid the conflict between these two demands for the use of Path 8 capacity and the West of Hatwai path capacity.

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Considerations for Adding Large Amounts of Wind Generation to the Colstrip Transmission System

The normal concerns for a transmission study to account for when examining any power system are thermal overloads, voltage control issues, and transient stability. For the CTS one should also consider RAS protection simply because of the long radial character of the system with two parallel lines. Also, because the CTS is series compensated one must study Sub Synchronous Resonation (SSR); however, the specific change from synchronous machines (coal fired generators) to non-synchronous machines (wind generators) makes this issue change in character. By far the biggest issue to address is the RAS protection one. If one assumes that the RAS protection is functioning correctly, the thermal overload issue is rather trivial, and the RAS addresses all transient stability issues automatically. Voltage control issues must be addressed in any case.

Thermal overloading occurs when there is too much power flowing over a specific transmission line or set of lines. The transmission system is designed to avoid thermal overloads, but when a portion of the system fails for whatever reason, thermal overloads become a possibility and must be mitigated.

There are line outage conditions along the CTS that can cause thermal overloading on certain elements of the CTS (at maximum flow conditions). The most important such outage is the outage of a single Colstrip – Broadview line (discussed in the executive summary above). There are also outage conditions that could result in overloading of lines that operate in parallel with the CTS.

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Voltage Control Issues

When the CTS is operated at its maximum transfer capability it is loaded somewhat above the Surge Impedance Loading (see note 1e on quadrature power for detail on this subject). At that flow level, voltages on key buses will begin to decrease below acceptable levels unless adequate reserves of VArs are available. The generators must produce more VArs to compensate for the tendency of the voltage to sag. If the generators are not capable of producing these VArs (as the coal-fired generators normally are) then other devices may be needed to produce these VArs. Continuous VAr control is desirable for quality performance. This topic is discussed further below.

Colstrip units 1 and 2 are each capable of approximately 115 MVAr of reactive power output at full output (continuously for long periods of time). Colstrip units 3 and 4 are each capable of approximately 270 MVAr of continuous reactive power output (these machines have a rated power factor capability of 95 percent). Together the four units can produce an approximate total of 770 MVAr. This VAr capacity is used to tightly control the voltage on the Colstrip 500 kV bus. They continuously supply VArs as necessary to maintain a constant voltage on that bus over a wide range of flow conditions. This is the principal voltage control on the CTS.

If the 2,100 MW of capacity of the coal-fired units is replaced with wind-powered generation, it would require approximately 1,400 large wind-turbine generators (these figures are based on a 1.5 MW wind unit size). The total reactive power capacity of the 1,400 wind-powered generators would be about 480 MVAr (based on an assumed power factor capability of 97.5 percent). Under partially calmed conditions the VAr capacity of the wind fleet would be diminished due to the generators that are stopped (or off-line). This means that the wind variation (at low speeds) may contribute to variability of system voltage as wind machines drop out at the critical low wind speed. It will be more challenging to maintain a constant voltage on the CTS using a fleet of wind generators that is constantly in a state of flux. It may be wise to install some VAr generating devices (e.g. synchronous condensers, VSCs, or SVCs) to assure acceptable voltage levels are maintained smoothly with some reserve VArs available.

A power flow study should be done to evaluate the minimum (and maximum) VAr capacity required of the wind fleet under partially (and totally) calmed conditions where some units are not available due to calm conditions. Using wind machines that are capable of producing some VAr output even when they are stopped would help to mitigate this issue. These studies should be done during heavy load conditions, and also during light load conditions (calm winds may occur during either condition). Voltage control issues may differ significantly for these two conditions.

The author has produced a single power flow case with no Colstrip generation, no auxiliary loads at Colstrip, and no wind generation in eastern Montana. The purpose of this case was only to “calibrate” the remarks in this white paper. The case solved, and voltages were in acceptable ranges (some buses were a few percent below the voltage they are operated at today). This case suggests that the existing switched shunt devices on the CTS buses are capable of achieving acceptable voltages on the CTS for heavy load conditions and no continuous VAr supply from either Colstrip generators or the wind generators in eastern Montana today. This was only a cursory look, loads were not varied (heavy summer loads 2025 were used), and no dynamic studies were performed. Under light load conditions, the voltage might be too high. This single case does not change the need for a comprehensive study.

Also, at maximum wind conditions a study would be needed to verify that sufficient VArs are available to maintain adequate voltage on the CTS using a realistic feeder system to connect the wind machines to the CTS (complete with transformers and intermediate transmission that is reasonably representative of actual generator interconnections). This should be performed at both heavy load and light load conditions because maximum wind conditions may occur during either loading condition. One should expect the maximum flow on the CTS to occur when wind generation is at a maximum and the load in Montana is at a minimum.

Reactive power (VArs) provided by ancillary devices (capacitors, reactors, “synchronous condensers” and static VAr devices, SVCs and VSCs) can be used to provide voltage regulation on an AC system. These become more necessary if the (real) power flow level on the system varies over a wide range, and if the flow level cycles more often. Problems caused by high flow levels (low voltage) can generally be mitigated by reducing generation to reduce flow, but problems caused by low flow levels (high voltage) would have to be mitigated by the use of shunt reactors (or comparable devices) that absorb the excess VArs that the lines are generating.

The CTS presently has an assortment of switchable shunt reactors that are used to absorb VArs under light power flow conditions (during generator outages primarily). When the real power flow on the CTS is low, the voltage tends to go high due to the VArs that are produced by the capacitive shunt reactance of the 500 kV lines. As the wind speed (averaged over the whole collection of wind turbines in Montana) decreases, the real power flow on the CTS would decrease. If calm conditions prevail generally, there would be a need to take measures to control high voltage as the 500 kV lines increase their VAr production. These switched devices allow step-wise control of the system voltage, but do not provide continuous control. The primary source of continuously variable VAr supply today is the set

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of coal-fired generators at Colstrip. It may be necessary to supplement the continuous VAr supply of modern wind machines with a SVC or VSC, especially under calm wind conditions. The cost of such devices does not represent a significant portion of the project costs.

There would be a need for power flow studies that specifically address how to mitigate this over a variety of possible conditions. Including light and heavy load conditions for both high wind (full generation) and calm wind (wind generators off due to very light winds). The CTS has many features that if appropriately used would likely be helpful for managing the CTS system voltages. Some of these options should only be used when all other methods have proven to be inadequate. These features include:

1. Switched shunt reactors that are already in place at Colstrip, Broadview, Garrison, and Taft.
2. Series capacitors that can be switched out to increase VAr losses in the lines when the power flowing in a line is low. Unfortunately these have little effect when the series power flowing is low.
3. Opening one segment of a line to deliberately increase VAr losses in the adjacent segment can help control high voltage. (This should not be common practice.)

It may be necessary to augment the voltage control features in the list above to provide more voltage control at very low flow conditions (partially calmed). This can only be assessed by performing the range of studies described above. Total system load cycles daily and both high and low wind conditions may occur at any time of day. The possibility that it may be necessary to augment the voltage control features above is greatest when all of the coal-fired generation is off-line. The number of duty cycles of the three types of devices listed above (per year) may well increase due to the variability of the wind resource (total output). This may cause the need to replace switches that are used for voltage correction more often than it is required for the system with coal-fired generation. One way to mitigate this would be to add some continuously acting VAr devices such as synchronous condensers, static VAr compensators (SVCs), Voltage Source Converters etc. to the system.

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Dynamic Study Issues ("Transient Stability")

Transient stability refers to a transmission system's ability to withstand a major fault and quickly return to a stable condition before additional problems occur or spread to other parts of the system. The CTS is currently configured with a RAS (the ATR) that is designed to trip generation at Colstrip in the event of the loss of a transmission line. This tripping mechanism protects the transmission system and allows for an increased transfer capability on Path 8. There is also a RAS owned by BPA that switches reactors off at Garrison for certain contingencies.

Early in the design phase of the Colstrip project (in the '70s) it was established that roughly 2,200 MW of generation would be constructed, and that this would require two 500 kV transmission lines operating in parallel. Intermediate stations at two locations between Colstrip and the western terminus were designed to allow for interconnection with the Montana system, and to improve transient stability by insuring fault events only resulted in a partial loss of either line. The idea was to sectionalize the system into three roughly equal segments. Historical events forced a change that made the central section much longer than the other two segments. This actually reduced the native capacity of the CTS. This had to be compensated for by supplying a more effective RAS.

In the early stages of planning for the CTS it was decided that this transmission system would be "just enough" to serve these plants. It was well understood that maintaining transient stability would be a challenge. Every known device for enhancing transient stability was at least considered. Much was done in the early study phase to review all options for ways to improve stability and keep the overall cost down. This idea led directly to the understanding that generator tripping would be needed for certain contingencies (especially the "side-by-side" line outages).

Thus, the CTS relied implicitly upon a Remedial Action Scheme (RAS) from its inception. The original presumption was that this RAS would be a "Direct Transfer Trip" (DTT) scheme. There are numerous such RAS schemes in the western interconnection. The basic idea of such a RAS is that each system outage (line or transformer) that would require generator tripping would be identified through our study effort. This is not too difficult if there are very few critical contingencies for which tripping is needed. Then communications line(s) between the switching station(s) where the line terminals for any outage occurs would deliver a tripping signal to the appropriate generator(s) to cause them to be tripped for the outage. This seems simple enough, but one must recognize that there are literally dozens of outages to study on the CTS to be sure that the RAS will cover all necessary contingencies. System performance without a RAS varies greatly with the total flow on the CTS. Some line terminals are hundreds of miles from the generators. Communication circuits that are highly reliable are sometimes hard to find (or to put it another way, very expensive) in Montana. These communication lines would need to be redundant (including route redundancy) and also secure to prevent excessive false tripping. For each outage the RAS must promptly initiate an acceptable amount of generator tripping, enough to assure system stability is preserved over a range of flow levels. Also, the precise amount of required generator tripping generally depends on the flow levels on the critical elements of the CTS. Tripping large coal-fired generators is quite expensive. It requires substantial quantities of auxiliary fuel to restart a plant, and there is a certain risk of damage to critical equipment every time a unit is tripped. For this reason it was always considered very important to minimize false tripping. Saving on the cost of communications is one of the great advantages of the ATR.

The existing generators at Colstrip are large steam turbine-generators. There are only four large steam turbine-generators in the Colstrip project. The RAS for these machines only needs to make four trip/no trip decisions, one for each of the four units. The total generation on each unit is tracked in real-time, and each of the 15 possible combinations of generators is totaled and sorted so that when the ATR produces a tripping decision, it can quickly select the appropriate combination of generators to trip to get just the right amount of generation tripping (within a “step-size” that is about the size of one small unit).

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Designing a "Wind RAS" for the CTS

To retire the existing generators at Colstrip and add a comparable amount of wind generation, a "Wind RAS" will have to be developed for the CTS in order to maintain a comparable transfer capability. All of the recent CTS studies discussed in this paper assumed (without proof) that a sufficient RAS was indeed in place and some assumed that it was as effective as the existing ATR RAS at Colstrip and compatible with it (under all scenarios where any of the four Colstrip units are still operating). No "Wind RAS" design has actually been proposed or chosen. Obviously, when a "Wind RAS" design is actually proposed, it will have to demonstrate its effectiveness through testing. This can be accomplished through additional studies. The interconnection studies for large wind plants connecting to the CTS conducted by Northwestern Energy so far suggest that the cost of such a RAS would be $1 million to $4 million. A large part of the cost of a RAS is in the engineering effort. The cost of the major equipment would depend very much on the chosen design. Long communication paths that involve stringing fiber optics over great distances could greatly increase the cost. The logic devices that are typically used are either large programmable logic controllers or hardened computers (rack mounted with special features for handling many digital inputs/outputs). Clever engineering might save some money, but it is not wise to "go cheap" on this type of equipment.

To trip the equivalent of one small unit of coal-fired generation would require approximately 200 wind-turbines to be tripped. The equivalent of one large unit would be about 500 wind-turbines. Tripping such massive numbers of wind generators might involve substantial amounts of switching equipment, depending upon how the wind generators are organized and connected to the CTS. It is not desirable to separate the wind generators into very many small parcels because the cost of a RAS would be higher if it were required to operate more switches. The best plan for such a RAS would be to bring all signals from remote lines in to a single location where the "brains" of the RAS is located (redundant of course). In order to "manage" the amount of generation to trip, there should some simple way to totalize the power from each group (that has individual tripping available) of wind machines so that one can trip the desired amount of wind power quickly, and avoid tripping all of it for every contingency. Giving the RAS the capability to trip partial sets would be highly desirable in order to maximize the collective "plant factor" for the full set of wind plants by avoiding excessive tripping. Since every group would have variable output, this could require a carefully engineered RAS design.

If one is contemplating replacement of the coal-fired generators with wind-powered machines on the CTS, there is little choice but to develop a DTT RAS. The best way to control the costs is to take the maximum advantage of communication paths that are already in place for the current relaying schemes that provide protection for the CTS (fault detection and breaker operations). Additional communication lines may still be required to provide the redundancy needed to meet present day RAS design requirements. This will require some research to determine how many of the needed communication lines for any proposed design are available in the existing CTS communications lines.

The most important design feature necessary to minimize the additional requirements for tripping the wind machines involves the topology of the connecting lines that feed power from the wind plants to the CTS system. The power from sizable groups (200 – 500 MW) of wind capacity each should be fed through intermediate voltage "trunk" lines to the Broadview and Colstrip switching stations. Tripping should be accomplished by opening these "trunk" lines (mostly 230 kV). Each tripping action would thus trip a sizeable amount of generation. The cost of the high-reliability redundant communications required to get signals to these "trunk" lines could thus be minimized. All of these "trunk" lines should terminate close by the existing CTS switching stations.

The controller for the "Wind RAS" probably should be at Broadview (it should be redundant too). The other choice is Colstrip. Another set of redundant communications lines from these two controllers should be set up between Broadview and Colstrip. This should carry tripping signals to Colstrip (or Broadview) from the controller for each "group" of generators connected there (all "feeders" should converge on these two stations). Costs could be kept down by minimizing the number of "groups" of generators connected at Colstrip. Also, tripping information (formatted data) should be transmitted to the ATR for those scenarios that the "Wind RAS" needs to coordinate.

One possible "simple idea" for scenario 1 (where Colstrip Units 3 and 4 are still operating) would be to have the ATR provide a communications signal to the "Wind RAS" controller that would trip the wind-powered generators that are designated to be "replacements" for Colstrip units 1 and 2 whenever it would be calling for their tripping at present. There would likely be a need to "recalibrate" the ATR to make sure tripping is reasonably accurate.

There are other ways that may work just as well. The main requirement for any proposed RAS design would be that a thorough study has been done in advance of the installation to verify the system performance is assured. The study would be fairly easy to perform, but if the first idea did not work, one would need to be prepared with other ideas.

Strong evidence needs to be provided to show that any such "Wind RAS" is reliable to the standards of the regulators that must approve any such scheme in the WECC.

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The Role of Inertia in Dynamic Events

The effect of having a large amount of wind generation concentrated in eastern Montana during a serious transmission outage is an area that requires focused study. A serious effort to model the dynamics of the system would be required to answer critical questions about how such a change would affect performance (long-term dynamics studies could be used to gain more understanding of this issue). The ratio of the total wind-generation to the total generation provided by rotating synchronous machines (including hydro-electric) is an important parameter in evaluating this concern. Most of the rotating inertia in eastern Montana (roughly 90 percent of it) is in the coal-fired machines at Colstrip. There are just a few small coal-fired generators in the area besides the Colstrip units. There are gas-fired combustion turbine generators in Anaconda, and numerous small hydro-electric plants in Great Falls and points further west. So, for scenario 2, 3 and 4 discussed in this paper, there are situations where the total rotating inertia in eastern Montana would be reduced by a factor of ten. If this part of the transmission network were islanded for any reason, the frequency would be ten times more sensitive to load and generation changes. While this suggests an investigation is in order, there is not proof that this would lead to unacceptable operation of the remaining system as long as it is connected to the WECC through tie lines.

Wind generators would actually eliminate some of the dynamic issues discussed above. Since the wind generators have no effective inertia, it takes less transmission strength to stop the over-speed event that can occur when there is a transient event caused by a line fault. However, steady state voltage performance would need to be maintained in the aftermath of a contingency that requires tripping of wind generators as necessary. A well done study could determine if a properly sized static VAr device or voltage source converter (or several that are strategically placed) could mitigate the low voltage dip that occurs during a dynamic event precipitated by a faulted line and the aftermath. Such a device might allow the amount of generator tripping to be reduced (compared to the ATR tripping amount) for some of the less critical contingency events.

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Other Dynamics Issues

A proper dynamic study must model each switching sequence in great detail using precise knowledge about the speed of the circuit breakers, protection relays, and any automatic switching that may exist (such as a RAS). There may be a need for a tripping signal to travel over great distances and relays must “pick-up” upon the arrival of this signal so there are additional time requirements here that must be properly modeled. It is very important that any “Wind RAS” that needs to “coordinate” with the ATR (to be compatible) must act after the ATR tripping algorithms have had time to act. If this is not done, the very action of tripping the wind generation early will tend to have the effect of “blinding” the ATR to the event. This may result in the failure of the ATR to act for a critical outage.

The existing coal-fired generators require auxiliary fuel to restart them. This makes the cost of tripping them significant even without regard to the cost of replacement energy. There is no such requirement for fuel for a wind machine. There also is no need for a lengthy delay before a wind machine can be restarted (assuming is has not been damaged by the shutdown). The author is not aware of a serious risk of damage that would result from frequent tripping of a “type-4” wind machine; however, this is not a trivial matter, since many units could be exposed to tripping each time the RAS must act. For this paper it is assumed this is not a problem. Thus, for this concern it would appear that wind generators have a certain advantage over coal-fired generators.

On the other hand, wind-powered generators have some features that may lead to difficulties not found with large coal-fired machines:

1. Wind turbine generators (including “type-4” machines do not have a large short term emergency capability (above their nameplate capacity) to generate VArs that improve system performance during emergency conditions such as a faulted line. The generators at Colstrip are equipped with high speed excitation systems. These respond to a fault by quickly causing the machines to generate VArs at very high levels (well above their steady-state rating) for a short period of time. With large amounts of new wind generation added to the CTS, Voltage Source Converters strategically placed near load centers could help with this concern, especially at Billings.
2. Wind turbine generators cannot be counted on to be available to serve local load during outages. Dispatchable reserve generation will be needed to serve local load during such events. In these discussions this is assumed to exist west of the CTS.
3. Wind turbine generators do not generally have the capability to provide frequency regulation in a way that advantages the reliability of the power system during large generation outages.

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4. When a dynamic event occurs the wind machines do not respond to the frequency increase by a measurable increase in its rotor speed in the way that a synchronous machine does. This implies that a device like the ATR cannot work on a wind machine (because its principles of operation are not compatible).

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Sub-Synchronous Resonance (SSR) Concerns

The CTS transmission lines are series compensated (series capacitors are connected to one end of each line section). This improves power flow and stability performance. It also reduces losses in the lines, and has other benefits (without series compensation one could argue that a third line would have been needed, or at least some other remedy would have been needed). However, series compensation also complicates the operation and protection of the CTS. A series compensated line has a natural resonant frequency. Typically, the capacitive impedance is smaller in magnitude than the reactive impedance of the line. This assures that the resonant frequency is less than the system operating frequency (hence “sub-synchronous”). Networks of such lines normally have multiple resonant frequencies depending on the network topology. If a voltage is applied at (or near) a resonant frequency of the network extremely high voltages may occur. This must be avoided to prevent a possible catastrophic failure or severe damage to the line. Line equipment (especially series capacitors) could be destroyed. Also, generators feeding power into the system could be severely damaged. The most serious negative effects of this phenomenon are collectively referred to as “Sub-Synchronous Resonance” (SSR).

There are three types of SSR,[5] all of which have severe effects that must be evaluated for a series compensated transmission system that is well connected to large steam turbine generators. All were studied for the CTS during the design effort.

When we performed the original SSR study work for Colstrip, we had to study each of the possible combinations of generators on line because the system resonant frequencies change for each configuration. Of the four Colstrip units, the SSR risk is greatest for Colstrip

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[5] The three types of SSR are:

1. Induction generator effect: Because of the natural resonance, a generator may spontaneously “feed” the system resonance generating current at that frequency). This can severely damage the windings in the generator.
2. Torsional Resonance: When a system resonance occurs a sub-synchronous torque is developed on the rotor of each connected generator due to the current flowing in the machine windings. This torque can stimulate a resonance in the turbine-generator mechanical system that can cause serious damage to the shaft of the machine.
3. Transient Torque Amplification: When switching occurs on the transmission system each switch operation causes a transient torque on each connected generator shaft. The first switching event stimulates a torsional vibration that may then be enhanced by the next switching event (timing is critical). This can lead to excessive stress on the generator shaft as it rings. Shaft failure is possible.

1 and 2. Thus the SSR risk to the Colstrip units would be greatly reduced for all of the scenarios treated in this paper since they are presumed to be retired for all scenarios.

The "Induction Generator Effect" is the only one of the three types of SSR described above that could be considered an issue for wind generators in general. Type 4 wind generators should not have this problem at all since their induction generator is isolated from the grid by the rectifier inverter interface. However, there have been cases where wind turbine generators had interactions with series compensated lines in close proximity to their terminals.

I believe the potential issue for modern wind machines is that the voltage regulators in these units have controllers that are capable of responding to voltage changes at frequencies that are high enough to stimulate the sub-synchronous resonances of the series compensated system. In some cases the time delay in the control loop between the voltage sensor and the amplifier controlling the voltage regulator may lead to a positive feedback loop which could be dangerous to the generator.

The length of the wind feeder lines, and the location of the POI, would change the resonant frequency of the system for each installation. This issue should be examined through a frequency-domain study for each generator location, and if there are issues identified for a particular location then the voltage regulators on the wind machines at that location should be modified with a filter (notch or low pass) that is designed to avoid this problem.

Special "frequency scan" programs are widely available that can be used to calculate the frequency response of the power system at any bus in the system to determine the system resonant frequencies at specific buses. This type of program should be applied before the generators are connected.

After the frequency scan study for each site is completed, a frequency response test must be applied to the inverters of the specific wind machines chosen for that site to determine if they are capable of exciting the system resonance(s). Filters should be applied to each machine at the site to block the generator from producing power at the undesirable frequencies.

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Existing Studies Review

a. 2014 Northern Tier Transmission Group ("NTTG") Public Policy Study:[6]
This study by NTTG examined the retirement of Colstrip Units 1 and 2 and the addition of 610 MW of new wind in the area. This was only a power flow study and although it naturally did not find any major issues, it is of limited use because it did not look at the more important transient stability questions. The power flow cases were created under the assumption that a RAS was in place to trip the appropriate amount of generation (without proof of the efficacy of any specific RAS design).

b. NorthWestern Energy Studies:[7]

NorthWestern has publicly released at least two studies examining components of scenarios where all of or some number of the Colstrip Units are retired and wind is added to the CTS. One of the studies looks at a scenario where Colstrip Units 1 and 2 are retired and replaced with a mix of different resources, but the remaining two Colstrip units continue to run. This study conducted a dynamic stability analysis and found no major issues, but it does identify the need for additional study work related to the RAS, frequency, voltage support, and path rating.

The other NorthWestern Energy Study looked at different scenarios where all four units at Colstrip are retired and as much as 2,520 MW of new wind is added to the system. This study did not examine the transient stability questions.

c. Western Wind and Solar Integration Study, Phase 3, Section 4.2.1:[8]

This study conducted by NREL looked at various scenarios of high levels of new renewables across the West and also conducted some focused analysis on the Colstrip area because of the history of stability issues there. It examined large additions of wind and solar in Montana while either all or three of the four Colstrip Units were still operating. Only one switching event in Montana was studied for dynamic performance. This event represents the most critical single contingency event for the CTS. For this event the system (today) would generally be stable with no RAS action, but may not meet voltage performance requirements. The case was run for the Base Case and for the "Hi-mix" case. The greater starting angle indicates that Montana was exporting

[6] http://nttg.biz/site/index.php?option=com_docman&view=download&alias=2405-nttg-report-for-the-2014-2015-public-policy-consideration-scenario-final-05-13-2015&category_slug=ppc-draft-report&Itemid=31
[7] http://www.mtaffordableelectricity.org/wp-content/uploads/2015/11/Attach-B-4-15-NWE-Study-Colstrip-111d-Shutdown-Impact-on-Transmission-5-8-15-Final.pdf
http://www.northwesternenergy.com/docs/default-source/cpp/epa-cpp-transmission-impact-11-17-15-final-pdf
[8] http://www.nrel.gov/docs/fy15osti/62906.pdf

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more power for the "Hi-mix" case. The fact that the change in angle at the maximum point in the swing was greater for the Base is a demonstration of the fact that wind machines can be expected not to accelerate as much as synchronous machines would during swing events. Interestingly, this study found that the stability of the system actually slightly "improved" with the additions of new renewables to the system (because the swing angle was reduced). This fact has little bearing on the over-all performance of the system with a high penetration of wind generation as a replacement for the coal-fired plants. The case is not a critical case. The over-all performance will need to be evaluated for all critical cases. It is quite likely, that the most critical case will "set the limit" for transfer capability. No RAS (not even the existing one) was applied for this study. If the ATR had been applied, there might have been generator tripping for either one or both of these cases.

d. NorthWestern Energy Generation Interconnection System Impact Studies, Project Numbers: 31, 99, 101, and 115.[9]

These interconnection studies examine the local system requirements for new generation interconnections for various wind projects. These studies do not typically examine the transmission questions we are considering here, but are useful in that they identify the need for these generators to have a new RAS and estimate the cost to be in the range of $1-$4 million.

e. 2016 NTTG Public Policy Study (draft):[10]

This study looks at retiring Colstrip Units 1, 2, and 3 and adding 1,494 MW of new wind to the CTS. The study suggests that replacing coal with wind may be feasible on the CTS. This study did conduct a transient stability analysis and found no violations under their scenarios and assumptions. However, the assumptions for this study were simply too optimistic. This study also assumed that an effective RAS would be in place but did not specify the design of such a RAS. Instead, all wind generation was tripped instantly (too fast to be realistic) for every critical outage. This is not even possible for a realistic RAS design. This may have effectively 'blinded' the ATR or at least delayed its response (see discussion above). This study did not consider sub-synchronous resonance issues nor does it constitute a path study.

In summary, none of these studies identified any fatal flaws for converting the CTS to transport wind energy, at least not for the scenarios and assumptions that were made for

[9] Available at: http://www.oatioasis.com/NWMT/NWMTdocs/GenConnect7.html
[10] http://www.mtaffordableelectricity.org/wp-content/uploads/2015/11/Attach-B-4-15-NWE-Study-Colstrip-111d-Shutdown-Impact-on-Transmission-5-8-15-Final.pdf

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each study. This is mostly because all these studies were limited in some fashion and thus not capable of revealing such flaws. All of the studies recognized the need for more comprehensive study work and, ultimately, the design and engineering of specific mitigations. The tools exist to make these scenarios run reliably, but the time it will take to do the study work and design the changes to the system is significant. This paper describes the additional study and engineering work that needs to be accomplished and timing considerations for completing this work.

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Examination of Four Colstrip Retirement and New Wind Scenarios

Scenario 1:

This scenario postulates that Colstrip 1 and 2 have been retired and 610 MW of wind-powered generation is added to the Colstrip switching station (the total net generation from units one and two is approximately 610 MW maximum).

For this scenario power flow issues would be minimal and this is partially supported by the previous study work discussed above. (Although, there was no demonstration of the effectiveness of any particular RAS design.)

Under this scenario, the variation of the wind power from zero to maximum does not represent a serious challenge to the ability of the existing CTS equipment to maintain voltages well within acceptable limits. This is because Colstrip 1 and 2 together, amount to only approximately 29 percent of the total Colstrip net capacity and the percentage of the available VAr capacity for these two units is less than 29 percent of the present total. The CTS total generation varies by this amount (610 MW) fairly often for various generator outages, or dispatching choices. The CTS works very well over this range on a steady-state power flow basis. Colstrip 3 and 4 have plenty of reserve VAr capacity for maintaining voltages in eastern Montana at full load when they are on-line.

If only one of the large units were in service for this scenario, VAr supply should still be adequate; however, to properly evaluate this scenario, one should study the system with either Colstrip unit 3 or unit 4 off-line (and unavailable). This is necessary because all coal-fired generation plants require annual (or nearly annual) maintenance outages that last for weeks. During the maintenance outage the plant would not be available at all.

If the wind power is off (or very low) under this scenario there are shunt reactors available at Broadview and Colstrip. These would help keep voltages under control. Planned generator outages for the coal-fired units (3 and 4) could be managed to avoid simultaneous outages (a forced outage of the last Colstrip unit should be manageable, but rare).

For this scenario a “Wind RAS” is needed to take some or all of the wind-powered generation out of service rapidly for certain contingencies at maximum flow. This RAS would have to coordinate well with the ATR which provides for the tripping of the Colstrip coal-fired generators. This means it would have to trip in a time frame that is after the decision time of the ATR, but fast enough to be effective. I would not expect this to be a prohibitively difficult thing to do, but there would be a serious need to adequately study this, and prove that one has a scheme that is mutually acceptable to the wind-power

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owners and the Colstrip owners. Qualifying a RAS in the present day regulatory environment takes significant time. The sooner this work can begin the less delay will occur between the time that Colstrip Units 1 and 2 retire and the time that new generation can take service. The WECC RASRS (Remedial Action Scheme Reliability Subcommittee) conducts the technical review of the proposed RAS design.

With a well-designed "Wind-RAS" there is little reason for concern about a significant reduction in the path rating of Path 8. Any increase (or decrease) in the rating would have to be demonstrated through the results of the study effort needed to qualify the RAS. This study would also be the definitive test of the significance of concerns about inertia. A proper RAS design needs to make sure that tripping of the wind-powered machines does not get initiated before the ATR has made its tripping decision, but before there is a significant deterioration of the power system conditions (dropping bus voltages) has occurred in any simulated event. The author has been involved in other studies that show this is in fact feasible, however these studies were not specifically focused on substituting wind for coal.

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Scenario 2:

This scenario postulates that Colstrip 3 has been retired (in addition to units 1 and 2) and that 1,355 MW (this is the total net capacity of the three units) of wind-powered generation is added to the CTS. This represents approximately 64.5 percent of the total coal-fired generation capacity at Colstrip.

This scenario would lead to a much greater variability (more than double that of Scenario 1 above) of the generation (both real power supply and VAr supply) available at the source end of the CTS. Meaningful studies should include examining this system with Colstrip 4 out-of-service (as a planned, long-term outage). This is needed because coal-fired generators generally require annual maintenance outages. These outages often last for weeks. For such an extended period of time it is reasonable to expect the wind to be calmed for a part of that time. This means there would be very little generation available in eastern Montana. The flow on the CTS would be reversed. With no VAr resources except for switched shunt devices and three much smaller coal-fired machines (one near Colstrip, one in Harden and the other in Billings) voltage control would be somewhat difficult. It may require extra-ordinary measures to operate the CTS under these conditions. Some wind-powered generators are capable of supplying VArs with no wind available—this could be helpful for providing smoother voltage regulation under calm conditions.

For this scenario a "Wind RAS" is needed to take some or all of the wind-powered generation out of service rapidly for certain contingencies. It would have to either coordinate well with the ATR which provides for the tripping of the one remaining Colstrip coal-fired generator (unit 4), or simply replace it. In any case this "Wind RAS" would have to be able to function when unit 4 is out of service (this outage implies that no ATR is available). There are two basic options for such a RAS design:

Option 1:

When Colstrip unit 4 is on-line, the "Wind RAS" would have to coordinate with the ATR. This means that the "Wind RAS" would have to execute its tripping action after the ATR has had enough time to evaluate the event for the trip/no trip decision for Colstrip unit 4. And, when Colstrip unit 4 is off-line, the "Wind RAS" would have to be able to apply any necessary tripping for the wind generation that is on line when a critical event occurs.

Option 2:

When Colstrip unit 4 is on-line the "Wind RAS" would need to include that unit in its tripping logic. When Colstrip unit 4 is off-line, the "Wind RAS" would have the same function as for option 1 above.

The study effort to design a "Wind RAS" for this scenario would thus have to be flexible enough to cope with two quite different situations. Effectively, the "Wind-RAS" must function for two quite different versions of the power system (with Colstrip 4 on, and with it off) and would likely require more time to produce (roughly 6-12 months).

One should expect the review process to be longer too (possibly up to 3 years). The WECC RASRS (Remedial Action Scheme Reliability Subcommittee) conducts the technical review of the proposed RAS design.

The main requirement for developing the "Wind RAS" would be to test the design adequately in advance of its installation through an extensive study effort. This would require examination of every single and every double contingency. Because this scenario involves a much larger fraction (but not all) of the existing Colstrip capacity, this study work would need to be more comprehensive and would take more time than the one required for scenario 1 above. All cases would have to be performed with and without Colstrip 4 on-line.

With a well-designed "Wind RAS" there is little reason for concern that there would be a significant reduction in the rating of Path 8. Any increase (or decrease) in stability concerns would have to be answered through the study effort to qualify the "Wind RAS". This would

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also be the definitive test of whether significance of concerns about inertia (at least for transient switching events on the CTS) is justified. A proper “Wind RAS” design needs to make sure that tripping of the wind-powered machines does not actually occur before the ATR has made its tripping decision, but does act in time to assure the proper recovery of the power system after the switching event. There have been studies that show this is in fact feasible.

Scenario 3:

This scenario postulates that all four of the coal-fired generators at Colstrip have been retired and that 2,100 MW of wind-powered generators are added to the CTS.

This scenario would imply that no VAr resources are available from the coal-fired generators regardless of the amount of wind-powered generation available. Some wind-powered generators are capable of supplying VArs with no wind available—this would be helpful for providing better voltage regulation under calm conditions though it may not be necessary given the existing generation and switchable shunt devices that are available in eastern Montana.

The total customer load in eastern Montana (connected through the Broadview and Colstrip switching stations) varies from about 300 MW to 600 MW. Under extremely calm conditions (low availability of wind generation) the flow would be west to east on the CTS. The power flow needed to supply loads in Montana would come mostly from the west and enter through the Garrison and Broadview switching stations. As the load varies, switched shunt reactors at Garrison and Broadview would need to be switched on (or off) in order to keep the voltages on the 500 kV buses (and the underlying Montana system) within their desired limits. The voltage change as devices are switched would be more noticeable since there would not be continuous control of the CTS voltage by the Colstrip generators. Continuous controller VAr resources can be applied in order to even out the voltage under these conditions. Devices that can provide this capability are: 1) Synchronous condensers, 2) Voltage Source Converters (VSCs), 3) STATCOMs and 4) Static VAr Compensators.

For this scenario a “Wind RAS” is needed to take some or all of the wind-powered generation out of service rapidly for certain contingencies. This “wind RAS” would have to be able to function adequately for every critical 500 kV contingency on the CTS. Ideally, it would issue measured amounts of tripping, instead of simply tripping all of the wind-powered generators for every contingency known to be an issue. At reduced amounts of wind generation, it may not need to trip at all.

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The main requirement for developing the "Wind RAS" would be to test the design adequately in advance of the installation through an extensive study effort. This would require a thorough study effort examining every plausible contingency.

With a well-designed "Wind-RAS" it should be possible to avoid a significant reduction in the rating of Path 8. Because of the intermittent nature of the wind power the amount of time that the system would be loaded high enough to require the maximum amounts of generator dropping should be lower. Any increase (or decrease) in stability concerns would have to be answered through the study effort to qualify the "Wind RAS". This would also be the definitive test for concerns about transient stability performance. A proper "Wind RAS" design needs to make sure that tripping a sufficient fraction of the wind-powered machines takes place in time to assure that the transient stability performance standards of the WECC are met. The RASRS (Remedial Action Scheme Reliability Subcommittee) conducts the technical review of the proposed RAS design.

Scenario 4:

This scenario postulates that all four of the coal-fired generators at Colstrip have been retired and asks the open question whether there might be "system benefits associated with moving some of the wind to other substations in Montana," as compared to simply connecting them to the Colstrip and Broadview switching stations as proposed.

In short, there are no obvious electrical benefits to be gained by connecting the wind to other stations. There may be some small benefit to connecting more to Broadview, and less to Colstrip, but this is not critical. (It would reduce the probability that a Colstrip – Broadview 500 kV outage would cause an overload.) The CTS is certainly the most substantial transmission to connect such a large amount of generation to the Montana transmission system.

It would be a wise choice to divide the wind-powered generators into substantially equal sized groups. Each group should be about the same size (say 300 – 500 MW). For example four equal groups with each group having approximately 525 MW. This would simplify the effort to properly study and design the "Wind-RAS". The RASRS (Remedial Action Scheme Reliability Subcommittee) conducts the technical review of the proposed RAS design.

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NOTES:

1. Power flow studies (steady-state):

Issues that must be addressed in power flow studies are:

a. Voltage regulation as the flow level varies from minimum flow conditions to maximum flow conditions both for the full system, and for outage situations. (Voltage at intermediate stations that are not regulated by generators may sag during heavy flow conditions on the lines, and float too high when the lines are lightly loaded.) Voltage regulation is generally achieved by using devices that produce quadrature power to manage the voltage when the system is under stress. Voltage regulation is the most important steady-state issue for the scenarios discussed in this paper.

b. Thermal overloading (flow may exceed rating of a line, or series connected line equipment such as series capacitors, switches etc.). Thermal overloading is generally caused when excess real power is flowing through critical elements in the network.

c. Real Power Issues:
The first thing I should say about real power issues is that there should be minimal problems provided the amount of wind-powered generation is no greater than that produced by the coal-fired generators in place today. Real power is real power whether it is produced by wind turbine generators or steam turbine generators. This is the underlying fact that promotes the idea that the coal-fired generators can simply be replaced with wind generators. This is why one should not expect new real power flow problems to come up because of the substitution of wind-power for coal-fired power. This implies, however, that studies that only examine steady-state real power flow issues will not reveal any problems and really does not address the primary concerns involved with the scenarios examined in this paper.

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d. Reactive Power Issues:[11]

In the power transmission study business we generally only use “reactive” units to avoid confusion as much as possible and simply treat the VArs as a signed quantity. In this terminology, a shunt capacitor injects “reactive” VArs into the power system, and a shunt reactor absorbs “reactive” VArs from the system. Generators can (and do) produce quadrature power of either sign. They do this while they simultaneously produce real power. Typically, coal-fired generators have larger capacity to produce VArs (of either sign) than do wind machines. Shunt capacitors can be used to generate supplementary VArs as needed, but these typically switch in large steps. Large “synchronous condensers” can produce VArs with continuous control similar to a coal-fired generator. You can think of a “synchronous condenser” as a generator that has no prime mover. Because there is no prime mover it cannot produce real power, but it has an excitation system just like a generator does, and can produce reactive power of either sign. These can be used to regulate the voltage on a bus smoothly.

e. Reactive power issues in transmission lines:

A transmission line produces (or consumes) VArs. In fact, a line cannot be stopped from doing this. The net VAr output of a transmission line depends upon how much real power is flowing through it. When a transmission line is idle (connected but with zero real power flowing), it generates the maximum amount of VArs possible. It does this as a natural outcome of the physical characteristics of the line (large parallel conductors stretching for miles over the surface of the earth which is conductive). A transmission line acts like a very long capacitor.

The longer the line, the more capacitance it has. (When phase wires are “bundled” this adds capacitive reactance because there are more wires.) All of the lines in the CTS are “bundled”. This is necessary to mitigate corona losses and to reduce the electric fields that the lines produce at ground level.

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[11] Definitions of two components of power: When AC current flows in any device (e.g. power line); the applied voltage is not necessarily in phase with the current. For any phase relationship, one may think of the current as having two components: 1) The component that is exactly in phase with the voltage: This component is called “Real power” (measured in Watts, Kilowatts (kW) and Megawatts (MW). Real power actually is carrying energy through the device that is capable of doing work over time. Normally, we just shorten the name to “power”, since it is the part of the AC current that carries energy from the source to the load. 2) The component that is exactly 90 degrees out of phase with the voltage. This component is called “Quadrature power” (or “VArs”). Quadrature power does not carry energy through a device that is capable of doing work. It can however, have a very important effect on the performance of a transmission system.

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As the real power flow on a transmission line increases, there are VAr losses in the line due to its series inductance. At a certain predictable real power flow level, the VAr losses in the line become large enough to match the VArs being produced by the shunt capacitance of the line. This flow level is referred to as "surge-impedance loading" (SIL). (Series capacitors have the effect of increasing the effective SIL of a transmission line.) When the flow is about equal to the SIL the line neither consumes nor generated VArs (VAr losses match the VArs that are being generated). At flows greater than the SIL, the VAr losses grow larger, and there is net loss of VArs in the line. At flows higher than the SIL a system will begin to have low voltage problems as the VAr losses in the line continue to climb.

If nothing is done to counter balance the effect of the VAr losses that are generated in the lines as described above, the voltage at the buses along the line may be too high at low flow levels, and too low at high flow levels. Neither condition is acceptable.

At low flow levels voltages on key buses could go too high unless there are devices available to absorb the excess VArs being generated by the transmission lines. Again, if the generators are not capable of absorbing the surplus VArs, other devices will have to be put into the system to do this. Such devices include synchronous condensers, large static VAr compensators, switched capacitor banks, and switched shunt reactors.

2. Transient stability studies:

Transient stability issues are about the dynamic performance of the transmission system during the first few seconds after a fault has occurred. For any AC power system there may be certain critical contingencies where the system may be dynamically unstable because a critical line (or set of lines) must be opened to clear the fault. Such an event may lead to a "black out" of a significant part of the transmission system. At a minimum, a proper evaluation of a proposal such as the replacement of the coal-fired plants at Colstrip with wind generators of equal net capacity requires a thorough stability study. This is because the CTS already relies upon a RAS for transient stability performance for numerous contingencies.

3. RAS issues:

The purpose of a RAS is to protect the reliability of a power system for events that cannot be allowed to proceed without intervention beyond that provided by "simple protection". RAS issues are about utilizing special relay protection schemes to perform non-traditional switching (such as generator dropping, or switching of other

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system components) to promote the ability of the system to recover from a critical contingency. A RAS can expand the operating range of a specific transmission system transfer path (perhaps one that is otherwise "weak") beyond what can be achieved through "simple" protection schemes. (Simple protection schemes can be considered to be those that are accomplished by using traditional line-relay protection to open a faulted line at both ends in order to remove it from service and "clear" the fault.) A RAS can be used to remedy a "power flow" problem such as an overload or low voltage condition, or a transient stability problem.

There are numerous critical contingencies in the CTS for which operation at full capacity with no RAS would result in unacceptable performance. In some cases the system would be completely unstable. For this reason it is mandatory that the CTS be equipped with a functioning RAS that is capable of protecting against the loss of system stability or in some cases unacceptable voltage performance (regardless of the type of generators used to supply the power).

With the existing system, the RAS that handles the bulk of these issues is the ATR. This device employs an unusual technology. It monitors the rotor speed of the synchronous machines at Colstrip, and makes all tripping decisions based on the relative speed, acceleration, and angle of the rotors during a potentially unstable event.
With the replacement of the Colstrip synchronous machines with wind generators, the ATR could not function because of the principles of operation of the device. Instead, it will be necessary to build a new RAS scheme based on some other technology. The most obvious choice is a conventional Direct Transfer Tripping scheme (DTT). In this paper the term "Wind RAS" has been used consistently to refer to this scheme. Regardless of the scenario, some form of "Wind RAS" will be necessary to provide for tripping the wind generators. This represents the single most critical engineering design issue that must be met in order to provide comparable reliability and capacity for the CTS under the scenarios considered in this paper.

4. Series Compensation:

Sometimes, "series compensation" is used to effectively reduce the series impedance of a line (capacitors are placed in series with some transmission lines). This has the beneficial effect of improving power flow capacity on the line, and voltage performance. It can be a solution to problems described in (Note 1) above and it can also help with transient stability issues, (Note 2) above. You can think of

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series compensation as a way to make a weak line stronger. When power is transferred over very long distances (hundreds of miles) it requires a careful design to achieve high power transfers. In general the longer the distance, the more important it is to use higher transmission voltages (to reduce the required amount of current), the more important it becomes to use series compensation (to effectively reduce the impedance), and the more likely it becomes that transient stability will also be a problem. All of these issues were important to the design of the CTS.

5. Inertia issues:

a. In a switching event caused by a fault, higher inertia in the source can "buy time" for the response of the protection system allowing for a longer fault clearing time.

b. The down side of high inertia is that if a high inertia generator gains enough speed during a fault, it will be harder to slow it down without having it lose synchronism. (There is no perfect value for inertia from a transient stability perspective.) During a switching event (caused by a fault) the acceleration of the units near the faulted line continues at least until the fault is cleared (normally this is 3-4 electrical cycles or about 0.050-0.067 seconds). As the circuit breakers open for the faulted line (removing it from the system) the remainder (weakened) system must be capable of slowing the machines that were accelerated by the fault and restoring equilibrium. All of the kinetic energy that has built up in the rotors of the generators must be absorbed and they must be restored to synchronous speed.

c. For long term frequency performance of a complete power system the more total connected inertia the better. The high inertia makes it easier to keep the system frequency constant. High inertia smooths the response of the system to changing loads and changing total generation. Reducing the inertia in a large system would eventually result in difficulties maintaining a constant frequency. Eastern Montana is well connected (through the CTS and other weaker ties) to the rest of the western interconnection. Reducing the total inertia in eastern Montana, as examined through the scenarios in the paper, will make eastern Montana more dependent upon the rest of the western interconnection to maintain a constant frequency. If the entire western interconnection is similarly reducing inertia, eventually the whole system will have difficulties maintaining a constant frequency.

d. For a switching event such as the one described in (b) above, wind turbines (type 4) would not accelerate as much (the inverter only tracks system frequency—the prime mover may begin to dump wind to avoid over-speeding the turbine) during the fault,

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but they would go on supplying constant electric power to a transmission system as long as their local voltage permits that. The inverter controller strives for constant power. During an outage, the system might need relief from this flow (depending upon which line must be opened). Any synchronous machine that might be occupying the same system would be accelerating from its own prime-mover—and from the presence of the wind machines too. So, it would accelerate even faster. As the synchronous machines nearby accelerate, the wind machines will match frequency with them.

Wind-powered generators actually do have a rotating inertia (on the wind turbine side of the rectifier), but this inertia is completely de-coupled from the synchronous power system. The "type-4" wind-powered generator (the type proposed) actually produces AC power with induction generators (on the wind turbine side of the rectifier, this power is then rectified to produce DC power, and finally, the DC power is again converted to AC power (on the system side of the inverter) at the system local frequency (regardless of the system conditions). With this design, the wind-powered machines should be considered to have no effective inertia (on the system side of the inverter).

6. Energy Management issues:

Power flow problems should not be confused with energy management problems. Of course the power generated by coal-fired generators is capable of remaining constant for very long periods of time (days). The power produced by wind-powered generators may stay fairly constant during windy periods but then drops off in a somewhat unpredictable way as the wind speed drops. This variability raises unique concerns that must be examined. From a transmission owner's perspective this merely means that the transmission will be idle much of the time if the regulating generation (generation that is there specifically to make up for the absence of the wind power during calmed periods) is not located near the location of the wind generation. When their output drops regulating generation is needed to meet load. The treatment of energy management issues will ultimately depend on the business structures underlying the buildout of the scenarios described in this paper. Although these issues are important, they are not the subject of this paper.

7. Sub-Synchronous Resonance:

A series compensated line has a natural resonant frequency that is lower than the system power frequency (hence the term sub-synchronous resonance). Networks of such lines have multiple resonant frequencies. Every transmission outage changes

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the overall set of resonant frequencies of the system. If a voltage is applied at (or near) a resonant frequency of the network extremely high voltages may occur across a capacitor bank or on any bus as very large sub-synchronous frequency voltages occur across system elements. This must be avoided to prevent a possible catastrophic failure. Line equipment (especially series capacitors) could be damaged, and also generators feeding power into the system could be damaged. The most serious negative effects phenomenon of this are collectively referred to as Sub-Synchronous Resonance (SSR).[12]

8. Path Rating Process:

The WECC has a path rating process that is designed to assure that when a new path is proposed or modified (new transmission tie line or old path improvement) the study work needed to justify the proposed rating is properly performed with full attention paid to the potential for conflicts with existing paths. This process is a part of the normal transmission planning process. Peer review is the keystone of this process. The path owner must announce their plan to build the new path or modify an existing one and invite interested WECC members to attend a series of meetings where the path owner presents the required information concerning the plan of service, expected rating and other basic information including the target date for completion of the project. Since Path 8 is an existing path, this process could be abbreviated. The document containing the rules for this process is: "Project_Coordination_Path_Rating_and_Progress_Report_Processes_proposed_changes_2015-09-11.pdf" (or a successor document available through WECC).

As Path operator, NWE would have to take the lead in conducting this series of meetings.

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[12] There are three types of SSR: 1) Induction generator effect (Because of the natural resonance, a generator may spontaneously "feed" the system resonance generating current at that frequency). 2) Torsional Resonance (When a system resonance occurs a sub-synchronous torque is developed on the rotor of each connected generator due to the current flowing in the machine windings. This torque can stimulate a resonance in the turbine-generator mechanical system that can cause serious damage to the shaft of the machine.) 3) Transient Torque Amplification. (When switching occurs on the transmission system each switch operation causes a transient torque on each connected generator shaft. The first switching event stimulates a torsional vibration that is then enhanced by the next switching event (timing is critical). This can lead to excessive stress on the generator shaft as it rings. Shaft failure is possible.