Exploration of Modular Power Flow Control Technology on the Manitoba Power System

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SUMMARY

The power industry is facing systemic changes, such as the decentralization of the grid via the integration of distributed energy resources, decarbonization and increased utilization of renewables, and digitization via the development of smart energy networks. These rapid and prolific changes will increase the amount of uncertainty that comes with planning and operating power systems and will bring several urgent challenges to the industry. This rapid pace of change clearly demands new ways of thinking and operating the network, in addition to the need for more advanced technologies.

Manitoba Hydro has been delivering clean, reliable energy to its customers for many years. As the province experiences increased demand, driven by electrification, the corresponding transmission system must also adapt to continue to provide the customers with reliable energy services. There is also a much greater need to increase interconnection capacity with neighboring jurisdictions. However, traditional transmission enhancements to provide such incremental capacity can take several years to be implemented. Therefore, some non-wires solutions are being examined.

A study has been performed to examine opportunities to leverage Smart Wires' SmartValve™ technology to address transmission constraints to increase interconnection capacity between Manitoba and US. This evaluation included a series of steady-state studies conducted using PowerGem's TARA software and Siemens PSS/E to assess areas where this could resolve constraints on the Manitoba power system. The SmartValve, a Modular Static Synchronous Series Compensator (M-SSSC), was considered due to its modular nature and ability to be deployed quickly in comparison to some legacy alternative solutions. The SmartValve operates by introducing a controllable reactive voltage in series with transmission lines and can provide various options for mitigating potential transmission limitations.

This type of study is beneficial for utilities as the industry should re-examine the potential need to integrate supply-side, demand-side, transmission, and distribution solutions to meet projected requirements and the challenges associated with decarbonization, decentralization, and digitalization. Therefore, the models, methodology, and study results presented in this paper should prove to be useful for the planning of power systems under the situation of rapidly evolving industry.

KEYWORDS

Power system utilization, grid enhancing technologies, non-wire solutions, SmartValve, interconnection capacity.

1. SmartValve Overview

A Modular, Static Synchronous Series Compensator (M-SSSC), the SmartValve, an example unit is shown in Figure 1 [1], injects a leading or lagging voltage in quadrature with the line current, providing the functionality of a series capacitor or series reactor respectively.

Figure 1) Image of SmartValve 10-1800 device

The modular nature of these solutions allows utilities to adjust transmission line reactance at a granular level in real-time to control power flows. This is mainly important during times of low transfers, when the reactance injection can be controlled to a very low injection threshold or bypassed altogether, thus keeping bus voltages within normal operating ranges. The SmartValve devices are rated for up to 3600A continuous current and be deployed on circuit voltages up to 550 kV. Each SmartValve device can inject a maximum voltage of between 2830V continuous and up to 6000V RMS short terms in series with the circuit. The MVAr Ratings of each SmartValve range from 1 to 16 MVAr, depending on the device.

A SmartValve solution provides a unique solution compared to traditional Series Compensation / Power Flow Control solutions. The SmartValve solution can introduce a capacitive and/or inductive voltage, providing an effective change to the reactance of the circuit independent of the line current. It can operate in several different control modes including Fixed Voltage Injection and Fixed Impedance injection. This flexibility in its operating principles and control capabilities offers several benefits including better voltage profile management. In addition, the ability to incrementally control the SmartValve solutions means voltage step changes can be managed much easier than for larger fixed series compensation solutions. The SmartValve solution can also be redeployed to a different part of the network with very little time and effort.

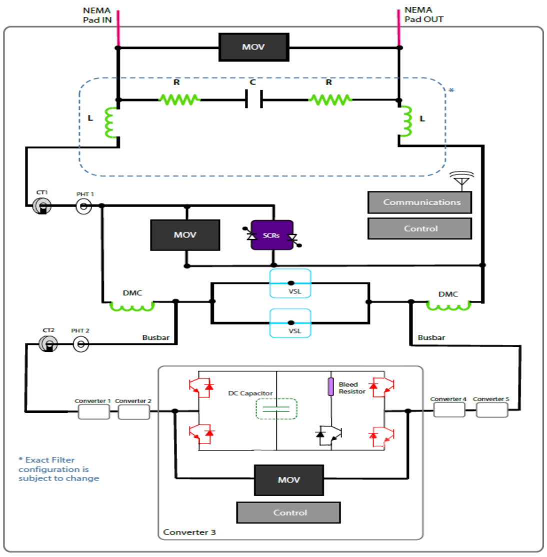

Figure 2) Principal Components of the SmartValve

From a Protection perspective, the SmartValve offers technical advantages over traditional series compensation solutions. The SmartValve device is comprised of two main parts – the voltage source converter (VSC) and the internal bypass, shown in Figure 2 [1]. The internal bypass can isolate the converter in the event of a fault in less than 1ms and can withstand fault currents of up to 63 kA for 1s. The fast bypass mechanism simplifies protection setting and co-ordination and negate technical constraints associated with traditional series compensation. This includes technical challenges such as distance overreach setting, voltage and current inversion, sub synchronous transient impacts on relay operation and influences of unbalanced currents.

The underlying SSSC and bypass technology of the SmartValve allows for a continuous range of operable series compensation levels. The available control methods are:

1. Reactance Set-Point – the SmartValve fleet outputs a defined equivalent amount of inductive or capacitive reactance. In this control method, the injected voltage will vary as the line current changes to keep the effective reactance at a defined level.
2. Series Voltage Set-Point – the SmartValve fleet outputs a defined level of voltage injection that is either capacitive or inductive. In this control method, the injected effective reactance will vary as the line current changes.
3. Current control – the SmartValve fleet actively regulates the magnitude of the current through the facility to stay below a given level or within a defined range.

The ability of fast injections provides utilities the opportunity to have SmartValve operated in bypass mode in normal operating conditions and minimizing losses by injecting voltage only when needed.

2. Problem Identification

The transmission networks in the US and Manitoba are tied with several paths shown in Figure 3 [2]:

1. **Line A:** 230 kV circuit terminating at Manitoba Hydro's Station 4
2. **Line B:** 230 kV circuit terminating at Manitoba Hydro's Station 2
3. **Line C:** 500 kV circuit terminating at Manitoba Hydro's system
4. **Line D:** 500 kV circuit terminating at Manitoba Hydro's system
5. **Line E:** 230 kV circuit terminating at Manitoba Hydro's system

Under high North Dakota exports (NDEX), Line B experiences high flows after critical contingencies. This issue is further exacerbated by Winter Peak conditions where Manitoba system is set to import power from the US. Critical contingencies include the loss of Line D or loss of Line A. Under these contingencies, Line B experiences high flow while the remaining tie lines are well below their limits.

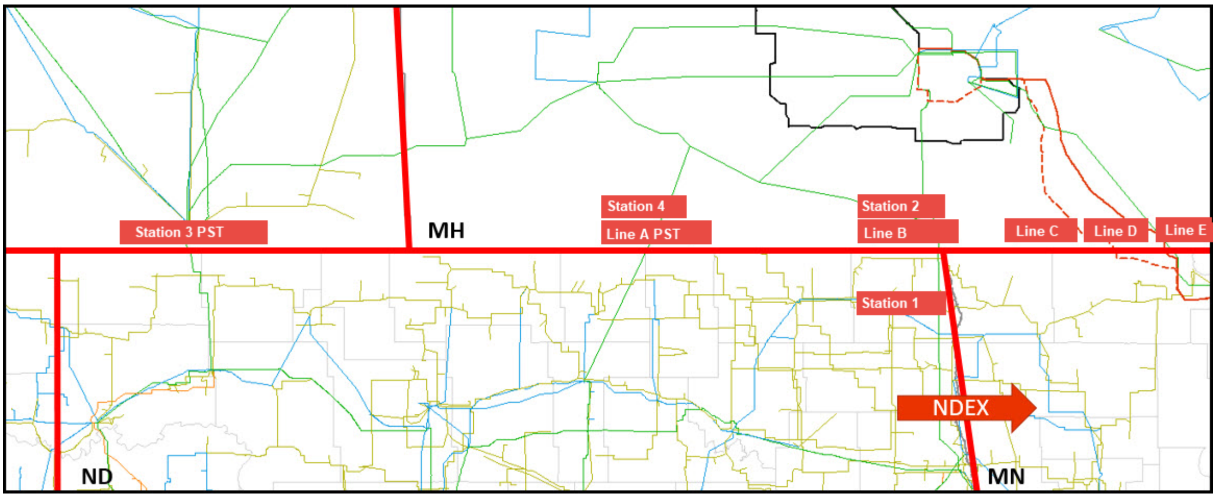

Figure 3) Overview of Study Area

Manitoba Hydro is exploring the potential to resolve the constraint on Line B. Traditional alternative solutions include a Phase Shifting Transformer (PST), reconductoring or rebuilding the line, or reducing imports to alleviate Line B loading. We have conducted an assessment aimed at resolving the constraints using SmartValve solution options.

3. Study Methodology and Results

The objective of this analysis is to identify solutions to address overloads on the Manitoba-US tie line, specifically on the Line B circuit, and focuses on system conditions driving the constraint. During Winter Peak conditions with high NDEX, and Manitoba Hydro experiences loop flow issues, which primarily flow through Line B following the outages of adjacent tie lines.

Different base cases with varying levels of export conditions from NDEX and two study years were considered, 2023 and 2028.

The primary constraint on Line B arises following the outage of a parallel facility. Two different post-contingency timeframes were considered, the latter of which is more constraining in this study:

1. Within the first 30 minutes following the contingency, it is assumed that system adjustments are not able to take place. These adjustments include the switching of shunt devices, the tapping of Load Tap Changing transformers (LTCs), the tapping of Phase Shifting Transformers (PSTs), and generation adjustments. Under these conditions, the loading of transmission lines and transformers should remain under their emergency ratings (Rate B), and system voltage should be within 0.9 per unit to 1.1 per unit.
2. Beyond the 30-minute period following the contingency, the previously mentioned system adjustments are permitted. Under these conditions, facilities are to be under their continuous rating (Rate A), and system voltage should be within 0.95 per unit to 1.05 per unit.

Full AC Contingency analysis was conducted using PowerGem's TARA software [3] and Siemens PSS/E [4]. TARA was used to conduct comprehensive batch analysis while PSS/E was used to conduct more detailed analysis and verify solutions.

The first step in the assessment was to identify the constraints as they were presented in the base cases. Table 1 and Table 2 display the contingency analysis results for both the *before system adjustments* and *following system adjustments* scenarios, respectively. The last three columns of each table display the loading of each monitored facility-contingency pair for the varying levels of NDEX. Also note that results for both study years are included.

As Table 1 considers loading before system adjustments are allowed, line loading was assessed with respect to the facility's emergency rating (Rate B). Similarly, Table 2 displays loading with respect to the continuous ratings (Rate A).

Table 1) Base Case Contingency Analysis Results (Before System Adjustments)

Study Year	Monitored Facility	Area	Rate A [MVA]	Rate B [MVA]	Contingency	Loading [% of Rate B]		
						NDEX Low	NDEX Med	NDEX High
2023	Station 1 (in North Dakota) – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line A	< 90	94.62	**104.95**
	Station 1 - Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line D	< 90	90.65	99.98
	Line A PST	667	300	300	P1:MH Line B	< 90	**119.31**	**121.43**
	Line A PST	667	300	300	P1:MH Line D	< 90	**107.51**	**106.91**
2028	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line A	< 90	93.3	**103.22**
	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line D	< 90	90.38	99.42
	Line A PST	667	300	300	P1:MH Line B	**109.06**	**118.02**	**120.22**
	Line A PST	667	300	300	P1:MH Line D	**109.72**	**106.9**	**106.33**

Table 2) Base Case contingency Analysis Results (Following System Adjustments)

Study Year	Monitored Facility	Area	Rate A [MVA]	Rate B [MVA]	Contingency	Loading [% of Rate A]		
						NDEX Low	NDEX Med	NDEX High
2023	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line A	< 90	**107.89**	**118.72**
	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line D	92.1	**106.21**	**116.09**
2028	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line A	< 90	**105.64**	**115.61**
	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line D	< 90	**105.61**	**114.02**

Notice the differences in loadings shown in Table 1 and Table 2. Once the system is allowed to adjust, Line A PST constraint is relieved. This is due to the Line A PST being able to adjust its tap settings to reduce its loading below its Rate A. As a result, power is diverted onto Line B after system adjustments. For this reason, Table 2 is considered to reflect the most limiting constraints and drive the investigation and development of the SmartValve solution options.

One additional variable which influences the loading of Line B once system adjustments are permitted, is the PST at Station 3 (in Saskatchewan). The base case flow schedule for Station 3 PST is 165 MW into Saskatchewan from North Dakota, however, the PST has a rating of 356 MVA. Allowing high Saskatchewan imports on Station 3 PST following the critical contingencies alleviates the loading on Line B without creating additional overloads. Table 3 displays the contingency analysis results following system adjustments, with Station 3 PST importing ~295 MW. At this 295 MW import level, Station 3 PST is near its rating of 356 MVA (including VAR flow).

Table 3) Contingency Analysis Results (Following System Adjustments) with BP PST Importing 295 MW

Study Year	Monitored Facility	Area	Rate A [MVA]	Rate B [MVA]	Contingency	Loading [% of Rate A]		
						NDEX Low	NDEX Med	NDEX High
2023	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line A	< 90	**100.41**	**111.66**
	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line D	< 90	95.99	**105.71**
2028	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line A	< 90	99.19	**109.95**
	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line D	< 90	95.88	**105.27**

Comparing the results seen in Table 2 and Table 3, Station 3 PST can reduce Line B loading by roughly 7% in the worst case. The worst loading was observed to be in the study year 2023 with high NDEX flow following the contingency of Line A. In this scenario, Line B is at 111.66% of its Rate A.

SmartValve Deployment on Line B

It was determined that 12x SmartValve 10-1800 devices could be deployed on Line B to adequately mitigate the 111.66% of Rate A constraint. The devices were modeled in reactance set-point mode to maintain an injection of ~18.8 ohms on Line B. With 18.6 ohm set-point represents the maximum inductive effective reactance, the devices are able to provide at Line B's 1200 A RMS continuous rating. The results shown in Table 4 display the loading on Line B with this solution modeled. This solution brings the worst-case loading from 111.66% down to 97.4%.

Table 4) Contingency Analysis Results (Following System Adjustments) with Line B SmartValve Solution

Study Year	Monitored Facility	Area	Rate A [MVA]	Rate B [MVA]	Contingency	Loading [% of Rate A]		
						NDEX Low	NDEX Med	NDEX High
2023	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line A	< 90	< 90	97.39
	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line D	< 90	< 90	93.57
2028	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line A	< 90	< 90	95.91
	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line D	< 90	< 90	93.09

With this solution in place, the US and Canada tie lines are fully utilized. Station 3 PST is holding a schedule of 295 MW; Line A is out-of-service for *P1:MH Line A* or is holding a schedule of 285 MW for *P1:MH Line D*; and SmartValves on Line B are maintaining a flow just below the continuous current rating. This results in flow being pushed toward the remaining tie lines in Eastern Manitoba tie lines (Line C, Line D, and Line E) as shown below in Figure 4.

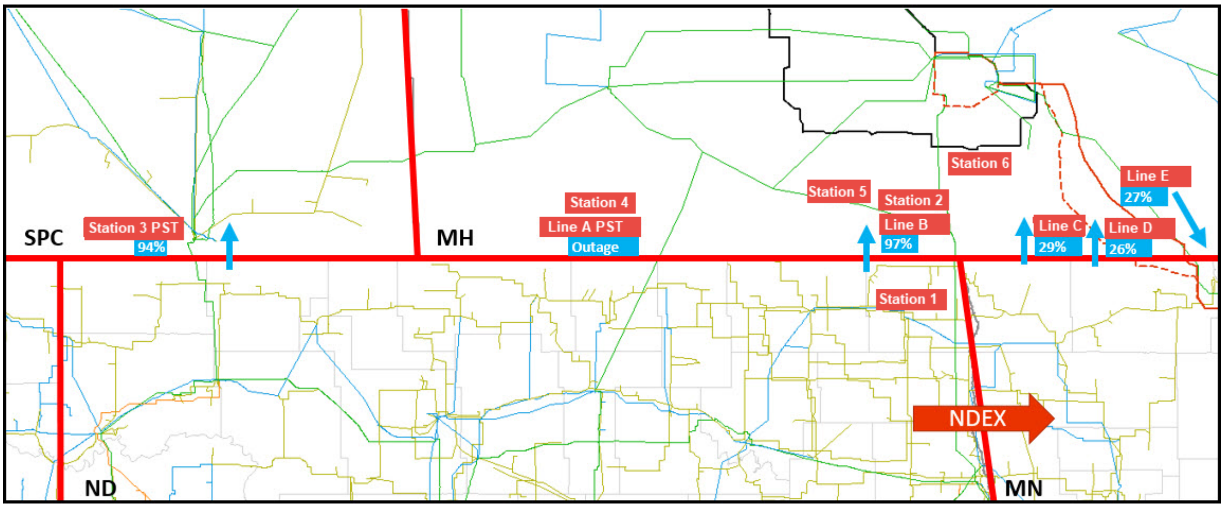

Figure 4) Snapshot of Worst-Case Cross-Border Flows with SmartValve Solution Modeled

SmartValve Deployments Adjacent to Line B (internal to Manitoba Hydro's System)

As an alternative to the solution developed above, SmartValve deployments in series with lines internal to Manitoba Hydro's network were explored. Various candidate locations were screened to understand their potential efficacy on resolving Line B constraints. For example, additional series compensation on the 500 kV ties between Manitoba and Minnesota would provide benefit to the Line B constraint, however, these solution options were found to be prohibitively expensive and in fact, had very little impact on flow on Line B. We carried out a full dS/dX analysis to identify the circuits that were most likely to have the highest impact on Line B constraint and Line C, Line D, and Line E were found to have very low impact.

SmartValve deployments near Station 2 provides the next highest impact, when compared to a deployment on Line B itself. The best alternative solution was to place SmartValve on 230 kV lines connecting Station 2-other MH internal 230 kV stations. The deployments in series with these two lines, which are adjacent to Line B, could act in reactance set-point mode and could be triggered to inject once a critical contingency occurs, or once loading on Line B exceeds a defined threshold.

The solution developed for this alternative included 33x SmartValve 10-1800 devices on one circuit and 12x SmartValve 10-1800 devices on the other circuit. The resultant loading on Line B for this solution is shown in Table 5.

Table 5) Contingency Analysis Results (Following System Adjustments) with Line B Adjacent SmartValve Solution

Study Year	Monitored Facility	Area	Rate A [MVA]	Rate B [MVA]	Contingency	Loading [% of Rate A]		
						NDEX Low	NDEX Med	NDEX High
2023	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line A	< 90	< 90	99.90
	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line D	< 90	< 90	96.80
2028	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line A	< 90	< 90	98.39
	Station 1 – Station 2 230 kV (Line B)	620/667	478	526	P1:MH Line D	< 90	< 90	96.44

Various deployment configurations between Station 2 and other internal MH stations were tested. The conclusion from all the testing was that placing SmartValve devices across two of these lines is more efficient than placing across all three. Additionally, it was found that increasing the reactance of 230 kV line was the most efficient in terms of relieving flows on Line B. As a result, the option to deploy 33x on a line from Station 2 to Station 5 and 12x on another line from Station 2 to Station 6 was deemed to be the optimal configuration, though other valid configurations exist.

Reduced SmartValve Solutions Combined with Manitoba Import Curtailment

This section of the analysis addresses the influence of US imports on the Line B constraint as well as SmartValve solution options. To conduct this assessment, a scaling methodology was used to reduce Manitoba imports from the US. Only the most constrained base case (2023, high NDEX) was used for this assessment.

It was found that with an approximately 400 MW reduction in imports, the Line B constraint is mitigated without the need for additional transmission solutions. Transfer cases were created to model various reductions in imports. The results for this transfer analysis are shown below in Table 6.

Table 6) Contingency Analysis Results (Following System Adjustments) for Various Levels of Manitoba Imports

Monitored Facility	Contingency	Loading per Manitoba Import Level From US (Loading as a % of Rate A)				
		1475 MW	1375 MW	1275 MW	1175 MW	1075 MW
Station 1-Station 2 230 kV	P1:MH Line A	**111.66**	**108.68**	**105.45**	**102.28**	99.09
Station 1-Station 2 230 kV	P1:MH Line D	**105.71**	**100.19**	94.87	89.85	84.59

4. SmartValve Solution Benefits

Smart Wires offers several benefits over traditional reinforcement solutions, including traditional Power Flow Control solutions such as Phase Shifting Transformers, Series Reactors and Series Capacitors for addressing the constraint on Line B. These benefits can be summarized as follows:

1. **Modularity provides flexibility –** Procurement of a flexible asset which can be scaled up in the future and/or redeployed elsewhere significantly reduces investment risk. The solution options proposed in this paper utilize the SmartValve 10-1800 which is broadly applicable to Manitoba Hydro's network. The devices have a continuous rating of 1800 A RMS, and can be deployed in series with most Manitoba Hydro lines without be the limiting series element. For example, devices deployed to resolve the constraint studied in this assessment can later be used elsewhere to increase the Manitoba-Saskatchewan transfer capacity.
2. **Reduced Procurement Timeline –**The hardware and firmware of a SmartValve are not specific to any one application. Every device that comes off the manufacturing line can be configured to meet the specific operating objectives for a project. The operating objective of SmartValve devices can also be changed several years down the road. Thus, the SmartValve is an *"off-the-shelf"* solution which significantly decreases procurement lead time, and Smart Wires can support delivery and commissioning within 1 year of a purchase order.
3. **Siting Flexibility –** A deployment of modular power flow control devices like SmartValve offers improved footprint flexibility. Devices can be located at both line end substations or along the right-of-way. This enables solutions to make use of existing substation space or contort to limiting spacing constraints that other solutions may face.
4. **Reduced Ancillary Equipment –** SmartValve requires no external power or communications cabling, operates at line potential and is self-powered by the line current. Additionally, the devices protect themselves inherently, and also do not have any influence on existing protection settings when operating in *push mode* (inductive). All solution options presented in this paper are operating in *push mode*.
5. **Fast Acting Control –** SmartValve can be operated in manual or automatic fashion and can also be configured to operate within a matter of seconds to rapidly alleviate high loading on

transmission lines. This enables near instantaneous response in the context of steady state analysis and is akin to an SVC or generator maintaining a voltage set-point.

6. **Greater Resiliency and no single point of failure** – The modular nature of the devices increases overall resiliency with respect to power flow controllers on the Manitoba-US interface. The loss of one SmartValve device does not lead to loss of overall SmartValve solution on a particular facility. In the rare event of device failure, the overall deployment will at most be fractionally derated. Given the devices are "off-the-shelf" and are not custom designed for a given application, failures can be remedied easily on an expedited timeline (e.g. hours or days, not months or years).
7. **Negligible Sub-Synchronous Resonance or Sub-Synchronous Control Interaction Risk (SSR/SSCI)** – SmartValve is an active device which injects only at voltage at 60 Hz, and thus has no sub 60 Hz interaction.

5. Summary

In this paper, we carried out a detailed study exploring potential solutions to increase the transfer capability of the Manitoba to US interface. Specifically, the study assessed the potential to leverage Smart Wires' SmartValve^{TM} technology to address loop flow issues under high NDEX to Manitoba. Under this condition, high power flows into Manitoba from North Dakota on Station 2-Station 1 (Line B) circuit, creating an overload on this circuit for certain contingency scenarios. Manitoba Hydro has deployed Phase Shifting Transformers at Station 4 230 kV substation to address similar issues on the line connection the MH 230 kV station to a substation located in North Dakota.

The SmartValve is a Modular Static Synchronous Series Compensator (M-SSSC) that can be used to increase or decrease line reactance. Due to its modular design, SmartValve installations can be scaled up or down as needs changes over time or redeployed across the network, helping to minimize investment cost and risk for transmission asset owners.

This paper presented the results of a power flow assessment, identification of SmartValve solutions to address issues on Line B, outline of SmartValve solution benefits as well as some outline information on implementation of a SmartValve solution. The study presented in this report lays out several options to resolve the constraint by both:

1. Deploying SmartValves directly in series with Line B; and
2. Deploying SmartValves on lines internal to Manitoba Hydro's system to address the same constraint.

Also considered in this analysis was the effect of reducing Manitoba imports from the United States. A SmartValve solution on Line B itself provides for the highest efficacy. Solutions on internal Manitoba Hydro circuits are not as effective, but by virtue of being installed on Manitoba Hydro's internal assets, these options can likely be approved and installed in quicker timeframes.

The SmartValve solution offers several benefits over traditional solutions and alternative power flow control solutions to improve transfer capability on this interface.

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