21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2013 Grid of the Future Symposium

ATC's Mackinac Back-to-Back HVDC Project: Planning and Operation Considerations for Michigan's Eastern Upper and Northern Lower Peninsulas

M. B. MARZ
K. D. COPP
A. C. MANTY
American Transmission Co.
USA

S. SANKAR*
J. S. RECTOR
P. M. FAIRLY
Black & Veatch
USA

G. D. IRWIN
Electranix
Canada

SUMMARY

The need for flow control between the upper and lower peninsulas of Michigan at Mackinac substation, near St. Ignace, Michigan, initiated a thorough investigation of available flow control technologies. This investigation determined that Back-to-Back Voltage Source Converter (VSC) HVDC technology best met American Transmission Company's (ATC) requirements. Pre-specification studies identified the need for new control techniques due to weak system conditions on both sides of the Back-to-Back Converter Station. The Mackinac HVDC Converter Station is now under construction and expected to be in service in 2014.This paper describes how system characteristics and the capabilities of available flow control technologies determined the selection of VSC technology and the converter station specification.

KEYWORDS

Flow Control, Back-to-Back HVDC, Voltage Source Converter (VSC), Static Synchronous Compensator (STATCOM)

INTRODUCTION

The transmission systems in Michigan's eastern Upper Peninsula (UP) and northern Lower Peninsula (LP) were designed to serve load, not transfer power across the UP. However when the eastern UP, which had earlier been served radially from the LP via undersea cables across the Straits of Mackinac, was connected to the rest of the UP, power transfers across the UP became possible. For years, high impedances and a relatively low west to east energy flow bias meant these transfers were low and rarely caused thermal or voltage issues. When issues did arise, they were usually resolved by splitting the system to separate the eastern UP from the rest of the UP as shown in Figure 1.

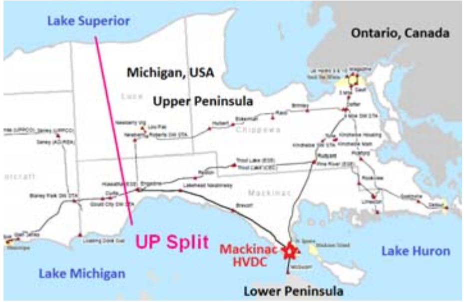

Figure 1: Eastern UP Transmission System Split

---

*sankars@bv.com

West to east flow bias is increasing as the demand for low cost western generation and environmentally friendly sources such as hydro and wind grows to the south and east of Lake Michigan (Fig. 2). Most of this power follows the low impedance path south of Lake Michigan; however, a small portion flows through the higher impedance path north of the lake. Redispatching generation to avoid thermal and voltage issues caused by this northern flow is difficult and expensive because there are few strong sources in the area. Although undesirable because it creates reliability risk when transmission line outages are required for maintenance, splitting the UP to control flows, once an occasional requirement, has now become an all but permanent condition. Building additional higher voltage lines to relieve the thermal and voltage issues created by the flow across the UP was investigated and found to be prohibitively expensive and unachievable in the required timeframe, making flow control the preferred alternative.

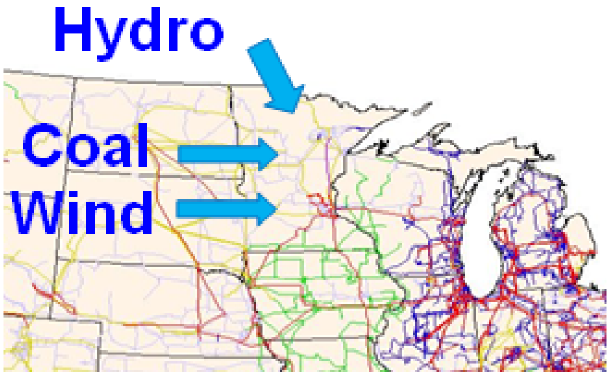

Figure 2: Flow Bias

MACKINAC POWER FLOW CONTROLLER REQUIREMENTS

In addition to other existing system constraints the power system near Mackinac also has a very low available short circuit current level. This requires the flow control technology implemented to operate under low fault conditions and not contribute to voltage control issues, or create the need for additional dynamic reactive support. It was also desired that whatever flow control technology was chosen, it should be a long term fix and system changes should not make the flow control device obsolete. Although the flow across the Straits of Mackinac is presently limited to less than 100 MW, the flow controller was designed for up to 200 MW to account for future growth and improvements.

FLOW CONTROL TECHNOLOGIES

Several flow control technologies were considered for the Mackinac Project [1]. They included (1) series reactors, (2) phase shifting transformers (PST), (3) variable frequency transformers (VFT), (4) Line Commutated Converter (LCC) HVDC (5) Capacitor-Commutated Converter (CCC) HVDC and (6) Voltage Source Converter (VSC) HVDC.

Series Reactors – Series reactors, more often applied on distribution systems, increase the impedance of one path to decrease the flow on that path. Their advantages include simplicity and cost. The disadvantages include (1) reactive losses and thereby requiring additional shunt reactive power compensation (2) a lack of adjustability (voltage regulation), and (3) potential obsolescence due to system changes. A fixed (or a variable tapped) series reactor solution is not a viable option at Mackinac because of the its limitation on the power flow controllability and in addition would add reactive losses in an area where low short circuit capability already makes voltage control challenging. A Unified Power Flow Controller (UPFC) was not considered as one of the alternatives.

Phase Shifting Transformers (PST) –PSTs control active power flow by changing the phase angle difference across the transformer. This is done by mechanical switches that change the tap on a regulating winding. These switches require periodic inspection, maintenance and total replacement after a given number of operations, which could be a concern if used to respond hourly to system flows. Designed for a specific maximum angle deviation, multiple phase shifters in series might be necessary to achieve the phase shift required at Mackinac. Studies have shown that either additional phase shifters might be required or the control flexibility will be limited after several years due to increase in through flows. In addition, the PST would be slow to re-adjust the flows to avoid potential voltage collapse during major contingencies described later in this paper.

Variable Frequency Transformers (VFT) – A VFT is essentially a doubly fed electric machine with one connection to the stator and the other to the rotor [2]. Changing the rotor position changes the phase angle and power flow across the device making it act as a continuously adjustable phase-shifting transformer with the added benefits that it can smoothly ramp from one power level to another (no steps). While a VFT allows for reactive power flow, it cannot use reactive power to regulate voltage. Although a VFT has some unique advantages, it would require adding dynamic reactive power compensation to keep system voltage within a reasonable range at a part of the system as weak as Mackinac. A very limited number of projects using this technology are in commercial operation.

Line Commutated Converter (LCC) HVDC – LCC HVDC has been in commercial use since the 1950s, primarily to transfer power over long distances economically or on cables without the charging current and voltage control issues associated with AC cables. Modern LCC HVDC installations use thyristors that use a short-duration positive current pulse to the device gate to turn it on (provided it is in forward-blocking state). The device is turned off when the gate signal is removed and the current passing through the thyrister hits a “zero-crossing”. LCC HVDC can be expensive because it requires special converter transformers, consumes reactive power up to 50 percent of its rating and requires harmonic filtering. It also requires a minimum short circuit current capacity, at least twice the converter rating, at the point of interconnection. LCC HVDC is not an option in this case because the short circuit capacity at Mackinac is too low and would require additional synchronous condensers on both sides of the converter station which would increase project losses and costs.

Capacitor-Commutated Converter (CCC) HVDC – CCC HVDC was developed to address the short circuit limitations of LCC HVDC [3]. CCC uses series capacitors inserted into the AC line connections, either on the primary or secondary side of the converter transformer, to partially offset the commutating inductance of the converter and reduce fault current requirements. This also allows for a smaller extinction angle, reducing reactive power requirements. The ability of CCC HVDC to operate under very low short circuit conditions is limited and pushing this technology to its limits can create cost and reliability concerns. Also, the need for reactive power compensation, although reduced compared to LCC HVDC, would probably require additional dynamic reactive power compensation to maintain system voltage at an acceptable level at Mackinac.

Voltage Source Converter (VSC) HVDC – The development of high power self-commutating insulated gate bipolar transistors (IGBT) has led to the development of STATCOMs and flexible VSC HVDC devices [4]. VSC HVDC can independently control voltages at each HVDC terminal separate from the active power order; also, with the DC connection between the terminals out of service, it can be operated as two independent STATCOM devices. VSC HVDC has no minimum short circuit capacity requirements, can be used to black start one side from the other and does not require specially designed converter transformers. A DC bus fault creates a current path thru the anti-parallel diodes and the fault current is limited only by the system impedance and the converter transformer impedance. Also, when the VSC is energized under zero DC voltage, there would be in-rush currents and will have to be limited by pre-insertion resistors. IGBT controllability makes it possible to serve an “island” (a system whose only connection to the grid is through the HVDC) and has allowed for improved HVDC control methods to be developed.

VSC HVDC converters use either series connected pulse width modulation techniques or multilevel switching to achieve lower losses, minimal distortion and an easily scalable design. VSC HVDC is generally more expensive than LCC or CCC HVDC, has increased control flexibility, and better control performance under very weak system conditions.

TECHNOLOGY DECISION

Voltage Source Converter (VSC) HVDC technology was chosen for the Mackinac project. The decision was primarily driven by three conditions: (1) the low short circuit current available in the area, (2) the need to consider voltage regulation, power flow controllability and reactive power consumption, and (3) the robustness of the solution. The minimum Short Circuit Ratio (SCR) at Mackinac is about 0.6, which makes VSC HVDC more suitable than the other HVDC technologies. Other concerns included cost, maintenance requirements, operation under fault and outage conditions, and losses. No technology was best at meeting all of these issues and compromises, especially the cost, were necessary. Although it was one of the more costly solutions, VSC HVDC addressed all three major project concerns listed above. Maintenance, control complexity, weak system operation, interaction with other power electronic controls and potential sub-synchronous resonance interaction were still concerns. Maintenance is expected to be three to seven days annually. This could be reduced as more experience with the equipment is gained. Figure 3 shows the existing system and the proposed flow controller scheme.

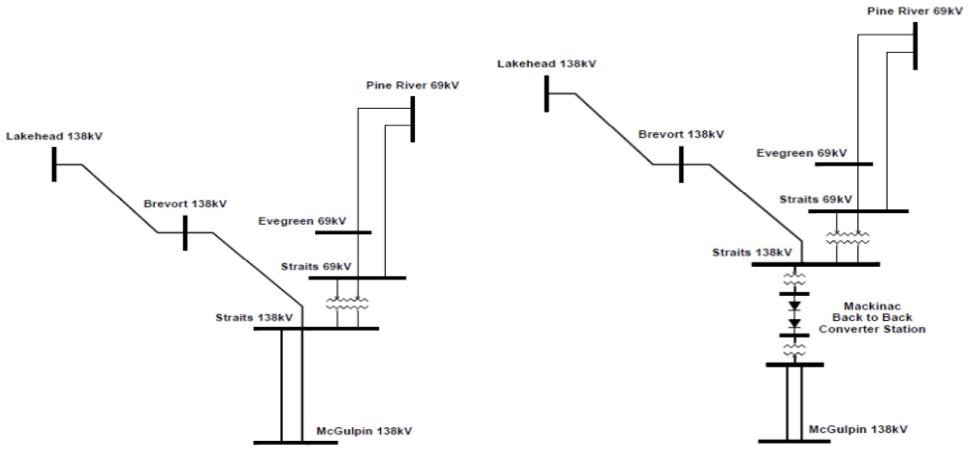

Figure 3: Existing and the proposed scheme

VSC CONTROL CHALLENGES UNDER CONTINGENCIES

The eastern UP power system is effectively connected to the rest of the ATC system via two 138 kV lines and one 69 kV line. Once the HVDC converter station is implemented between the UP and LP systems, any N-1-1 or N-2 outage of these circuits in the UP would make eastern UP either islanded (connected to the rest of the system only through the Mackinac HVDC) or quasi-islanded (connected to the rest of the system through the Mackinac HVDC and a single 69 kV connection). Extensive power flow, transient stability and PSCAD studies performed during the pre-specification stage indicated that the proposed VSC HVDC converters should have the functionalities to address the following issues associated with the islanding and quasi-islanding situations:

- For UP faults that result in a trip of 138 kV paths from the Converter Station to the western part of the UP, a high speed change in the VSC power order (which may result in a power reversal) based on the pre-fault 138 kV flows would be required to maintain stability and to avoid voltage collapse.

- Studies (with generic VSC models) indicated that where two or more 69 kV paths remain, the system showed acceptable performance providing the VSC real power flow is quickly modified to make up the pre-fault 138 kV power flow.

- Cases where only one 69 kV line remains after the 138 kV fault (connecting the eastern UP to the western UP) may show voltage instabilities until the Converter Station is converted to full island mode, after which acceptable recovery was demonstrated.

To implement the above functions, it was realized that extensive communication signals (circuit breaker statuses and power flow values) from many substations may be required so as to determine the DC power levels following contingencies. Alternatively, an automatic power reduction or reversal scheme based on power / angle characteristics emulating an AC line was also envisioned, which would use locally sensed signals and not dependent on the remote communication signals. Accordingly, during the bid stage, the bidders were encouraged to study the islanding and the quasi-islanding issues and offer solutions based on locally measured signals.

CONVERTER STATION SPECIFICATION

Mackinac HVDC converter station is designed for 200 MW bi-directional power transfer and also to provide reactive power (+/- 100 MVAR) for local voltage support during steady state and dynamic conditions. Figure 4 shows the P-Q capability of the VSC converters specified for the Mackinac project. Positive reactive power indicates the reactive power supplied by the converters and the negative reactive power indicates the reactive power absorbed by the converters. In addition, the converter station is being designed with the following features:

- When not transferring power, the two VSC converters can be operated as two individual STATCOM or as one STATCOM while the other converter is out of service.
- During certain contingencies, the converter connected to the UP side may be left connected to an islanded system with this converter designed to operate at fixed frequency / voltage mode with droop settings.
- Black start capability to start up a passive ac system network in UP

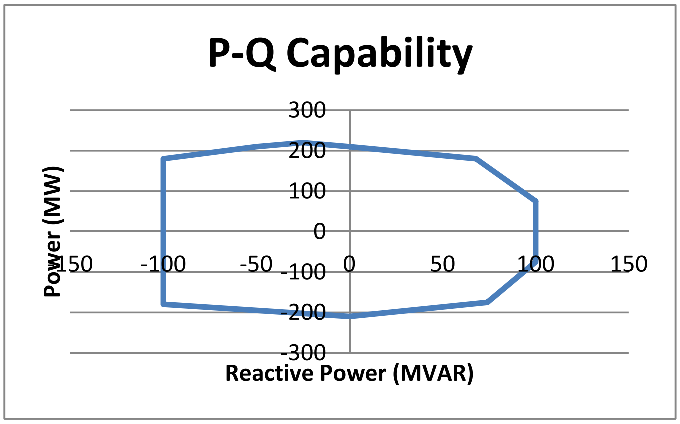

Figure 4: P-Q Capability of the VSC Converters

DESIGN AND CONSTRUCTION PROGRESS

A turnkey contract for Mackinac HVDC Converter Station was awarded to ABB in early 2012 and the project is expected to be in service by the third quarter of 2014. The voltage source converters are of symmetrical monopole type and a simplified one line diagram the converter station is shown in Figure 5.

The design studies which involve new control concepts to avoid the need for complex communication signals are currently being finalized by ABB. These control designs will be reported in future publications.

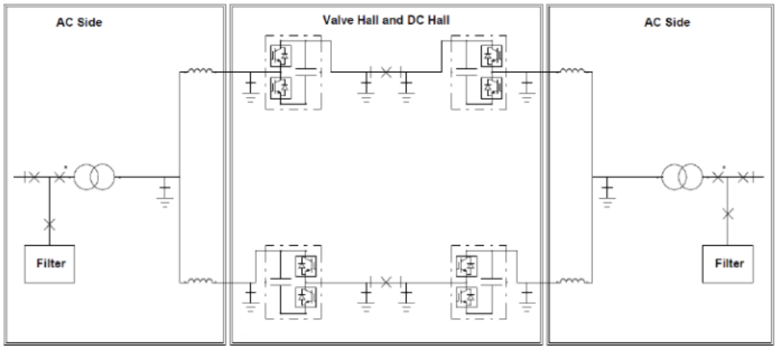

Figure 5: Simplified One Line Diagram of Mackinac HVDC Converter Station
(With permission from ABB)

The project is located on a 40 acre site in the Upper Peninsula of Michigan, three miles north of the Mackinac Straits, in St. Ignace, Michigan. The station was designed for temperature extremes ranging from 102˚ F to -50˚ F and a snowfall up to 200" annually. The station will be unstaffed and controlled and monitored remotely at the ATC operations facilities in Pewaukee and Madison, WI. Local, trained technicians will provide first response troubleshooting and monthly inspection. The converter building housing the valves, reactors, cooling and control equipment is approximately 300 feet long, 100 feet wide, two stories tall, and is divided into four valve halls (a +DC and –DC for each converter), two reactor halls and a control building.

CONCLUSION

The decision to use VSC HVDC technology to control the flow between the Upper and Lower Peninsulas of Michigan was made after a thorough evaluation of available flow control technologies and their compatibility with the system at Mackinac. While all of the technologies have advantages, disadvantages and applications that could make each the most appropriate choice, the unusual conditions at Mackinac made VSC technology the best choice for this application on mainly the technical advantages. The condition that drove the decision was primarily the weak system conditions at Mackinac, which precluded some of the flow control options and made the reactive power capabilities of the VSC particularly attractive.

BIBLIOGRAPHY

[1] M. B. Marz. “Mackinac VSC HVDC Flow Control Project Design” Minnesota Power Systems Conference, November 6-8, 2012. Available at: http://www.cce.umn.edu/Documents/CPE-Conferences/MIPSYCON-Papers/2012/MackinacVscHvdcFlowControlProjectDesign.pdf

[2] Merkhouf, A, Upadhyay, S, and Doyon, P, “Variable Frequency Transformer – An Overview”, IEEE Power Engineering Society General Meeting, 2006.

[3] Bahrman, M.P., “HVDC Transmission Overview”, IEEE Transmission and Distribution Conference and Exposition, 2008.

[4] Flourentzou, N, Agelidis, V.G and Demetriades, G.D, “VSC Based HVDC Power Transmission Systems: An Overview”, IEEE Transactions on Power Electronics, Vol. 24, Issue 3, 2009.