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Mackinac Back-to-Back Voltage Source Converter HVDC Interaction with Power Line Carrier and Automatic Meter Reading Communications

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SUMMARY

The Mackinac back-to-back voltage source converter (VSC) HVDC went into service in 2014. Located between the upper (UP) and lower (LP) peninsulas of Michigan, it controls flows that would otherwise overload the eastern UP following certain contingencies. VSC HVDC was chosen for this weak system because it has no minimum short circuit capacity requirement and can independently provide reactive power to both station terminals whether or not its two dc terminals are connected.

During project commissioning, low voltage Power Line Carrier (PLC) equipment used for 138 kV line protection failed near Mackinac. Simulations confirmed this was due to a high frequency resonance in the PLC equipment excited by HVDC switching. Although no other failures occurred, higher than acceptable voltages were measured in some remote PLCs. The HVDC was originally designed with a doubly tuned, 5th and 30th, harmonic filter that met project requirements. Although not sharply tuned, it did not effectively filter frequencies above 5 kHz. Minor modifications to the filter retuned it into a 5th harmonic and high pass filter that met distortion requirements and prevented PLC failure.

VSC HVDC uses Insulated Gate Bipolar Transistors (IGBTs) to achieve fast power and independent reactive power control. Unlike the thyristors used in Line Commutated Converter (LCC) HVDC that only produce periodic (harmonic) distortion, IGBTs also produce non-periodic (interharmonic) distortion. The level of interharmonic distortion varies with system conditions as well as with HVDC MW and Mvar flow. A distribution cooperative near Mackinac uses a two-way Automatic Meter Reading (AMR) system that operates by putting non-periodic distortion on the system. The AMR uses a signal processing algorithm that makes it immune to integer harmonic distortion, but not to interharmonic distortion. With higher levels of interharmonics at the HVDC, the AMR system may be unable to communicate or may require multiple attempts before achieving successful communication with certain meters. Continuing investigations are underway to determine how the AMR can be made more immune to interharmonics and how the HVDC can be either operated or modified to limit interharmonic distortion to a level that will allow acceptable AMR communications.

KEYWORDS

Automatic Meter Reading (AMR) - Cascaded Two-Level - HVDC - Interharmonics - Power Line Carrier (PLC) - Power Quality - Smart Grid - Voltage Source Converter (VSC).

INTRODUCTION

The Mackinac back-to-back VSC HVDC controls flow between the upper and lower peninsulas of Michigan that would otherwise overload the weak eastern UP system following certain contingencies [1]. It also increases system reliability and allows the outages necessary to perform maintenance to be taken. Unlike other flow control technologies, VSC HVDC requires no minimum short circuit capacity, can help damp system oscillations and independently provides reactive power to both station

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terminals with or without the DC bus connecting the two terminals in service. The IGBTs that allow the fast switching necessary for these benefits create high frequency and non-periodic (interharmonic) distortion that, while not harmful to power system equipment at the levels seen at Mackinac, can create issues with communications equipment connected to the power system.

The project was designed to meet IEEE 519-1992 (IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems). It meets these requirements as well as the requirements of IEEE 519-2014, which was published after the project was begun. Nevertheless, PLC terminal equipment failed at Mackinac during commissioning and a distribution cooperative located near Mackinac is intermittently experiencing degraded performance of their AMR system when the HVDC is on line. These issues are attributable to high frequency and interharmonic distortion that are beyond the scope of IEEE-519. This paper discusses how the PLC issue was resolved and how the AMR issue is being addressed.

MACKINAC VSC HVDC OPERATION

Although limited to significantly lower MW levels by system constraints, the Mackinac HVDC is designed to transfer up to 200 MW bi-directional with +/-100 MVAR reactive power delivery at each terminal. A symmetrical monopole with a cascaded two level (CTL) converter design (Figure 1) is used to reduce losses, harmonic distortion and filtering requirements when compared to earlier controllable switch type two level converter VSC designs.

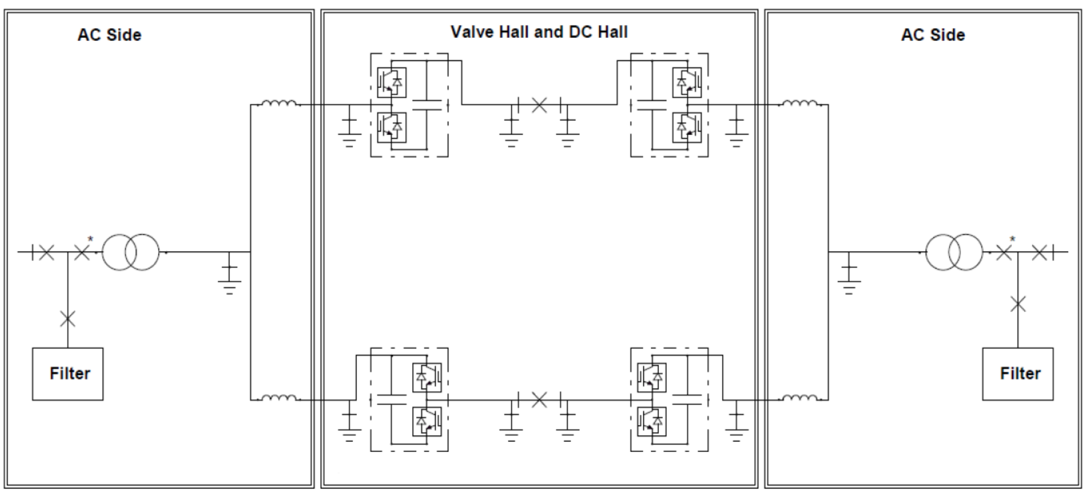

Figure 1: Simplified One-Line Diagram of Mackinac HVDC Converter Station

Mackinac converters use pulse width modulation (PWM) to produce a controllable power supply type voltage waveform (Figure 2) similar to that of modular multilevel converters (MMC) [2]. This PWM switching and the high speed controls that change IGBT switching each cycle to give the HVDC many of its stability benefits both contribute non-periodic (on a 60 Hz basis) interharmonic distortion. The non-periodic IGBT cell switching frequency/pulse number required to prevent converter capacitor damage also produces interharmonic distortion.

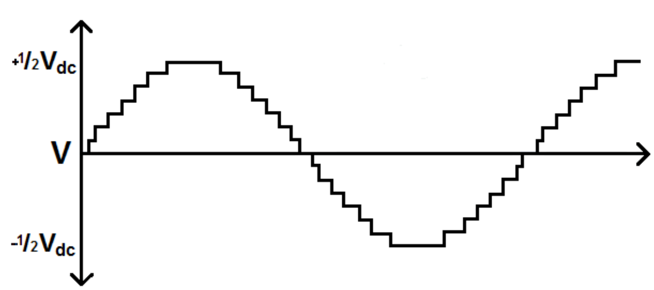

Figure 2: Cascaded Two Level (CTL) Converter Voltage Waveform

The Mackinac South converter connected to the relatively strong LP system uses vector current control, a robust and reliable scheme which controls instantaneous active power and reactive power independently through a fast inner current control loop that decouples current into q and d components. Outer control loops then use the d component to control active power or dc voltage and the q component to control reactive power or ac voltage.

Under certain contingencies the Mackinac North (UP) converter bus can be extremely weak, making vector current control unacceptable, so a "phasor voltage control" based on direct control of the converter's internal ac voltage amplitude and phase was developed. In the steady-state this control keeps the internal converter voltage phasor fixed with constant amplitude and phase. Impedance correction is used to extend amplitude control to the point of common coupling (PCC). Phase control is extended to the PCC by a frequency droop and phase angle offset to adjust synchronizing power control. Synchronizing power is the power flow opposing the increase in relative rotor angle between synchronous machines that keeps machines synchronized.

The North converter also has a damping controller tuned to approximately 1 Hz, to ensure positive damping at a natural mode related to the phasor voltage control strategy. This controller responds to North bus frequency deviations that while small, are continuous. As a result of this damping controller Mackinac real power does not flow at a fixed value, but continually varies by a few MW around its set value. This provides the HVDC damping controller and governor function benefits that give the Mackinac North bus converter dynamic characteristics similar to that of a large synchronous machine. These MW variations can be minimized by reducing the governor time constant, but too low of a time constant could contribute to stability issues.

The north converter also has additional specialized control features to allow operation under intentional or unintentional island or "quasi-island" conditions. The north converter will automatically determine that it is connected to an island (connected to the rest of the system only through Mackinac HVDC) and then change to a fixed frequency and voltage mode with droop settings that will allow indefinite operation. For "quasi-island" conditions (connected only through the Mackinac HVDC and a single 69 kV line), an ac line emulation (ACLE) function was developed using only local measurements. This control emulates the power-angle characteristics of an ac line during large disturbances and determines a new MW operating point following disturbances that significantly change the ac network impedance to maintain stability, reduce the possibility of overloads and aid post-disturbance recovery by synchronizing the North and South ac networks [3].

POWER LINE CARRIER ISSUES

Soon after the HVDC was first energized, 138 kV power line carrier (PLC) low voltage terminal equipment at a substation near Mackinac failed. This failure was traced to a 13.4 kHz distortion in the PLC equipment. This frequency approached 20 kHz during tests when the underwater cables connecting the upper and lower peninsulas were out of service. Although no failures occurred at other PLC locations, higher than acceptable voltages were measured at remote PLC equipment. Signals of such high frequencies are usually blocked or attenuated to acceptable levels by transformers or by traveling a significant distance and hence not a concern for most power system equipment.

To investigate these PLC failures a high frequency model of the transmission system and PLC equipment was developed using PSCAD. The model demonstrated a resonance between the HVDC, through the PLC line trap and CVT capacitance and into the PLC drain coils, which caused it to appear on the PLC amplifier. Although the model did not precisely match the measured resonance frequency due to the difficulty in obtaining precise high frequency model parameters, the phenomena was conclusively demonstrated. Similar harmonic resonance with PLC equipment has been encountered in LCC HVDC [4]. Other than PLC equipment, there is little, if any, equipment located at transmission voltage levels that will resonate at these frequencies.

The source of the damaging distortion is IGBT switching transients, which appear as step changes on the converter transformer secondary voltage. Tests determined it is unlikely that damage caused by this wide spectrum noise can be avoided by retuning the PLC. Filtering the distortion close to its source was determined to be the most practical solution. The simulations also revealed significant attenuation of this high frequency distortion through the underwater cables connecting the peninsulas and at remote locations, explaining why PLC failures were not experienced at these locations.

The Mackinac HVDC was originally designed with a doubly tuned, 5th and 30th harmonic, filter and although not sharply tuned, it did not sufficiently filter out high frequencies. Adding a high pass filter to filter the small amount of high frequency currents produced by the converters was investigated. Although cost was an issue, the time required to add the filter was a greater concern. The PLC was part of a redundant protection scheme, however its long term outage was still unacceptable. Replacing the local PLC with a different communication method was also considered, but filtering was determined to be the best solution because it would eliminate remote PLC overvoltages and allow other components with potential high frequency resonances to be connected to the system.

After a thorough investigation, the project contractor determined that the originally installed doubly tuned filter (Figure 3a) could be modified to change the filter's 30th harmonic tuning into a high pass filter (Figure 3b) by bypassing one filter inductor. The modified filter reduced the high frequency voltage amplification at the PLC terminal equipment and met project distortion limits without overstressing its components. This solution was implemented quickly at minimal cost and has allowed the Mackinac PLC to be returned to service when the HVDC is operating.

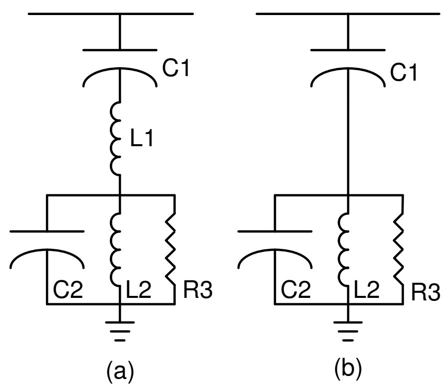

Figure 3: HVDC (a) Original 5th and 30th and (b) Modified 5th and High Pass Filters

AUTOMATIC METER READING ISSUES

LCC HVDC uses thyristors that switch periodically on a 60 Hz basis and produce integer harmonic distortion that is unchanged as long as the system is operating in the steady state. VSC HVDC uses IGBTs that use a non-periodic cell switching frequency (non-integer pulse number) and makes continuous minor adjustments to its operating point to improve system stability. This produces non-integer harmonic (interharmonic) distortion that can change each cycle.

To improve distribution system operations, utilities are utilizing smart meters with communication capability to perform a variety of functions including reporting energy usage and tracking outages. While several communication media, including radio frequency and cellular technology, can be used by these meters, one economical medium is the power system. By intentionally transiently distorting power system voltage or current (or both), two-way communication signals can be sent between meters over power lines. Signal processing algorithms can extract the non-periodic communication signal with essentially any level of harmonic (60 Hz periodic) distortion on the system. The use of error checking and multiple communication attempts can make these systems very reliable.

Some distribution providers near Mackinac have smart meter systems that use power lines as their communication medium. One has experienced intermittent communication difficulties with a minority, but operationally significant portion of their meters when the HVDC is in service. At present, essentially all connected meters can be communicated with, but this may require multiple manually triggered attempts over a period of hours until distortion levels are acceptable. In addition to energy usage functions, these meters are also used to determine outage locations and hence delayed communications could delay service restoration.

Preliminary analysis has shown the most severe communication issues occurring at specific meters connected to particular substations near Mackinac, but not necessarily the stations closest to Mackinac. While these issues have been related to high interharmonic distortion at the converter PCC, the specific reasons some stations are more affected than others, including feeder grounding, voltage and length and meter age (technology), are being investigated. Interharmonic distortion and power line communication failures are not unique to VSC HVDC, but have been experienced near other devices that produce non-periodic distortion, such as arc furnaces [5].

The AMR system in use near Mackinac is designed to be immune to harmonic distortion and frequencies greater than 1000 Hz. To characterize the interharmonic voltage distortion affecting these meters, the 1st through 16th voltage interharmonics [6] at the converter PCC are combined into a single value by taking the square root of the sum of the squares of the individual interharmonics. The result is our "total interharmonic distortion" or TIHD, which appears to better reflect meter sensitivity to distortion than any individual interharmonic. Our initial experience suggests that a TIHD greater than approximately 0.6% will significantly affect AMR communications. This is similar to the 0.5% distortion (undefined) limit the AMR supplier suggested for successful AMR operation. It should be noted, that when the AMR is attempting to communicate, it produces a TIHD of approximately 0.25%.

Measurements at Mackinac show that TIHD levels increase when the HVDC is in service and fluctuate over time, whether or not the HVDC MW flow changes (Figure 4). Measurements have shown that TIHD varies with system configuration, usually increasing with decreased system strength, and system loads, whose relationship with TIHD is harder to quantify.

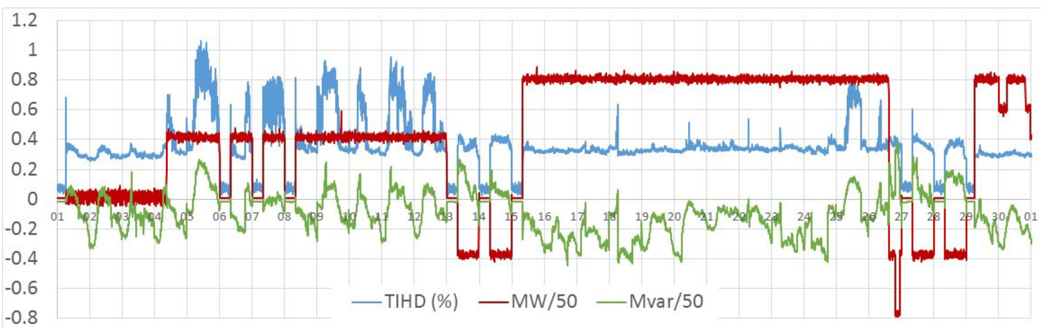

Figure 4: TIHD (%), MW and Mvar at Mackinac PCC (one month of 5 minute data).

The system parameter that has been found to most consistently track TIHD is the Mvars out of the HVDC at the PCC. This includes not only the Mvars into or out of the HVDC, but also 30 Mvars from filters. By dividing the Mvars at the PCC (positive into the system, negative into the HVDC) by a scalar and adding a constant, PCC Mvars will track TIHD. Figure 5 uses a scalar of 25 and a constant of 0.6. The plots do not match when the HVDC is off or Mvars are negative (going into the HVDC), because when the HVDC is on the TIHD does not go below approximately 0.3%.

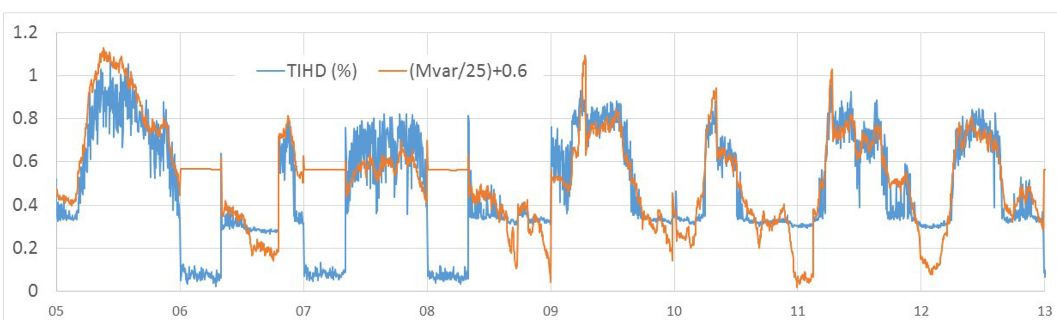

Figure 5: PCC TIHD (%) and Scaled Mvars.

The scalar and constant needed to relate HVDC MVARs to TIHD can change when HVDC and system conditions change. In general it seems that a higher scalar provides a better match when

HVDC MW flow to the north is greater or the flow is to the south, but there is limited data and no known reason for this relationship. The relationship could be related to system strength, which may be reflected in the HVDC MVAR output, or to something in the HVDC switching algorithm. Investigations are continuing to determine what can be done to limit interharmonic distortion or improve communications to achieve acceptable AMR performance.

There are no IEC [7] or IEEE [8] interharmonic limits beyond those for frequencies below 120 Hz based on flicker effects. IEEE 519 recognizes that interharmonic can effect communications and "due consideration should be given" and "appropriate interharmonic limits should be developed on a case-by-case basis." The IEC has a suggested reference level of 0.2% for each interharmonic below the 50th, which appears to be designed to allow some communication over the power system. Limits based the effects of interharmonics on power system equipment rather than communications would be similar to existing harmonic limits. At 69 kV IEEE recommended harmonic voltage distortion limits are 1.5% for each individual harmonic and 2.5% for total harmonic distortion, approximately an order of magnitude greater than the IEC reference levels based on power line communication interference and approximately double the levels at Mackinac.

CONCLUSIONS

The Mackinac HVDC is an economical and timely solution to the problem of excessive flows in the UP that improves system reliability and operational flexibility. Investigations are continuing into how communication over the power lines can be improved when the HVDC is in service. Industry standards for allowable interharmonic distortion would help guide these investigations.

The Mackinac HVDC project has raised two issues that should be addressed when considering VSC HVDC or any modern VSC technology (Type 4 wind turbines, solar inverters, machine drives, etc.). The first, which is also a concern for thyristor switched LCC HVDC, is the importance of analyzing the effects of high frequency signals on system equipment and, if necessary, designing appropriate mitigation strategies. The second is the potential for VSC produced interharmonics to interfere with smart grid communication systems that use power lines as their communications medium and the necessity to address this issue on a case-by-case basis.

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