ATC's Mackinac Back-to-Back HVDC Project Update

Michael B. Marz
American Transmission Company

Summary

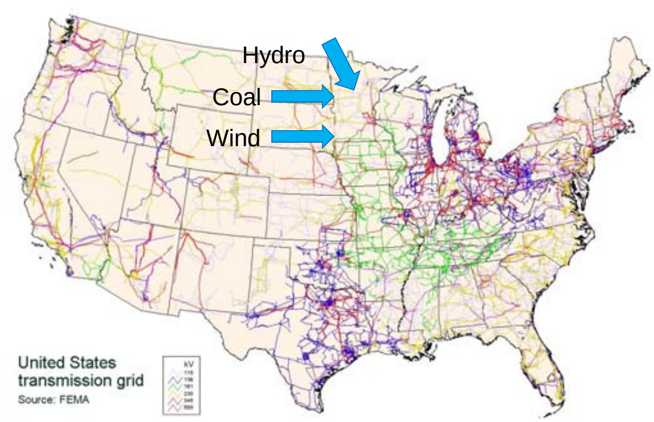
- The Need For Flow Control at Mackinac
- Mackinac Flow Control Requirements
- Available Flow Control Technologies
- Technology Decision
- HVDC Control Challenges Under Contingencies
- Mackinac HVDC Specification
- Design and Construction Progress

History of Eastern UP

- Designed to Serve Load, NOT Transfer Power
- Originally Served Radially from LP
- High Z and Low West-to-East Bias Kept Flows Low
- Address thermal/voltage issues by splitting system

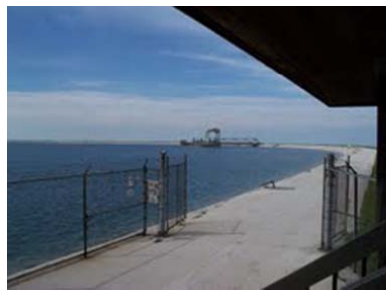
West to East Bias Flows

- Low cost/environmentally friendly power from north west is creating a stronger south east bias.
- Most flows on low impedance path south of lake. Small, but significant flow through Mackinac.



Ludington Pumped Storage

- Located on the East Side of Lake Michigan
- Stores Cheaper Power at Night (6 x 333 MW)
- Generates During the Day (6 x 250 MW)
- Can Contribute to Flows in Either Direction
- Could Increase Output in the Future



Split Angle is Getting Worse

- A measure of the severity of the issue
  - overload at 44º under certain outage
- System splitting once rare is now normal
- This Trend is expected to continue

Year	Maximum Split Angle
2007	72.8º
2008	78.2º
2009	80.1º
2010	83.5º
2011	87.6º

High Flow and Splitting System Issues

- Why do We Need to Split the System?
  - High flows overload UP equipment
  - High flows cause low voltages
- What Problems Does Splitting System Cause?
  - Outage constraints – can't schedule outages
  - Difficulty regulating voltage (UP Flat Load)
  - Multiple transients during splitting and reconfiguring, especially on underwater cables

Alternatives to Splitting System

- Re-dispatching Generation
  - Few strong sources nearby
  - Difficult, expensive and impractical
- Build Our Way Out of the Problem
  - Creates new overloads and voltage issues (fixing one problem creates another)
  - Expensive and Would Take Too Much Time
  - Required outages - very difficult to impossible
  - Necessary only if we want the UP to be an alternate path for significant flows
- Control the Flow Across the Straits

Mackinac Flow Control Challenges

- Very Low Available Short Circuit – Especially under Outage Conditions
- No Large Generators Nearby and Some Nerby Generators May Retire
- Voltage Control Can't Be Made Worse
- Must Be A Long Term Fix – System Changes Can't Make it Obsolete (Robustness)
- +/-200 MW (Existing Cable Rating)
- Cost, Maintenance, Losses, Contingency Operation

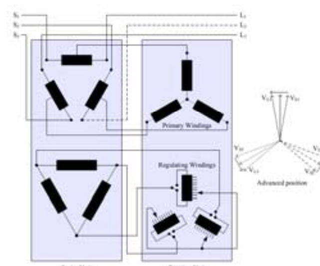
Available Flow Control Technologies

- Series Reactor
- Phase Shifting Transformer (PST)
- Variable Frequency Transformer (VFT)
- Line Commutated Converter (LCC) HVDC
- Capacitor Commutated Converter (CCC) HVDC
- Voltage Source Converter (VSC) HVDC
  - IGBT - Insulated Gate Bi-Polar Transistors
  - Series Connected PWM or Multi-Level

Series Reactor

- Increasing Impedance Decreases Flow
- Balance Flow on Parallel Lines
- Advantages: Simplicity & Cost
- Disadvantages: Reactive Losses, Lack of Adjustability, Obsolescence
- Mackinac Weakness Makes this Unacceptable

Phase Shifting Transformer



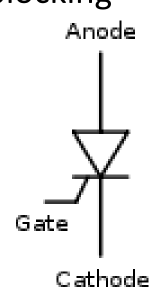
- $P_{12} = \frac{V_1 * V_2}{X} * \sin\delta$
- Increase/Decrease Angle
- Series PST for Large Angle
- Mechanical Tap Switches
  - Inspection 80k Ops, Parts Replacement 800k Ops, Total Replacement 4M Ops
- Operate for Market Conditions?
- No Harmonics, Allows Needed Flow Through
- Consumes Some Vars

Variable Frequency Transformer

- Single Supplier (GE)
- Essentially a Continuously Adjustable PST
- Can Connect Asynchronous Systems (3 Hz)
- Fully Adjustable to +/- Its 100 MW Rating
  - Multiple Units Can Be Paralleled
- Allows Reactive Flow, Does Not Regulate V
- No Harmonics, Sub-Synchronous Torsional or Control Interaction Issues
- Can Supply Real & Reactive Power to Faults
- Inertia Helps Stability

Line Commutated Converter HVDC

- In Commercial Use Since 1950's
  - Economically transfer high power long distances overhead
  - Transfer power underground w/o var & voltage issues
  - Can control flow and connect asynchronous systems
- Thyristers – conducting (forward mode) or blocking (forward or reverse mode)
  - Requires zero crossing to turn off
  - Low conducting & switching losses
- Six or Twelve Pulse Configurations
  - Harmonic Filters Required



LCC HVDC

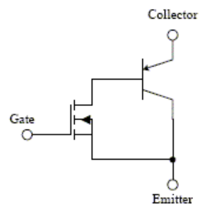
- Advantages
  - Lower construction, right-of-way & loss costs
  - Full flow control (never obsolete)
- Disadvantages
  - Terminal Costs (Converter Transformers)
  - Var Consumption (up to 50% of rating)
  - Harmonic Filter Requirements
  - Minimum short circuit requirements (2x rating)
  - Possible Control Interaction
  - Possible Sub-synchronous Resonance

Capacitor Commutated Converter HVDC

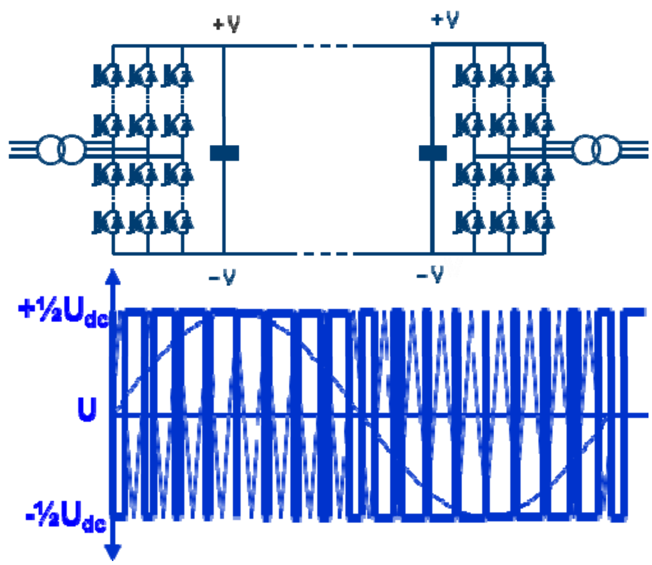
- Thyristers Need Minimum Short Circuit Current to Turn-Off (need reverse voltage)
- CCC Designed to Address this Issue
- Series Capacitors in AC Line Connections of Converter Transformer Primary or Secondary
- Partially Offsets Commutating Inductance (reduces fault current requirements)
- Allows Smaller Extinction Angle (reduces reactive power requirements)
- Mackinac Short Circuit Still an Issue

Voltage Sourced Converter HVDC

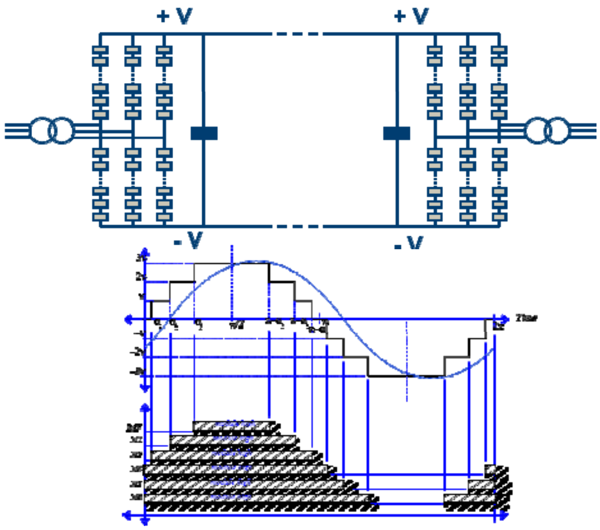
- Cheaper, Higher Rated Self-Commutating Insulated Gate Bipolar Transistors (IGBT) Drive VSC Design
- Reverse Voltage to Turn Off Gate
- Independent Dynamically Controllable Vars on Each Side (Two STATCOMs)
- No Minimum Short Circuit, Has Black Start Capability, Can Serve Islands, Easier Multi-Terminal HVDC, No Special Converter Transformers



Series Pulse Width Modulation



Multi-Level VSC HVDC



PWM vs. Multi-Level VSC HVDC

- Series Connected PWM
  - Conceptually Simple
  - Creates Harmonics & Inter-harmonics
  - Higher Switching Losses
- Multi-Level
  - More Complex Controls (?)
  - Lower Losses
  - Minimal Distortion (no filters, smaller substation)
  - Easily scalable design
- Concerns with Both: Cost, Maintenance, Weak System Control

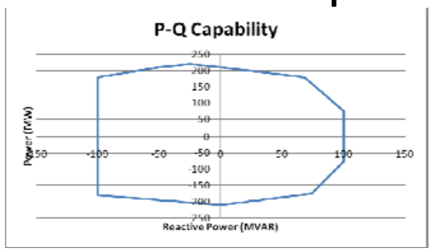
Technology Decision

- All Technologies have Advantages and Disadvantages
- VSC HVDC Chosen
  - Operation with Low Short Circuit Currents
  - Independent Dynamic Var Production
  - Robustness
- Concerns to Be Addressed By Studies
  - Maintenance, Control Complexity, Sub-Synchronous Resonance, Interaction with other Control Systems
  - Control Under Very Weak System (Outage) Conditions

Very Weak System Conditions

- Eastern UP Connected by HVDC, Two 138 kV lines and One 69 kV Line. What if only HVDC (Island) or HVDC and One 69 kV (Quasi-Island)
- Existing Option: Multiple Breaker Status and MW sensors with Communication to HVDC
- Innovation (Currently Being Finalized): AC Line Emulation Under Very Weak System Conditions (Stay Tuned)

Converter Station Specification



- +/-200 MW, +/- 100 Mvars
- Operate as STATCOMS w/o Power Transfer
- Islanding Operation Available
- Black Start Capability
- “Unstaffed” (No Bathroom in HVDC Building)

Design and Construction Progress

- Symmetrical Monopole (PWM)
- Awarded Early 2013 In Service 3Q 2014
- -50 to +102 Degrees, 200” Annual Snow Fall
- 300’ x 100’ Two Stories
- Foundations In, Steel Going Up

Questions?

Is Mackinac the Only HVDC Project Built Exclusively for Flow Control?