Great Northern Transmission Line: Behind the (Electrical) Design

November 8, 2017

Christian Winter, P.E. – Minnesota Power
Sivasis Panigrahi, P.E. – POWER Engineers, Inc.
What is the Great Northern Transmission Line?

The Great Northern Transmission Line Is...

- A 225-mile 500 kV line
- Starting at the Manitoba/Minnesota Border Crossing near Roseau, MN
- Ending at the existing Blackberry Substation site near Grand Rapids, MN
- Including a 500 kV Series Compensation Station near Warroad, MN
- Including a new 500/230 kV substation at the Blackberry Substation site
- Originating near Winnipeg, MB, Canada
- Needed to be in-service June 1, 2020
- Needed to enable up to 883 MW of additional Manitoba – United States transfers
GNTL Project Timeline

- **6/1/2011**: Execute PPA Agreements
- **10/21/2013**: Certificate of Need Application Submitted
- **4/15/2014**: Route Permit & Presidential Permit Applications Submitted
- **6/30/2015**: Certificate of Need Approved by MPUC
- **2/26/2016**: Route Permit Decision by MPUC
- **11/16/2016**: Presidential Permit Issued by DOE
- **6/1/2020**: Contractual In-Service Date (250 MW Purchase Begins)
Electrical Design Studies

Transmission Line Electrical Studies
- Insulation Coordination
- Energization
- Fault Clearing
- Lightning
- Hardware Corona
- Steady State Imbalance
- Parallel Resonance
- Induced Voltage
- Communications Interference
- Pipeline AC Interference

OPGW & Shield Wire
- Live Line Working Clearances
- Tower Clearances
- Ground Clearances
- Conductor Sizing
- Transpositions
- Surge Arresters
- EMF & Audible Noise
- Signal Strength

Substation Electrical Studies
- Neutral Reactor Sizing
- Transient Recovery Voltage
- Insulation Coordination
- Substation Clearances
- Short Circuit Capability
- Transformer Inrush
- Ferroresonance

Series Capacitor Studies
- Size (Percent Compensation)
- Preliminary MOV Rating
- Protection System Operation
- Sub-Synchronous Resonance

Typical 200 foot ROW
Today's Presentation

Transmission Line Electrical Studies
- OPGW & Shield Wire
- Insulation Coordination
- Energization
- Fault Clearing
- Lightning
- Hardware Corona
- Steady State Imbalance
- Parallel Resonance
- Induced Voltage
- Communications Interference
- Pipeline AC Interference

Substation Electrical Studies
- Neutral Reactor Sizing
- Transient Recovery Voltage
- Insulation Coordination
- Substation Clearances
- Short Circuit Capability
- Transformer Inrush
- Ferroresonance
- Series Capacitor Studies
  - Size (Percent Compensation)
  - Preliminary MOV Rating
  - Protection System Operation
  - Sub-Synchronous Resonance

Issues Involved in Today's Presentation
- Live Line Working Clearances
- Tower Clearances
- Ground Clearances
- Conductor Sizing
- Transpositions
- Surge Arresters
- EMF & Audible Noise
- Signal Strength

Typical 200 foot ROW
Minimum Approach Distances

• Live line working clearances characterized as Minimum Approach Distances (MADs)

• Based on:
  • Maximum system operating voltage
  • “Maximum anticipated per-unit transient overvoltage, phase-to-ground” (Maximum TOV)

• OSHA provides default values but permits reduced MAD levels based on engineering analysis (29 CFR 1910.269)
OSHA Default MAD Values

- OSHA Default MAD Values
  - Shown in Red →
  - Phase-to-Ground 16’ 8”
  - Phase-to-Phase 27’ 1”

- Default values preclude live-line maintenance for GNTL tower design

- Studies conducted to identify GNTL design considerations to limit Maximum TOV to facilitate safe live line working clearances
  - Shown in Yellow →
Insulation Coordination - Definition

• Insulation Coordination (IEEE)
  • The selection of insulation strength consistent with expected overvoltages to obtain an acceptable risk of failure
  • The procedure for insulation coordination consists of
    • determination of the voltage stresses
    • selection of the insulation strength to achieve the desired probability of failure
  • The reduction of voltage stresses by application of surge-protective devices
  • Surge arresters are commonly applied and selection is based on MCOV rating (Maximum Continuous Operating Voltage)
Electrical Transients – Illustration

- Origin:
- Waveshape:
  - Temporary
  - Switching
  - Lightning
Different Events – Frequency Range

- 10-20 minutes
- seconds
- milliseonds
- microseconds

Frequency (Hz)

- Electromechanical Phenomena
- Electromagnetic Phenomena

Power System Control & Dynamics

Transients & Surges
Overvoltage - Units

Peak Line-ground voltage

RMS Line-ground voltage = \( \frac{V_{\text{peak}}}{\sqrt{2}} \)

Peak Voltage Line-ground = \( V_{L-L_{\text{rms}}} \times \frac{\sqrt{2}}{\sqrt{3}} \)
500 kV Transmission System

- System Layout

- MMTP
- Canada-US Border, 224 miles from IR
- Transposition Location #2
  - 55.2 miles from IR
  - Series Capacitor Bank, 191.2 miles from IR
  - Transposition Location #1
    - 156.8 miles from IR
  - Transposition Location #2
    - 55.2 miles from IR

- GNTL

- DORSEY
  - 357 miles from IR
  - Transposition Location
    - 299.4 miles from IR
  - Transposition Location
    - 229 miles from IR

- IRON RANGE (IR)
GNTL Project Design

• Line Design:
  • Guyed Delta for the structure design with 1192.5 ACSR “Bunting”
  • Three subconductor bundle for the entire line length

• Two transpositions on GNTL and two transpositions on MMTP (Manitoba side of 500 kV Line)

• 60% - Series compensated (Located at Warroad River Station, approximately 191 miles from Iron Range Substation)
GNTL Structure Geometry

- Guyed Delta Structure Geometry

33 feet

26.25 feet

33 feet
Series Capacitors – Benefits

- FSC (Fixed Series Capacitors) or TCSC (Thyristor Controlled Series Capacitors) are available
- FSCs are more commonly used
- Improve voltage profile on a long transmission line
- Improve reactive power balance
- Power balancing on GNTL to facilitate transfer due to the existing parallel line (M602F)
Fixed Series Capacitor (FSC) Design

(1). Capacitor Bank

(2). Discharge Current Limiting & Damping Equipment – Reactor limits and damps the capacitor discharge current during a bypass operation

(3). Bypass Breaker - Bypass of capacitor and MOV

(4). MOV (Metal Oxide Varistor) - Limits the voltage stress across the capacitor immediately during a fault or excessive line current

(5). OCT (Optical Current Transducer) – Measures current. Can detect faults at low line currents
Series Capacitor Platform Layout
FSC Design with a Triggered Gap

1. Capacitor Bank

2. Discharge Current Limiting & Damping Equipment – Reactor limits and damps the capacitor discharge current during a bypass operation

3. Bypass Breaker - Bypass of capacitor and MOV

4. MOV (Metal Oxide Varistor) - Limits the voltage stress across the capacitor immediately during a fault or excessive line current

5. OCT (Optical Current Transducer) – Measures current. Can detect faults at low line currents

6. Fast Protective Device – Triggered Air Gap or CapThor ABB
Electrical Transients – Substation

- System events that can generate electrical transients and affect equipment selection
  - Energizing or de-energizing shunt capacitor Banks and shunt reactor banks
  - Inrush transients, outrush transients and transient recovery voltages are of concern
- Transient Recovery Voltage (TRV) is important
- The voltage appears across breaker terminals after current interruption. This is called recovery voltage
- Breaker capability must exceed the recovery voltage for a successful breaking operation
- A common approach is to apply a higher voltage class breaker to meet TRV requirement
Electrical Transients – TRV

- System TRV and Breaker Capability Plot
  - Fault interruption is successful only when the system recovery voltage is under the breaker TRV capability envelope

![Graph showing System Recovery Voltage and Fault current interrupted by the circuit breaker.](image-url)
Electrical Transients – Line

- Variety of system events can generate electrical transients on a transmission line
  - Lightning strike
  - Line energization
  - Clearing of faults on adjacent lines (external faults)
  - Internal fault clearing
  - Reclosing operations after fault clearing (internal faults)
- In this instance line circuit breakers operate to clear the fault(s)
- Line Insulation Strength – Meet or exceed the stress
- Insulation coordination study is usually performed on all EHV systems
- Live-Line Maintenance – A major requirement
Transient Studies – Determine TOV

• Identify what event can generate the highest transient overvoltage
• Perform Analysis:
  • Line Energization (No live-line work will be performed during this event)
  • External Faults (Adjacent to Dorsey or Iron Range Stations)
  • Internal Faults (Faults on the line between Dorsey and Iron Range which are cleared by the line breakers)
• All fault types considered
• Simulated fault types along the line and monitored transients along the line
• Results indicated that internal fault clearing resulted in highest transient overvoltages
Transients – Initial Study Setup

• Started by modeling line arresters on or near the transposition structures for a total three locations on GNTL

• All line arresters are rated 353 kV MCOV

• Locations selected in consultation with line design team to ensure all weather accessible location.

• Self-Supporting Structures only for line arrester installations

• Highest transient observed was 2.7 per unit

• GNTL tower design criteria for Live-Line maintenance is 2.5 per unit (2.3 per unit + safety margin of 0.2 per unit)
Transients – Maximum TOV Plot

- Voltage Plot Showing Maximum Overvoltage

Peak Voltage about 2.7 per unit
Transients – Plot

- Voltage Plot Showing FSC discharge circuit without mitigations

FSC Bypass near peak of each phase
Bypass Circuit – Observations

- Switching transients are sensitive to bypass time
- Bypassing near peak voltages (2 out of 3 phases) of the series capacitor results in higher transient overvoltages
- Bypassing near zero voltages (2 out of 3 phases) of the series capacitor results in lower transient overvoltages
Bypass Circuit - Effect of timing

- Plot Showing FSC discharge circuit bypassed near peak on one phase and near zero on the other two phases
Bypass Circuit – Observations

• Line Breaker TRV capability stressed if bypass time and fault clearing time are close

• For example, a 2 cycle breaker clearing a Zone 1 fault interrupts in about 2.5 to 3 cycles while FSC bypass breaker closes in about the same time

• This can be mitigated by either with a triggered gap or by delaying the bypass time (about 75 milliseconds or 4.5 cycles).

• A secondary benefit is that these mitigations also reduce the switching transient levels!
Transient Studies – Mitigation Options

- Redesign GNTL towers to accommodate the higher clearances required *(Not a feasible option!)*
- Bypass the series capacitor bank *(Least preferred option)*
  - Results in reduced power transfer capability
- Primary focus was therefore to:
  - Add more line arresters on GNTL to limit switching transients
  - Allow the FSC vendor to optimally design the series capacitor and meet the system requirements
  - Meet the TRV requirements of the line circuit breakers
- Consulted with the FSC vendors that mitigation options were feasible (and realistic)
- Confirmed that proposed mitigations have been used in many other FSC applications
Transmission Line Surge Arresters

- Transmission Line Arresters
- Five GNTL locations selected in consultation with design team
- Design challenges with implementing arresters on Guyed Delta
- Self Supporting structures for transmission line arresters
Line Surge Arrester Locations
Line Surge Arrester Installation
FSC With Triggered Air Gap – Option 1

- Fixed series capacitor design – with triggered gap and damping resistor

(7). Damping resistor further reduces the time constant and the discharge frequency
  - In parallel with the discharge reactor
  - The spark gap (or an MOV) in series with the resistor avoids a steady state drain
  - This eliminates rating the resistor for steady state conditions

- A range is between 5 ohms and 15 ohms

- Optimized by manufacturers during FSC design
FSC With Gapless Design– Option 2

- Fixed series capacitor design – Gapless and damping resistor
  - Bypass circuit unchanged with a damping resistor
  - Line breakers clear fault in about 33 to 40 milliseconds
  - The bypass time is delayed
  - This will allow the MOV to conduct and absorb the energy from the transients
  - MOV selection optimized by manufacturers during FSC design
FSC Discharge Circuit

- Discharge Circuit with Damping Resistor
Transients – Validation Study Setup

- Selected five line arrester locations along GNTL after consultations with transmission line design
- All line arresters are rated 353 kV MCOV
- Arresters on the MMTP were not included in the model. They do not have noticeable impact on the transients observed
- Included a triggered gap in the FSC bypass time and also a delayed bypass time to simulate a gapless FSC design
- Included damping resistors in the FSC damping circuit
  - Damping resistors reduce (damp out) the oscillations very fast minimizing the effect on the switching transients
- The bypass time used for each fault clearing event was adjusted to bypass at a time when two of the phase voltages were near maximum values to model conditions that result in the highest transients
Transients – Mitigated Values

• During normal system operation, highest transient observed was 2.3 per unit during the most controlling fault case and during a contingency (loss of a line arrester)

• Highest transient observed was 2.45 per unit during the most controlling fault case and during a contingency (loss of a line arrester)

• The mitigations allow Live-Line performance without the need for tower design modifications
Transients – Plot

- Voltage Plot Showing TOV after mitigation
  - Peak Voltage of about 2.2 per unit
Transients – Plot

- Voltage Plot
  Showing FSC discharge circuit with resistor

FSC Bypass near peak of each phase
Transients – Plot

- Voltage Plot Showing FSC bypassed
- All line arresters intact

Peak Voltage about 1.6 per unit
Summary of Design Considerations

- Limit transient overvoltage to 2.5 pu or less for adequate MADs (shown in yellow)

- Include 5 transmission line surge arrester locations on GNTL

- FSC Specification Considerations
500 kV Transmission System

- System Layout (Final Design)
FSC Specification Considerations

- Allow FSC vendor to optimally design based on system requirements
- Minnesota Power to provide:
  - PSCAD Model & Fault Events
  - Performance Criteria (TOV, Breaker TRV)
- FSC Vendor to provide:
  - Alternative proposals for “Gapped” (Triggered Air Gap-based) and “Gapless” FSC design
  - FSC protection system design must not result in violations of Performance Criteria
- Minnesota Power will confirm Vendor design with independent time domain studies
Other MAD Considerations

• No auto reclosing while live line work is being performed

• The TLSAs on either side of the work site (total of two TLSAs) are in service

• TLSA remote condition monitoring equipment
QUESTIONS