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A New 500 kV AC Overhead Transmission Line Delivering Clean Hydroelectric Power from Canada to The State of Minnesota USA Utilizing 500 kV Dry Type EHV Current Transformers

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SUMMARY

In 2020 a new 575 km 500 kV AC transmission line was put into service between the Province of Manitoba in Canada and the State of Minnesota in the United States of America. The transmission line was built under two separate projects. The 215 km northern portion, the Manitoba - Minnesota Transmission Project (MMTP) built by Manitoba Hydro from the City of Winnipeg area to the Canadian – United States of America border. The 360 km southern portion, the Great Northern Transmission Line built by Minnesota Power from the Canadian – United States border to the Iron Range 500 kV AC Blackberry substation near Grand Rapids, Minnesota, USA.

In accordance with Manitoba Hydro's stated commitment of using new technologies that support the environment, and promote safety and reliability, the Canadian portion of the line used a new 600 kV AC dry type EHV current transformer technology for the transmission line's protection and metering requirements. This paper will discuss in some detail the theory and design of the 600 kV AC dry type EHV current transformer technology and the significant benefits compared to traditional SF6 and oil insulated instrument transformer technologies

KEYWORDS

Manitoba – Minnesota Transmission Project (MMTP), EHV dry type current transformer, dry insulation technology

1. INTRODUCTION

In 2011 Manitoba Hydro and Minnesota Power signed a power sale agreement for 250 MW of power each year, over a 15-year period beginning in 2020. This sale required the construction of a new 500 kV AC transmission line from the Winnipeg, Manitoba Canada area to the State of Minnesota's Iron Range area around Lake Superior in the USA and Canada. The new transmission line improves the reliability of the Manitoba Hydro system by bringing electricity to Canada from the United States of America in emergency situations, while providing a clean, reliable source of hydroelectric energy for the increasing load growth in Minnesota's Iron Range region.

2. OVERVIEW OF THE MANITOBA, CANADA TO MINNESOTA, USA TRANSMISSION LINE PROJECT

The Regulatory Process

As with any new high voltage transmission line the Manitoba-Minnesota Transmission Project (MMTP) was subject to a long and very rigorous regulatory approval process. For the Canadian portion of the line both provincial and federal requirements had to be met. The Province of Manitoba requirements included the Public Utilities Board, Manitoba Hydro and Environment Acts. The provincial reviews resulted in a project approval with 64 conditions. The federal requirements included the National Energy Board, Canadian Environmental Assessment (2012), International Boundary Commission and Aeronautics Acts. The federal review process resulted in the National Energy Board approving the project in 2018 with 28 conditions.

Environmental Impact

Manitoba Hydro was required to file an Environmental Impact Statement for the project scope. This included nature of the lands to be crossed or impacted (privately-owned, Crown lands, Aboriginal traditional territories) and impacts on the atmospheric and acoustic environments (air, greenhouse gas, noise emissions, electric and magnetic field and corona, discharges and wastes), water environment (including fisheries and species at risk), land environment (including vegetation, wildlife and species at risk), and socioeconomic environment (including heritage resources, First Nations and Métis).

Stakeholder Participation

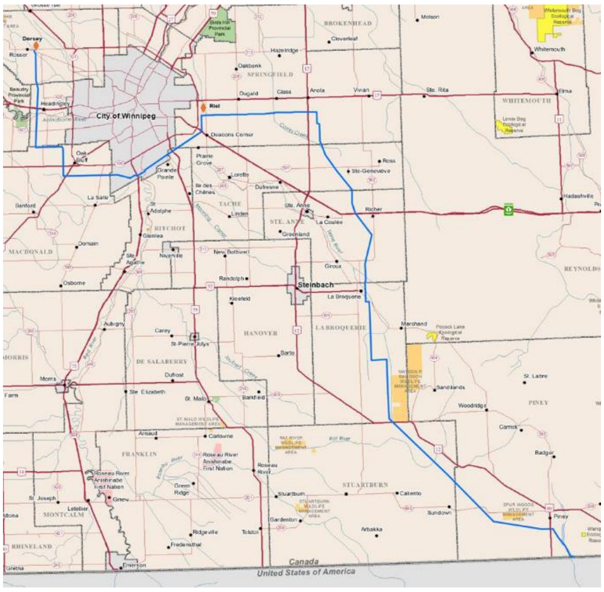
Through the Public Engagement Process inputs from over 150 stakeholder groups (First Nations, Metis, Aboriginal organizations, affected landowners, local municipalities, government departments and the general public) were documented and questions answered.

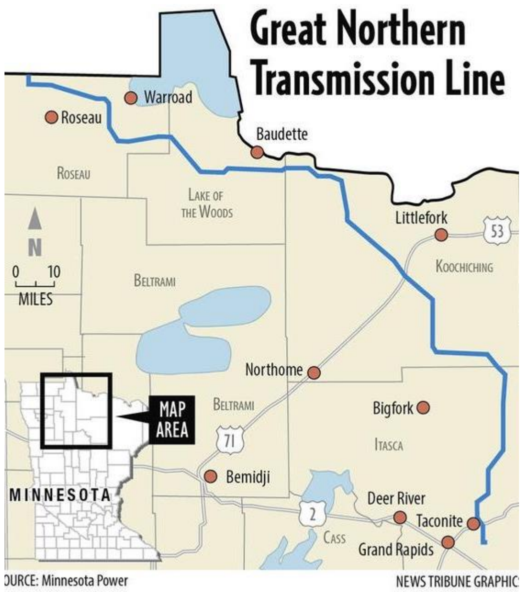
Final Route Selection

The Canadian portion of the Project consisted of the construction of a single circuit 215 km, 750 MW, 500 kV AC transmission line from Manitoba Hydro's Dorsey Converter Station located northwest of Winnipeg, to the Manitoba-Minnesota border just south of Piney, Manitoba, Canada. The route planning used a quantitative, computer-based methodology developed by the Electric Power Research Institute (EPRI) and Georgia Transmission Corporation (GTC) for locating new overhead transmission lines.

Feedback from stakeholders, environmental assessment, and socio-economic considerations were included for routing decisions. Routing criteria included residential density, major developments, conservation lands, resource uses, riparian areas, and existing rights-of-way. Routing also considered sensitive sites - locations, features, areas, activities or facilities identified by discipline specialists, through the First Nations and Métis and Public Engagement Processes to be ecologically, socially, economically or culturally important or sensitive to disturbance in relation to Project infrastructure. Sensitive sites included valued and protected vegetation, wildlife, habitats, cultural sites, unique terrain features, erosion- and compaction-prone soils, and other important locations for route avoidance. The Public Engagement Process was used to present the various routes being considered and gather feedback for a preferred route.

The following maps show the final routes for the Canadian and USA portions of the line.





Engineering Challenges

Existing transmission corridors and right-of-ways (ROW) were used when possible. Close to half of the route used existing transmission line corridors. About 75% of the majority land that would be crossed by the new line is privately owned, with a large 74 km portion consisting of land either already under easement or owned by Manitoba Hydro.

Extensive modifications were required at 3 substations. The Dorsey Converter Station added a 500kV shunt reactor, circuit breakers, switches, disconnects, current transformers, capacitor voltage transformers, surge arresters, air core neutral grounding reactor, towers, and transmission lines. The Riel Converter Station added a new 500 kV bay which included 500/230/46kV autotransformers, circuit breakers, switches, disconnects, current transformers, capacitor voltage transformers, surge arresters, towers, and transmission lines. Additions to the Glenboro South station included 230kV phase shift power transformers, circuit breakers, switches, disconnects, current transformers, towers, and transmission lines.

In accordance with Manitoba Hydro's stated commitment of using new technologies that support the environment, and promote safety and reliability, the Canadian portion of the line used a new 600 kV AC dry type current transformer technology at the Dorsey and Riel Converter Stations for the transmission line's protection and metering requirements installing a set of 3 at each station. The main focus of this paper is to introduce this new EHV dry type current transformer technology and the expected life cycle benefits it will provide.

3. THE EMERGENCE OF A NEW DRY TYPE CURRENT TRANSFORMER TECHNOLOGY FOR EHV APPLICATIONS

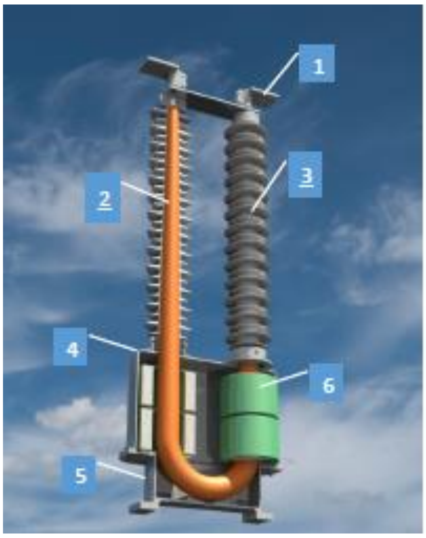
The HV DryShield® Insulation Technology

The HV DryShield® insulation is the primary insulation for a new line of MV, HV and EHV dry type current transformers.

This composite insulation consists of PTFE (PolyTetraFluoroEthylene) film layers with interstitial silicone gel. PTFE is an excellent electrical insulation material with an extremely low dielectric dissipation factor and high physical, thermal and chemical stability. Because of these characteristics, a PTFE tape was developed by the inventors for the production wrapping process for these current transformers. Silicone gel is used along with the PTFE tape as a capillary interface to fill the micro gaps and expel air bubbles in the tape. Using these materials in a finely graded condenser structure, results in a current transformer with residual partial discharge, small tan δ and high withstand voltage.

Using these synthetic materials, the design of the dry current transformer consists of a sealed U-shaped primary winding and sealed secondary windings fitted in a lower air insulated base box. The external insulation housing is built from individual high quality silicone rubber sheds, each formed to exactly fit the profile of the primary conductor that are glued directly to the condenser structure. An insulated board provides mechanical support of the primary winding's two arms. Figure 1 shows the build of the MV and HV dry current transformer.

For EHV applications a cascade style design (see Figure 2) was developed as an economical alternative to the conventional single stage design.

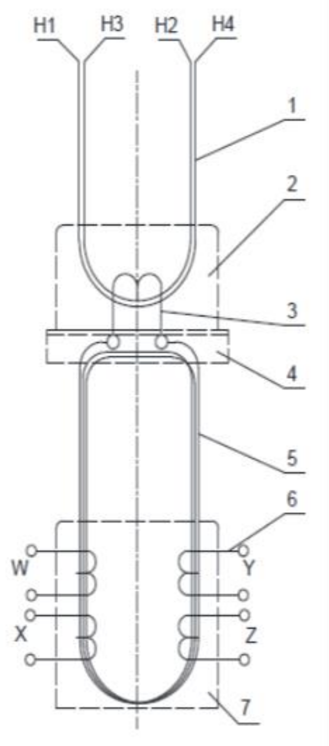


1 – Primary Terminal 2 – Primay Condenser Core 3 – Silicone Rubber Sheds 4- Base Box Upper Casing
5 – Base Box Lower Casing 6 – Secondary Winding

Figure 1 - HV DryShield® 230kV Current Transformer

Cascade Style Design EHV Dry Type Current Transformer

An EHV DryShield® cascade style CT is composed of not less than two CTs, each with lower voltage levels. Figure 2 shown below is the basic construction of a 2-stage cascade style EHV dry current transformer.



1 – Upper CT; 2 – Upper primary winding; 3 – Upper secondary winding; 4 – Duct board; 5 – Lower CT; 6 – Lower primary winding; 7 – Lower secondary winding

Figure 2 - Cascade EHV DryShield® 600kV Current Transformer Construction

In the cascade style configuration, the primary winding of the upper CT is connected to the grid and is at transmission line system voltage. The primary winding of the lower CT and upper casing are at intermediate voltage, and the primary winding is connected in series, with the secondary winding of the upper CT. The secondary windings and casing of the lower CT are at zero voltage and the secondary windings are connected to the external relaying and metering burdens.

The cascade style CT is based on the following principles. If the current ratio of the upper CT is K_1 and the current ratio of the lower CT is K_2 the current ratio K of the entire cascade style CT is $K = K_1 \times K_2$. For example, the current ratio of the upper CT is 2000/20A, and the current ratio of the lower CT is 20/5A, then the current ratio of the entire cascade style CT is 2000/5A.

If the current error of the upper CT is f_1 the phase error is δ_1 the composite error is $\dot{\varepsilon}_1$ and the current error of the lower CT is f_2 the phase error is δ_2 the composite error is $\dot{\varepsilon}_2$ then the current error, phase error and composite error for the entire cascade style CT will be defined by the following equations: $f = f_1 + f_2$ $\delta = \delta_1 + \delta_2$ $\dot{\varepsilon} = \dot{\varepsilon}_1 + \dot{\varepsilon}_2$

The cascade style design can greatly reduce the insulation material costs, thereby providing a more economical EHV current transformer. For example, by building a 500 kV cascade style CT using 245 kV upper and lower CT units, you reduce the amount of insulation material used by 8 times, compared to what would be used in a single stage 500 kV CT design.

The Manitoba Hydro, Dorsey and Riel Converter Stations, EHV Dry Type Cascade Style Current Transformers

Six EHV dry type cascade style current transformers were installed in new circuit breaker positions at Manitoba Hydro's Dorsey and Riel converter stations for the new transmission line's relaying and metering requirements, Figures 3 and 4. The technical parameters specified by Manitoba Hydro for these current transformers were:

Nominal system voltage: 500 kV r.m.s
Maximum continuous operating voltage: 600 kV r.m.s
Rated primary current of top C.T. part: up to 2000×4000 Amp
Rated primary current of bottom C.T. part: 16 Amp
Primary current rating factor: 1.0
Rated Secondary current of top C.T. part: 16 Amp
Rated Secondary current of bottom C.T. part: 5-5-5-5 Amp
Secondary current rating factor: 1.0
Current ratio of top C.T. part: up to 2000×4000:16
Current ratio of bottom C.T. part including taps: 16 to 1.6 :5:5:5:5
Accuracy class and burden: 10L800 and 0.3B1.8 at 0.9P.F (on maximum taps)
Number of primary sections: 2
Number of cores: 4

The performance of the current transformer is set according to the requirements of Canadian Standards Association CAN/CSA-C61869-1 & -2:14 instrument transformer standards and Manitoba Hydro RFP 038201 specification.

Manitoba Hydro's standard commissioning procedures were used for these CTs. The commissioning tests performed were:
1) Capacitance Bridge Testing – Upper CT section) C1, C2 parallel C3 & C5. Lower CT section C1. Complete Upper & Lower CT sections together – C1 (top, & measure lower tap), C1, C1 parallel C5, C5 (H), C2 (L), C2 (L) parallel C3 (L), C3 (L), C4 (L).
2) Insulation Winding Resistance Tests – Primary winding and secondary windings W, X, Y, Z
3) Ratio Tests – secondary windings – W, X, Y, Z.
4) Excitation Tests full windings and taps.
5) Megger Tests – all secondaries
6) CT primary injections

Figure 3 – Dorsey Converter Station **Figure 4 – Riel Converter Station**

4. AN INTERNAL ARCING FAULT EVENT

On April 19, 2021 an internal arcing fault occurred in one of the EHV cascade style current transformers at Manitoba Hydro's Riel Converter Station after approximately 1 year in-service, Figure 5.

Figure 5 – Riel Converter Station "B" Phase CT After Internal Arcing Fault

The CT was designed with instrument transformer standards Class II internal arc fault protection which allowed the CT to safely pressure relieve the fault while remaining physically intact. This is particularly noteworthy when considering the dangerous projection of porcelain parts outside the station's perimeter fence that occurred in a previous failure Manitoba Hydro experienced in 2014 of a 500 kV oil-filled CT at its Dorsey Converter Station, see Figure 6.

Figure 6 – Dorsey Converter Station 2014 Failure of a 500 kV Oil-Filled CT

The EHV cascade style CTs were delivered to Manitoba Hydro in 2017 but because of delays in the project's regulatory approval process and construction schedule, and storage and shipping damage, the CTs were not installed until 2020. After their initial acceptance tests at Manitoba Hydro's High Voltage Test Facility the CTs were put into storage. When project final approvals were received in 2018-19, and construction could begin, it was discovered that the CTs had been improperly stored in a horizontal position in their crates outdoors. This exposed the CTs to three seasons of rain ingression and ice build-up in their crates which caused corrosion damage, some deformation to the silicone rubber sheds from the ice build-up in the crates, and moisture ingression into the secondary windings, Figure 7. This was contrary to the manufacturer's recommendation that the CTs be stored vertically for long term storage which would allow any moisture ingression into the base boxes to drain out and not accumulate. The six CTs were therefore returned to the manufacturer's service facility in New Hampshire, USA for repair and remedial work. The CTs were repaired and retested at the manufacturer's service facility.

The CTs were shipped back to Manitoba Hydro in Winnipeg, Canada to the Dorsey and Riel stations. This extra shipping subjected the CTs to additional transportation stresses. As a result, some minor bolt and threaded hole deficiency damage was discovered on some of the CTs secondary and capacitance tap boxes. Also, a few of the CTs capacitance tap boxes showed signs of damage which were repaired by Manitoba Hydro site staff with new parts from the manufacturer. Because of the firm contractual in-service date, the normal Manitoba

Hydro practice of acceptance testing at their High Voltage Test Facility could not be performed before the commissioning testing at the two stations.

Figure 7 – Rubber Shed Deformation and Corrosion Damage of 600kV CT after Several Seasons of Rain and Winter Freezing Exposure.
CT Crates were Stored Incorrectly Outdoors in the Horizontal Position (Manufacturer Designed Crates to be Stored in Vertical Position for Long Term Outdoor Storage) which Caused Ice to Build Up and Rain to Accumulate Inside the Crates

Root Cause and Autopsy Dissection Investigation

To try and determine the root cause of the failure of the Riel station “B” phase CT serial # EU17005, this CT was returned to the manufacturer’s Beijing factory for a forensic investigation. The investigation revealed that the fault started in the upper CT due to its capacitance tap wire (lead wire from the last capacitive screen of the upper CT’s primary core insulation) becoming disconnected from its base box ground connection. This resulted in a high voltage (approximately ⅓ of the operating voltage) and arc discharge occurring between the last screen, the upper base box casing and the secondary windings and the gradual puncturing of the upper CT’s primary core insulation layers from the outside inwardly. After the complete breakdown of the upper CT’s primary core insulation the lower CT was then subjected to the full operating voltage. This in combination with the transient overvoltage from the arc discharge in the upper CT finally led to the breakdown of the lower CT.

A complete dissection of the upper and lower CT’s primary and secondary winding insulation was also performed and a layer by layer examination revealed nothing untoward, confirming the soundness of the insulation design.

It is hard to speculate on why the capacitance tap wire disconnected from its base box ground connection. From the dissection and the analysis completed it seems clear that the capacitance connection of the upper CT's primary was severed, creating a destructive floating voltage. The cause and time of this disconnection cannot be ascertained after it left the plant, where the connection was tested and confirmed fully operational at the manufacturer’s plant and by Manitoba Hydro’s acceptance testing in 2017. However, the damage reported to the capacitance tap box during installation at site indicated that the CT had experienced some rough handling and/or transportation shocks during the trip from the manufacturer’s New Hampshire service facility back to the Manitoba Hydro Riel Station site.

Overall, this unexpected event validated the initial motivation to use dry type technology for its safety and resilience by keeping the unit in one piece. It is also noteworthy to mention here that the manufacturer can provide their dry type CTs with optional built-in smart measuring circuitry that continuously monitors in real time the primary core’s insulation condition. This option monitors any changes in the capacitance and alerts the customer to a possible deteriorating insulation condition. Had this CT been equipped with this option it is highly probable that the pre-alarm indication from this monitoring would have allowed the customer to investigate the situation long before it became a full fault.

5. CONCLUSIONS

As with any new high voltage transmission line project the Manitoba – Minnesota Transmission Project (MMTP) was subject to a very rigorous regulatory approval process taking 9 years from the signing of the initial sales agreement to its final 2020 in-service date. Construction of the new transmission line provided both countries with enormous benefits; a clean reliable source of energy from hydroelectric generation for the development of Minnesota’s mineral rich Iron Range region and economical and reliability benefits for the Province of Manitoba. The Canadian portion of the MMTP line also spotlighted a new dry type insulation technology for EHV current transformers providing a more economical and maintenance-free alternative to the traditional oil and gas insulation technologies.

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