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Permanent Overload Operation of the Hydro-Québec – New England Multiterminal HVDC Interconnection: Simulation Study and Live System Testing

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SUMMARY

This paper discusses the efforts that led to the increase in the permanent overload capacity of the ± 450 kV, 2 000 MW multiterminal bipolar HVDC network that links Hydro-Québec TransÉnergie's (HQT) system to the New England system. The interconnection, commissioned in 1990, stretches over a distance of 1 500 km between the Radisson terminal in the James Bay region in northern Québec all the way to the Sandy Pond terminal in the Greater Boston area, with an intermediary stop at the Nicolet terminal in southern Québec. The newly proposed operating limits, based on the inherent continuous current overload capability at low ambient temperature of the HVDC converters, make it now possible to operate at a DC current of 2 700 A, which can represent up to 2 700 MW at the Radisson terminal in bipolar operation.

The multiterminal HVDC interconnection is of critical importance to HQT and to its New England partners – National Grid and ISO-NE – both from an operational perspective as well as from a market perspective. As such, the authorization of the newly increased operating limits was contingent not only on the successful conclusion of a complete and thorough simulation study, but also on the successful planning and execution of live system tests.

Thus, in order to validate the dynamic stability and the transient behaviour of the multiterminal HVDC interconnection following a series of benchmark disturbances, a real-time Hardware-in-the-Loop (HIL) simulation study was conducted on the HYPERSIM simulator interfaced with complete replicas of the ABB control and protection systems of all three HVDC terminals. The simulation study was performed in collaboration with National Grid at the Power System Laboratory of the Hydro-Québec Research Institute (IREQ), which is well-equipped for such activities. This paper presents a summary of the results of that simulation study as well as the selected methods of their analysis, including the performance criteria that were considered.

Then, in order to validate the adequate behaviour of all real-time operational software systems and procedures at the provincial and regional control rooms, live system tests were successfully organized and executed in coordination with National Grid, ISO-NE and other relevant entities on February 23, 2020. Moreover, various real-time measurements were taken at all three HVDC

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terminals to validate and compare the behaviour of the actual control and protection systems of the interconnection with simulation results obtained at IREQ. Importantly, this paper discusses the various lessons learned during these live system tests and consequent actions, some of which have influenced final operational strategies.

Lastly, this paper also touches on the operational benefits of the multiterminal HVDC interconnection in the context of HQT's unique 735 kV AC system constraints, as well as on the increase in operational flexibility procured by the successful implementation of these new operating limits. Further, practical examples are provided that show the manner in which the interconnection is managed and operated in order to address real-time system situations at the provincial 735 kV system level, notably in the case of stability limit exceedances on main system interfaces.

KEYWORDS

HVDC, Multiterminal, Permanent Overload, Hardware-in-the-Loop, Control and Protection Systems, Live System Testing

1. Hydro-Québec – New England Multiterminal HVDC Interconnection

The ± 450 kV multiterminal bipolar HVDC interconnection that links the HQT system to the New England system, commonly known as *Phase II*, is composed of three terminals and boasts a transmission capacity of 2 000 MW at the international border, making it HQT's most important HVDC interconnection.

The Radisson terminal is located in northwestern Québec within the James Bay hydroelectric complex, whose eleven power stations built along the La Grande river have an installed generating capacity of over 17 400 MW. This abundance of generation, coupled with the relative absence of local load in its proximity, has led to the Radisson terminal being designed to operate in rectifier mode only.

About 1 000 km to the south of the Radisson terminal, the Nicolet terminal is located in southern Québec amidst the significant load centers of the HQT system. Depending on the requirements and on the constraints of the system, the Nicolet terminal can be operated either in rectifier mode or in inverter mode.

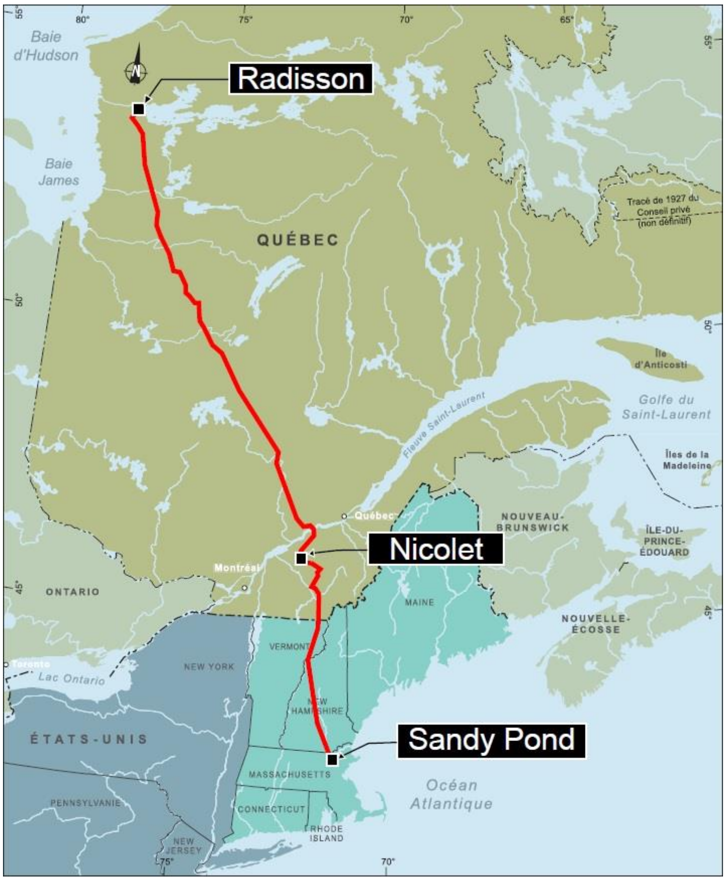

Figure 1: Phase II multiterminal HVDC interconnection

About 500 km further to the south of the Nicolet terminal, the Sandy Pond terminal is located in the Greater Boston area in New England and can also be operated either in rectifier mode or in inverter mode, although the latter is the mode that is most utilized.

An interesting and distinctive feature of Phase II is that the interconnection can be configured in a number of different ways, thus procuring a significant amount of flexibility to operators. Table 1 shows the six distinct configurations that can be applied to either pole of Phase II. In bipolar operation, both poles are online and in the same configuration. In monopolar operation, only one pole is online while the other normally serves as a metallic return (ground return is also possible and exceptionnally permitted). In hybrid operation, both poles are online but each in a different configuration (e.g. network configurations #22-25 or #4-9). All in all, twenty-two different network configurations are currently authorized for normal operation on Phase II.

Configuration Number	Radisson	Nicolet	Sandy Pond
1	Rectifier	–	Inverter
4	–	Rectifier	Inverter
9	Rectifier	Rectifier	Inverter
16	–	Inverter	Rectifier
22	Rectifier	Inverter	–
25	Rectifier	Inverter	Inverter

Table 1: Possible configurations per pole

2. Permanent Overload Capability of the HVDC Converters

The inherent continuous current overload capability at low ambient temperature of the Radisson, Nicolet and Sandy Pond HVDC converters makes it possible to operate at 20% current overload continuously at 0°C and thus allows a substantial increase in the power transmission capability on Phase II. The ambient temperature considered is based on a 24-hour average and is calculated for each converter in real-time by the control and protection systems of the interconnection.

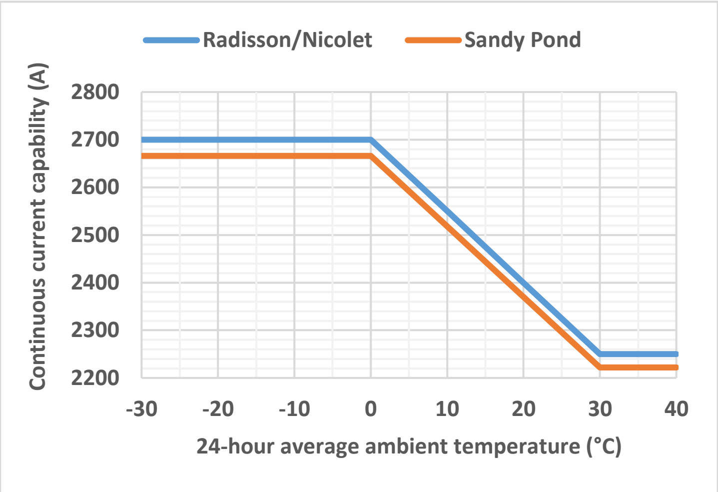

Figure 2: Inherent continuous overload capability of converters

As such, the HVDC converters at the Radisson and Nicolet terminals, which are rated for 2 250 A at 30°C, can be operated at 2 700 A at ambient temperatures of 0°C and below, and overload operation at these two terminals has been authorized since 2011. As for the HVDC converters at the Sandy Pond terminal that are rated for 2 222 A at 30°C, while their continuous current capability can theoretically reach 2 666 A at 0°C, overload operation at this terminal has to this day never been authorized.

Consequently, the only Phase II network configurations that were authorized in 2011 for overload operation were configurations #22 and #25, up to the operating limits shown in Table 2 for the Radisson and Nicolet terminals. In the case of bipolar and hybrid operation, it is immediately apparent that these operating limits were not maximized with respect to the inherent continuous current capability of the converters at the Radisson and Nicolet terminals (i.e. 2 700 A). In the case of bipolar operation, this was essentially due to constraints internal to the Radisson substation that limited the power made available to the converters by the HQT system. As for hybrid operation, the studies and live system tests required to authorize overload operation had yet to be performed.

Phase II Network Configuration	Operating Limit
Bipolar #22-22 – #25-25	2 550 A
Monopolar #22-0 – #0-22 – #25-0 – #0-25	2 700 A
Hybrid #22-25 – #25-22	2 250 A (no overload)

Table 2: Operating limits in overload operation authorized in 2011

3. Revisiting Phase II Overload Operation

Approximately 25 years following the original commissioning of the Phase II interconnection, HQT and the New England Asset Owners mandated ABB to completely upgrade and modernize its control and protection systems [1]. As part of this major project, and as standard HQT practice, the IREQ Power System Laboratory was equipped with complete replicas of the new control and protection systems. Following the successful delivery of the project in 2016, these complete replicas were then made available to HQT and IREQ personnel to conduct various specialized studies pertaining to Phase II.

One of the very first of those studies focused on eliminating the constraints internal to the Radisson terminal that had limited Phase II overload operation in bipolar configuration to 2 550 A. Following the successful completion of that study in 2018, the conditions were met to fully revisit the overload operation of Phase II with the main objective of increasing operating limits up to the converters' maximum continuous current capability of 2 700 A.

4. Scope of the Project and Anticipated Benefits

The objectives of the project were essentially twofold: to increase the existing operating limits in bipolar configurations #22 and #25 and to authorize overload operation in hybrid configurations #22-25 and #25-22. In both cases, the final operating limits would match the converters' maximum continuous current capability of 2 700 A, which up until now was only attained in monopolar operation. Figure 3 shows a summary of the anticipated gains in transmission capability – in units of power – at the Nicolet and Sandy Pond terminals for all relevant configurations. The gains in orange were the ones sought after by the project, while the gains in yellow were already authorized and available through existing overload operation.

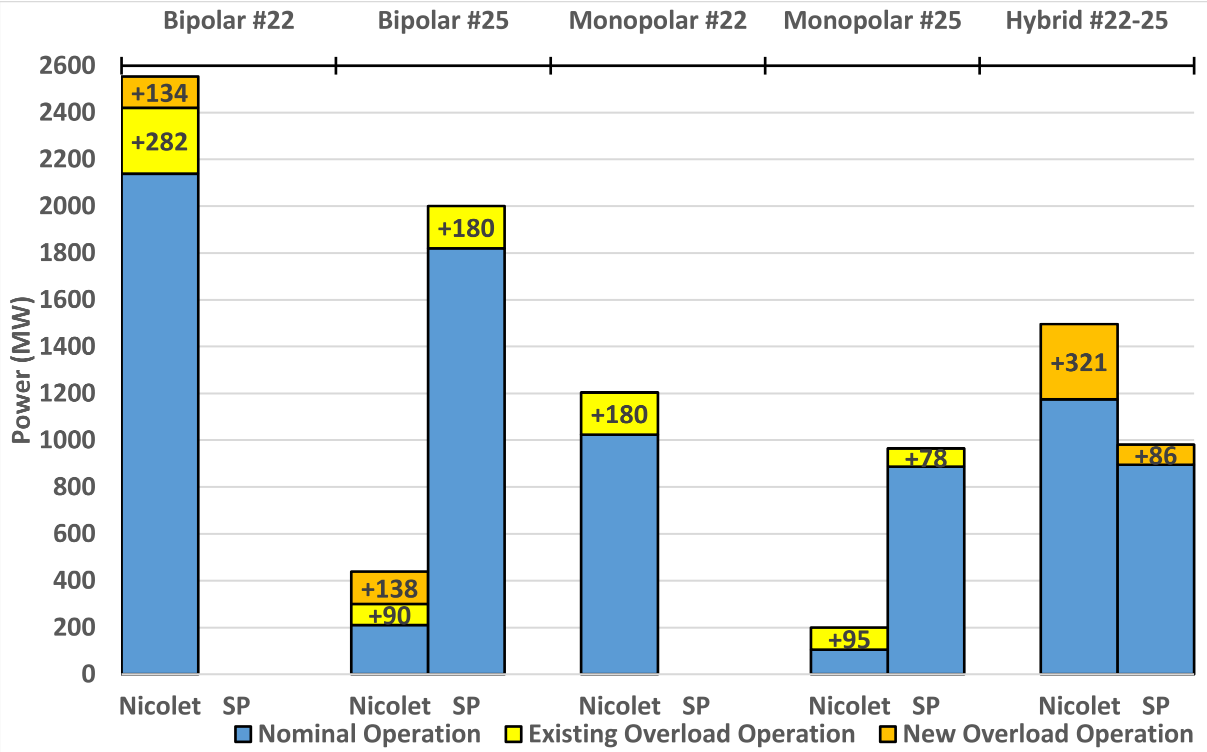

Figure 3: Benefits of Phase II overload operation

It is important to note that the values indicated for configurations bipolar #25, monopolar #25 and hybrid #22-25 presume maximum power transmission to the Sandy Pond terminal before dispatching remaining available power to the Nicolet terminal. This approach underlines the net gains in transmission capacity that are possible at the Nicolet terminal without compromising HQT's export capabilities to New England.

Considering the critical importance of Phase II to HQT as well as to its New England partners, the project was comprised of two phases: a thorough simulation study of the dynamic behaviour of Phase II using the complete replicas of the control and protection systems at the IREQ Power System Laboratory, followed by the successful execution of live system tests.

5. Simulation Study at the IREQ Power System Laboratory

The simulation study at IREQ made use of a Hardware-in-the-Loop (HIL) configuration in which the HYPERSIM real-time digital simulator was interfaced with complete replicas of the ABB control and protection systems of all three HVDC terminals of Phase II. The simulation network model within HYPERSIM included the detailed modelling of the AC and DC yards of each terminal, thus allowing the switching between Phase II network configurations without stopping the simulation. At each terminal, the corresponding AC system was modelled by a Thévenin equivalent characterized by a representative short circuit power. Additionally, the model of the Radisson terminal was further detailed to include a representation of the nearby LG-2-A generating station, along with all of its relevant command systems. This particularity was required in order to enable the simulation of the *islanded* operation of the Radisson terminal, in which the HVDC converters and the LG-2-A generating station form an island that is electrically isolated from the rest of the HQT system.

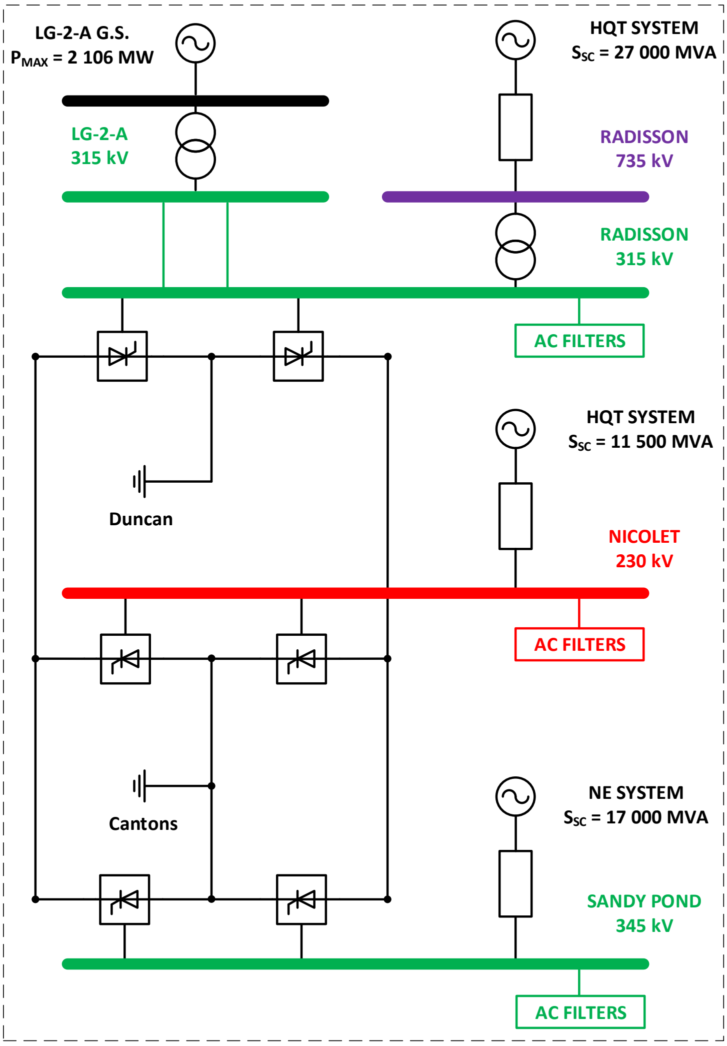

Figure 4: Network model within the HYPERSIM digital simulator

The mandate of the simulation study boiled down to the validation of the dynamic stability and the transient behaviour of Phase II following a series of benchmark disturbances in bipolar configurations #22 and #25, and hybrid configuration #22-25. The operating points that were considered for each of these configurations corresponded to the existing operating limits in nominal and overload operation, as well as to the newly increased operating limits in overload operation (a total of 16 operating points). The advantages of this approach were mainly twofold: to enable comparisons with results from previous studies for validation purposes, and to better characterize the consequences of increasing the existing operating limits. Also, the benchmark disturbances that were applied were varied and included both AC events (three-phased and single-phased; normal and delayed clearing) and DC events (temporary and permanent line faults; converter trips).

Case ID	Radisson	Nicolet	Sandy Pond	Descr.
B25-0	2 250 A	2 025 A	225 A	Reference
B25-1	2 550 A	2 325 A	225 A	Reference
B25-2	2 550 A	300 A	2 250 A	Reference
B25-3	2 700 A	2 475 A	225 A	Projected
B25-4	2 700 A	450 A	2 250 A	Projected
B25-5	2 700 A	225 A	2 475 A	Projected

Table 3: Operating points considered for bipolar configuration #25

Then, the hundreds of obtained simulation results were subjected to the performance criteria shown in Table 4, the respect of which was judged sufficient to attest to the adequate behaviour of the control and protection systems of Phase II. Of these criteria, the settling time of the DC power signal at all three terminals was perhaps the most telling indicator of the general dynamic behaviour of the interconnection. Here, the success of a simulation required that the post-disturbance steady-state DC power signal settled within ± 10 % of the pre-disturbance steady-state value, and that it did so within 200 ms of the fault clearing. The great majority of the simulations did meet this criterion, and those that did not were investigated further and determined to be not problematic. For example, it was observed that the calculated settling time in some cases was significantly and unduly prolonged due to minor oscillations in the unfiltered DC power signal, and that filtering the signal successfully addressed the issue. In another example, post-disturbance commutation failures were observed following certain AC faults at the Radisson terminal, but were determined to be not problematic due to their non-successive nature and to the fact that they occurred even at nominal operating points. Overall, the final acceptance of all simulations was also contingent on a qualitative analysis of the results that confirmed the absence of any concerns regarding the general dynamic stability of the interconnection.

	Performance Criteria
#1	Settling time of DC power signals
#2	Duration of AC overvoltages superior to 1.2 pu
#3	Occurrence of loss of current margin
#4	Steady-state post-islanding frequency at Radisson

Table 4: Performance Criteria

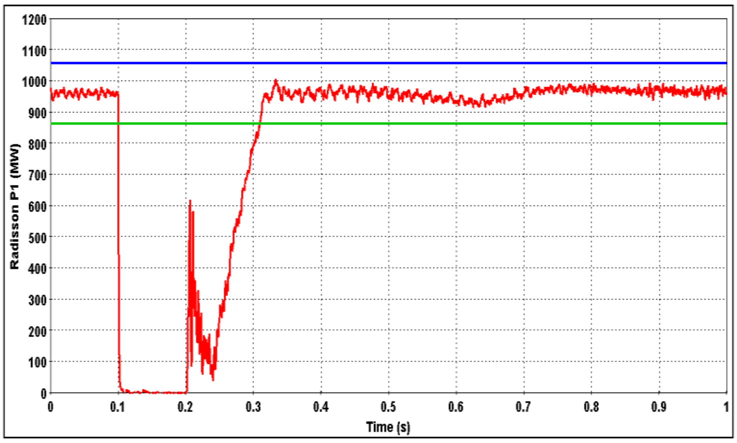

Figure 5: Example of the application of the settling time criterion

6. Live System Testing

The simulation study undertaken at the IREQ Power System Laboratory demonstrated conclusively that the dynamic stability and transient behaviour of the Phase II interconnection was acceptable at the new operating limits. Nonetheless, final authorization of the latter was also contingent on a validation of the adequate behaviour of all real-time operational software systems and procedures at the provincial control room in Montréal, as well as at the regional control room in Rouyn-Noranda. To that end, live system tests were successfully organized and executed in coordination with National Grid, ISO-NE and other relevant entities on Sunday, February 23rd, 2020, between 16h00 and midnight. This particular period of time was purposefully selected so as to minimize the impact of the tests on commercial operations.

The live system tests consisted in the observation of the steady-state operation of Phase II at the new operating limits in the three network configurations that were studied, according to the testing program shown in Table 5. As bipolar configuration #22 implies shutting down the Sandy Pond terminal, its testing was

Hour	Step
16h00 to 17h00	Verification of all preconditions
17h00 to 18h00	Overload in #25-25
18h00 to 19h00	Switching to #22-25
19h00 to 20h00	Overload in #22-25
20h00 to 21h00	Switching to #22-22
21h00 to 22h00	Overload in in #22-22
22h00 to 23h00	End of testing
23h00 to 00h00	Resuming of commercial operations

Table 5: Phase II Overload Operation Testing Program

sequenced last so as to coincide with a reduced forecasted load in the New England system. For all network configurations, the power setpoints of all three terminals were calculated so as to attain a DC current of 2 700 A at the Radisson terminal.

It is worth noting that the tests did not involve any application of a forced disturbance either on the HQT system or on Phase II, the latter's dynamic stability having already been thoroughly validated with a high degree of confidence through simulation. Rather, the tests were essentially an operational dry run intended to identify any potential issue before final authorization. That being said, transient fault recorders (TFRs) were still triggered at all three terminals at the start and at the end of each overload testing period in order to measure steady-state values, notably DC voltage and DC current. Those real-time measurements will mainly serve to validate modelling parameters at the IREQ Power System Laboratory such as DC line impedances.

Overall, although no major difficulties were encountered throughout the tests, a number of lessons were learned and some have influenced final operating strategies. For example:

- While Phase II was operating at maximum power, it was observed that the AC voltage at the Radisson terminal was slightly inferior to acceptable operational thresholds. The issue was solved in real-time by ordering an increase of the voltage setpoint of the generating units at the nearby LG-2-A generating station, and that solution has since been integrated in operating procedures.
- On the day of the tests, the 24-hour average ambient temperature at the Nicolet terminal was slightly superior to 0°C, thus lowering the latter's maximum current capability slightly under 2 700 A. Nonetheless, these conditions made it possible to observe in real-time that the control and protection systems automatically interrupt any power ramp that would cause an exceedance of the calculated maximum current capability.
- While the Nicolet terminal was operating at maximum power, alarms were triggered at the regional control room indicating that the current in the converter transformers exceeded operational thresholds. Upon further investigation, it was determined that these thresholds were in contradiction with specifications and did not allow any overload whatsoever, and so had to be revised. Similarly, alarms were triggered at the provincial control room that were also due to an overlooked programming issue in operational software, which has since been corrected.

Although relatively minor, some of the issues encountered would have had to be managed for the first time in real-time had it not been for the live system tests and, in some cases, could have led to a temporary shutdown of Phase II. Instead, the live system tests allowed HQT and its New England partners to obtain valuable operational experience in a controlled environment before permanently authorizing the new operational limits.

7. Operational Benefits of Phase II Overload Operation to HQT

In a general sense, a peculiarity of the HQT system is undoubtedly the considerable geographical distance – about 1 000 km – separating its generation centers to the north from its load centers to the south. Historically, it is this distinctiveness that has paved the way for Hydro-Québec's development of the world's first 735 kV AC system. The operation of such a longitudinal system presents its own set of challenges, which are then amplified by the fact that the HQT system is also asynchronous to its neighbouring AC systems. Taken together, these two characteristics render the HQT system particularly vulnerable to stability issues, which are typically addressed by the careful application of operational stability limits on the power transferred down HQT's major north-south 735 kV corridors.

In this context, Phase II offers HQT the means to not only export power to its New England partners, but also to relieve some of the burden on its own AC system via the operation of the Nicolet terminal in inverter mode. This latter feature is extremely advantageous as it allows HQT to effectively bypass its major 735 kV power corridors and supply power directly to its important southern load centers. As such, an increase in transmission capacity at the Nicolet terminal is akin to an increase in an operational stability limit on a major 735 kV power corridor.

Particularly, Phase II network configuration #25 typically represents the most flexible option for HQT as it allows simultaneous power delivery to both the Nicolet and Sandy Pond terminals. Moreover, AC system constraints can sometimes effectively obligate HQT to switch to network configuration #25 in order to urgently reduce the strain on its system by delivering power directly to the Nicolet terminal. However, nominal operation of network configuration #25 also reduces HQT's export capacity to the Sandy Pond terminal to about 1 800 MW instead of 2 000 MW, due to Radisson being the only rectifier terminal and limited to its nominal capacity.

And so, Phase II overload operation allows HQT to reap the benefits of network configuration #25 without compromising its full export capacity of 2 000 MW to the Sandy Pond terminal. Furthermore, the newly obtained gains in transmission capacity at the Nicolet terminal further reduce the risks that HQT be obligated to redispatch power from Sandy Pond to Nicolet in order to alleviate hypothetical AC system constraints.

As for the other Phase II network configurations in which overload operation is possible, these are often utilized as a result of a pole outage (i.e. monopolar configurations) or an outage at the Sandy Pond terminal (e.g. network configuration #22). Although the probability of occurrence of such outages is normally minor, it remains that their consequences can be significant for HQT. In such cases, Phase II overload operation helps to attenuate the resulting loss of capacity by significantly increasing the transmission capacity of the remaining equipment on Phase II.

8. Outlook on the Future of Phase II Overload Operation

Following the successful delivery of the present project, HQT and its New England partners can now take advantage of the full permanent overload capability of Phase II's Radisson and Nicolet terminals as early as next winter. It is worth noting that Phase II overload operation is currently authorized only for a period of four consecutive months per winter, typically starting on November 1st of each year. This technical constraint is not due to the HVDC converters, but is rather associated with Phase II's 4 km underwater cable crossing of the Saint Lawrence River. Essentially, the design specifications of the ± 450 kV cables composing the crossing are such that their overload operation is limited to a period of four consecutive months in order to guarantee their specified useful life expectancy. Nevertheless, work is already underway to address and potentially eliminate this constraint through an improved real-time monitoring of the cables' thermal properties. Should this effort succeed, the operational gains obtained via the present project would become available during a majority of the year, considerably amplifying their resulting benefits both to HQT and to its New England partners.

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