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Power flow control of carbon-neutral energy to industrialized urban areas

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SUMMARY
Two independent sets of phase-shifting transformers combined with voltage regulators (PSRTs) will be installed at Hydro One St Lawrence TS to regulate the power flow continuously in either direction through the system interconnection between the Ontario Hydro and Power Authority of the State of New York. The phase-shifters will be used for the control of MVAr and MW interchange in either direction regulating the renewable energy sources between Canada and USA.
A “like for like” replacement of the old PSTs and voltage regulator was not considered by Hydro One and NYPA, as power transfer requirements have changed over the decades. Therefore, all bidders were invited for a site visit and were requested to prepare various options in order to initiate request for quotation. Hydro One prepared a draft requirement, at that time, and showed site constrains.

PSRTs are a special type of power transformers with regard to concept and design (competence), manufacturing (accuracy), factory acceptance test (two large units to be placed at same time in the high voltage laboratory), installation, on-site testing, commissioning, and maintenance. Hydro One also specified capabilities of high phase angle, overload, and operation at very low ambient temperature to account for better flow regulation, system contingencies, and final physical location of the PSRTs.

The selection and development of the on-load tap-changer (OLTC), which is the most critical and limiting component of a PSRT, and meets all the requirements above, will be explained in detail. To foster an efficient selection and development process of the OLTC, a detailed design of the PSRT is necessary in the bid phase of such a project. That means winding arrangements including all details resulting in an induction matrix, as base for the OLTC dimensioning, has to be worked out. Amongst the necessary design competence and development of in-house tools all the bid efforts are a remarkable upfront investment for all players.

The latest generation of VACUTAP® allows the realization of phase shifting transformers with significantly increased phase angle and rating. The reason is that the step capacity has been almost doubled compared to the standard oil tap changer with highest step capacity of 6000kVA with single phase OILTAP®R or the older VACUTAP® generation respectively. However, the previous generation of VACUTAP® requires a design with enforced current splitting for step capacities higher than 6000kVA, which isn’t feasible all the time. The latest developed on- load tap-changer – the VACUTAP®VRL3001 with a step capacity of 10,000kVA overcomes this problem.

For this special application of a PSRT, with the very high phase angle of +/-60° and additional in-line voltage regulation, it was determined that the best arrangement would be to have all tap changers at the neutral end. This arrangement is technically challenging but preferred by electric utilities. Combining phase shifting transformer and voltage regulator

saves utility additional transformer and associated no load and load losses. In addition, there are savings related to the maintenance of the additional unit and its components.
Necessary calculations for proper selection of phase shifter on-load tap changer, interaction between parties and final solution for overall concept are presented in this paper. The paper will demonstrate that only with detailed studies and a close collaboration between utility, supplier, and sub-supplier during bid phase an overall optimized solution can be reached for the grid power flow control by means of phase shifters.

KEYWORDS
Load flow regulation and control, system interconnection, Phase Shifting Transformer, On-load tap changer (OLTC), carbon neutral energy, urban areas.

Paper Cont'd

Background on the Ontario New York Phase Shifters at St. Lawrence TS

The Phase shifters PS33 and PS34 are part of the Ontario-New York 230kV interconnection circuits L33P/L34P at St. Lawrence TS near Cornwall Ontario. The L33P tie with phase shifter PS33 (Nom. Rating 300MVA) and regulator R33 was installed in 1962. The L34P tie with the combined phase shifter and voltage regulator PSR34 (Nom. Rating 300MVA) was installed in 1978. The phase shifters are owned jointly by Hydro One and NYPA and are planned to be replaced under a joint Hydro One – NYPA project with an in-service date of summer 2023.

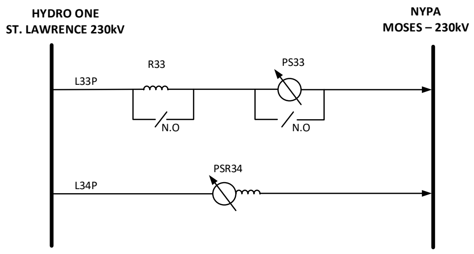

Figure 1: 230 kV interconnection circuit between Hydro One and NYPA

In the 1960s and 70s there were significant power purchases by Ontario from Quebec. Without the phase shifters a large part of the Saunders GS generation (connecting to St Lawrence switchyard) and the Quebec purchases would tend to flow out at St. Lawrence over into New York and then back through Niagara interconnection. The phase shifters reduce flow on the interconnections, maximize east-west transfers in Ontario and helped reduce overall transmission losses. The phase shifters also reduce loading on northern New York circuits, out of the Moses switchyard

St. Lawrence TS – Phase Shifters Operation Explained

Figure 2: Flow without Phase Shifters

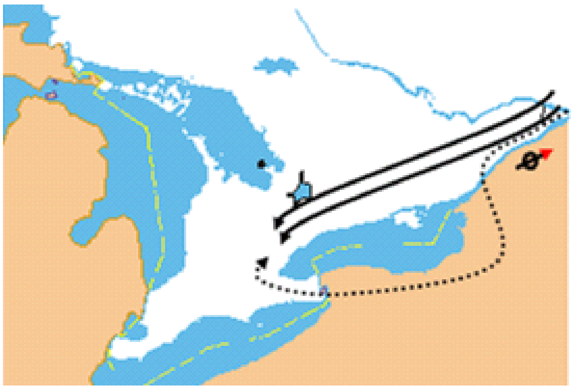

Figure 3: Flow with Phase Shifters

Today the St. Lawrence phase shifters are regularly used for both economic transfers and congestion management.

The phase shifters are used to:

- Manage loop flows following schedule changes on the Ontario - Quebec and Ontario – New York interfaces.
- Alleviate post-contingency loadings on the Ontario – New York and the Ontario – Michigan interfaces.

Phase shifter flows over a two year period are shown in Figure 4.

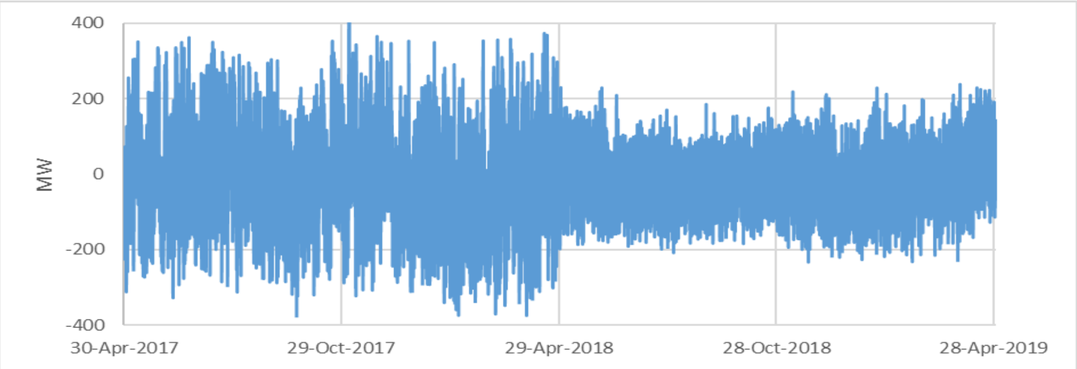

Figure 4: Power flow across the St Lawrence – Moses Interconnection.

Importance to power flow CAN – US (carbon neutral energy)

The New York State Climate Leadership and Community Protection Act (CLCPA) establishes targets for the reduction of greenhouse gas emissions; most notably, requiring 70% of electricity to come from renewable resources by 2030. Consequently, there is a move to develop wind and solar production statewide. The Phase-Shifter controlled lines will provide the operational flexibility needed to optimize the renewable resources in Northern NY and Ontario.

Different solutions in the concept phase

The role of Equipment Engineering Group (EEG) in Hydro One is to provide the most reliable, and the most economical technical solution for requirements outlined by Asset Management Group (AMG). There is a formal and well-established process in place, which leads to creation of a technical specification further used for public tender.

In this particular case, EEG invited several potential suppliers in order to review existing technologies and industry practices with respect to Phase Sifting Transformers (PST). Based on the review Hydro One started to consider two the most “popular” designs: extended delta concept and quadrature booster concept.

Extended delta concept has one big advantage. This construction is a single core design, which means single core loss with lower cost for the Utility, and single transformer to maintain over the lifetime of the unit. However, there are also several disadvantages: a) expensive HV tap changers, usually 2 per phase, to manage high voltage at the line end location, b) all tap changer leads needs to be insulated for full BIL level Ph-Ph and Ph-Grd, which is 900 kV in this case c) transformer impedance is close to zero at zero degree phase shift and Current Limiting Rectors (CLR) needs to be installed in series with PST, which adds additional components and lower overall reliability.

The main advantage of quadrature booster concept is the location of the tap changer in the neutral end of the Exciter unit, where required BIL withstand levels are reduced. This translates itself to more reliable and better dielectrically controlled solution. Main disadvantage is a fact that quadrature booster is a dual core design, and as such, generates significant core loss. In addition, the Utility need to maintain two large, interconnected power transformers with two separate cooling systems.

For St. Lawrence project, AMG requested also in phase voltage regulation. This requirement drastically changed the selection criteria, as extended delta type phase shifter required additional regulating transformer or autotransformer. In this case the main advantage of this solution, single core design (single unit), cannot be utilized. Unlike extended delta PST, quadrature booster PST required only additional tap changer, which again could be installed in the neutral end. After detailed technical considerations EEG has decided to proceed with quadrature booster PST with in phase regulation, which was considered as more relatable solution for this particular project.

Design solutions with the available OLTCs

Single core PST with separate autotransformer for voltage regulation:

Phase angle regulation: 3xVRLII 1302-300

In phase regulation: 3xVRMI 1301-300

Two core two tank PST with additional regulating winding for in phase regulation connected to the line terminals:
phase angle regulation: 3xVRLI2602-123 or 3xVRLI3000-123. The VRLI2602 requires forced current splitting. However, as we have experience with this solution and this tap changer we would have used the VRLI2602 and not the new development VRLI3000.
In phase regulation: 3xVRMI130I-300

Two core two tank PST with separate autotransformer for in phase regulation:
The same tap changers as above would have been used.

Final developed solution with all regulation possibilities

In order to provide a solution with highest reliability, Siemens Energy goal was to develop a design with all tap-changers in the neutral end. This led to the standard two core and two tank solution, well known for phase shifters, with high rated power in combination with high phase angle and voltage classes up to 550kV. The main challenge was the in-phase regulation (LR) under load of +/-10% in combination with the high phase angle regulation (PAR) of 60°. The simple solution would have been the phase shifter with separate autotransformer for the in-phase regulation. Even this ‘simple solution’ would not have been so simple because of the high phase angle. This requires forced current splitting for the tap-changer, which already results in a sophisticated design. With additional tap-changers inside the delta of the exciter transformer, the concept of forced current splitting via the winding arrangement in the series unit was not possible anymore.

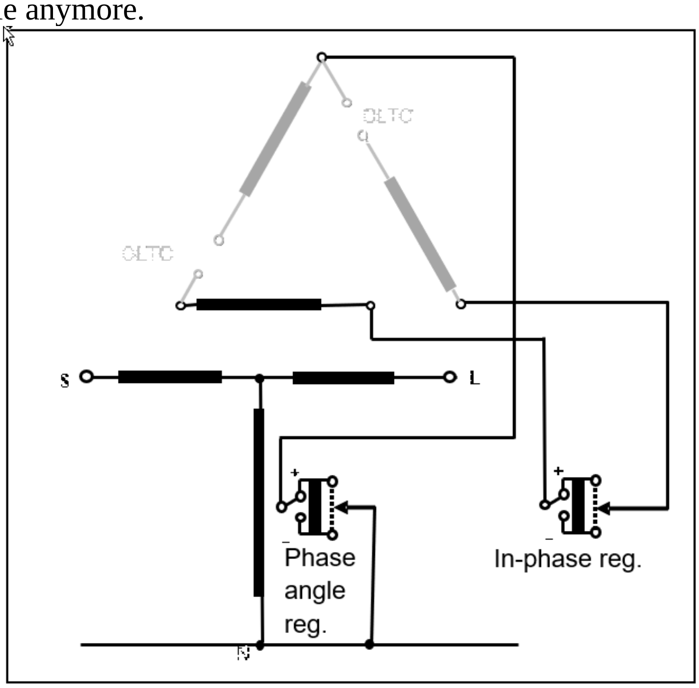

Figure 5: Two core phase shifter with additional in-phase regulation (LR)

Fortunately MR had a new tap-changer with significantly increased step capacity under development, which does not require forced current splitting - VACUTAP®VRL I 3000. Very detailed discussions with MR were required, in offer stage, especially because not all the limits of this new tap changer were known. In order to avoid problems at the order stage, beside the load phase angles and voltages under load, Siemens Energy submitted an inductance matrix of the active parts to MR for additional calculations. In addition, the magnetic stray field nearby the tap-changers was calculated and provided to MR, in order to check possible influence on the tap changer operation.

The benefits of this solution can be summarized as follows:

- None of the tap-changer is located at the line end - high voltage
- Only Vacutaps are used to lower maintenance cost
- Small footprint. An additional autotransformer would have had a footprint of approx. 9 x 4 m
- Low losses in comparison with the alternative solution with autotransformer appr. -35%
- The no load phase angle does not change with the in-phase regulation (LR).
- The newest OLTC needs no forced current splitting

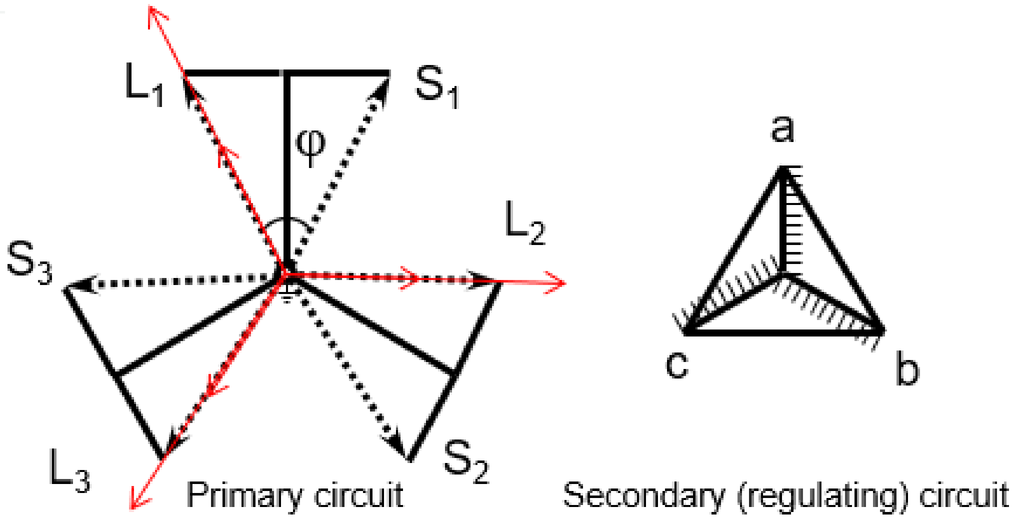

Figure 6: Phasor diagram. The phase angle is independent of the in phase regulation (LR)

Selection of OLTC

The selection of on-load tap-changers (OLTC) is of great importance when designing phase-shifting transformers (PST). There are some special topics, which should be considered very early in the design stage, because they may have an impact on the OLTC selection as well as on the design of the PST itself [1], [2]. Some guidance is given in IEC60214-2:2014 [3] and IEEE C57.135 [4].
The dual core design with an additional in-phase regulation (LR) in the delta winding of the booster transformer, which is realized in this application, consists of a series and an exciting unit. When using this design, the step voltage and the through-current of the regulating winding can be varied and optimized with respect to the rated step voltage and rated through-current of the available OLTCs. The high rating of this project demands a solution with three single-pole OLTCs of type VACUTAP®VRL I 3000. The insulation level, the highest voltage for equipment of the OLTC is independent of the PST's system voltage and can be kept low (U_m = 123kV).

The basic selection of the OLTC is carried out with the maximum through-current and the maximum step voltage [5]. The determination of these values has to be considered well. The maximum phase shift is defined under no load conditions and is symmetrical (+/-60°). However, the phase shift varies under load due to load losses and leakage impedances, resulting in increase of the phase shift in the retard position, but a decrease in the advanced position of the PST (see Figure 10). Additionally, the overloading of a PST amplifies the above mentioned effects and influences the rated values of the transformer and the OLTC.

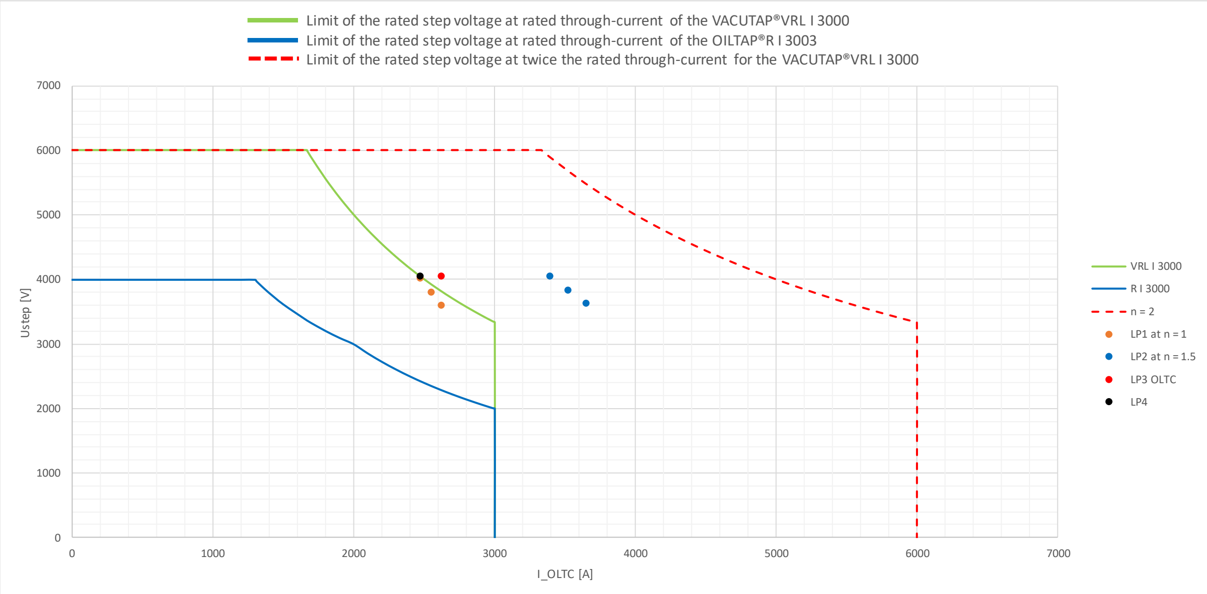

Figure 7: Step voltage limits at rated and twice the rated through-current of VACUTAP®VRL I 3000

Figure 7 shows the step voltage limits (switching diagram) as function of the rated through-current as well as of twice the rated through-current of VACUTAP®VRL I 3000. With the brand new VACUTAP® VRL I 3000 a step capacity P_{StN} of 10MVA has been achieved. In comparison with the old OILTAP® R I 3000 (blue curve in Figure 7) the maximum rated step voltage U_{Im} is increased by 50% and step capacity P_{StN} is increased by 66%. The three load points LP1 represent operating points in three different positions of the in-phase regulator LR (mid-position and both end positions) at 1 p.u. Load points LP2 represents these operating points under overload condition at 1.5 p.u. As mentioned above, LP3 represents that pair of variants, for which the OLTC's transition resistors have to be dimensioned. It is obvious that this point is beyond the limits. Forgoing switching capability of twice the rated load current and with the knowledge that the dimensioning of the transition resistors is carried out considering mainly the overload, it now becomes possible to adjust the transition resistors to the operating point LP4.

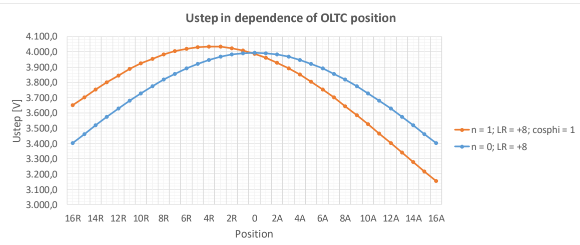

Figure 8: Step voltage PAR in dependence of the OLTC position

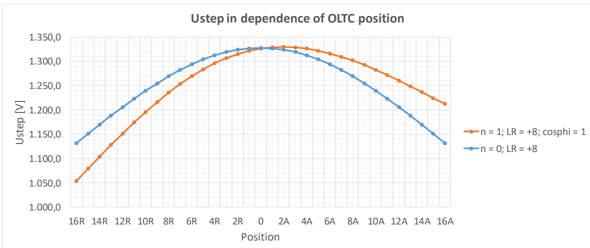

Figure 9: Step voltage LR in dependence of the OLTC position

For both OLTC's (phase angle regulator PAR and in-phase regulator LR) the step voltage is almost independent from the load factor (see Figure 8 and Figure 9). Voltage increase for phase angle regulator (PAR) is only 1.5% and for in-phase regulator (LR) is 0.5%. A reason for this small increase is the high number of taps and the high regulation range of 60°. The higher the regulation range, the smaller excitation of the exciting winding and consequently the step voltage. Voltage increase under load through leakage impedance is compensated with smaller excitation at high regulation range.

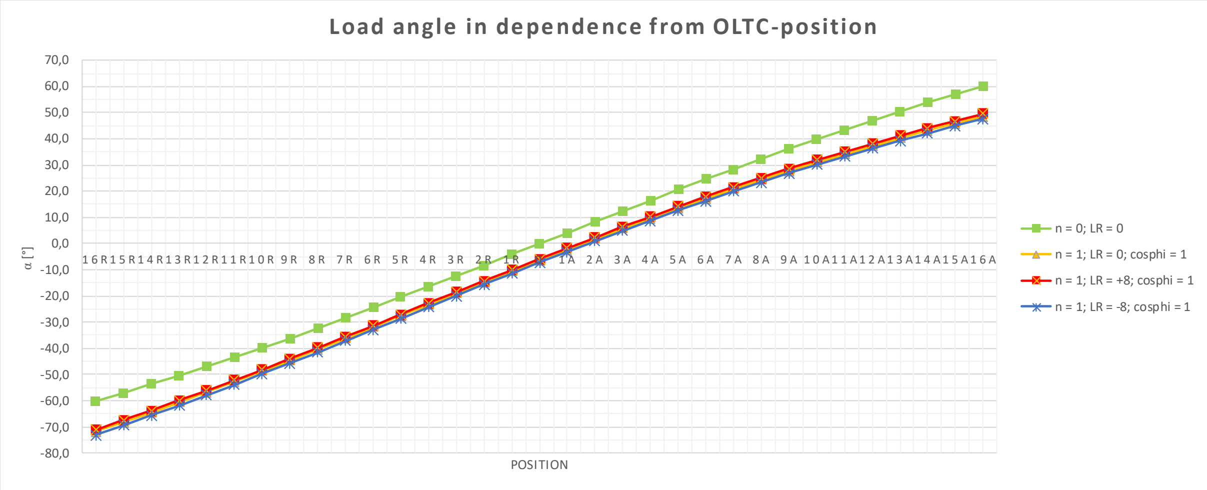

Figure 10: Load phase angle in dependence from OLTC position of the PAR

Figure 10 shows the load phase angle in dependency on the OLTC-position of the phase-angle regulator (PAR) at mid-position and both end positions of the in-phase regulator LR. It can be seen that the load phase angle is independent from the position of the in-phase regulator (LR). Maximum deviation of load phase angle amounts only 2°. That means position of the in-phase regulator LR has nearly no influence on the load angle.
The phase angle α will only be increased (retard) or decreased (advanced) by the load. The difference in α depends on the values of the load and the leakage impedances (booster impedance Z_B + exciter impedance Z_{Ex}). Based on a leakage impedance of $Z_B + Z_{Ex} = 25\%$, the deviation of phase angle α will differ about 14° at rated load and at a power factor of cos phi = 1.

Parallel operation of PSTs

When paralleling two or more transformers, an out-of-step-condition, for a short time, can't be prevented due to the non-synchronous operation of the different OLTCs. In this condition a circulating current between the transformers will flow, which is driven by the voltage difference between tap positions and is limited only by the impedances within the circuit. PST impedance in position "0" is only the impedance of the booster unit because the exciter unit is not loaded in this position. Circulating current Ic has, in this position, its maximum value. In that application, a circulating current of approximately 630A is flowing (depends on the position of in-phase regulator LR), which has to be added to the load current. The out-of-step-condition of the in-phase regulator LR can be neglected. The circulating current in this case is less than 20A which is considered insignificant. The reason for the low circulating current at an out-of-step-condition of the in-phase regulator is the phase shift between load current and circulating current (approx. 90°).

Challenges during transport, installation & commissioning

Transport of the heavy parts of such two tank PSRTs with about 170.000 kg from manufacturer SIEMENS Energy Austria GmbH, Weiz/Austria to Hydro One Networks Inc, Cornwall/Canada needs special attention. The transport sections are: from the manufacturer's factory to river port by train; from river port to North European Sea port by river barge; from North European Sea port to Canada Sea port by ocean vessel, from Canada Sea port to Cornwall site entrance by train. Every loading/unloading must be managed in a safe way and therefore the whole trip is documented with shock recorders.

Planned application (control & protection)
Each phase shifter is provided with duplicate A and B protections. Both A and B are similar but will use relays from different manufacturers
The A and B protections consists of two differential zones using different relays. The first zone covers the series winding and the exciter unit primary windings with second harmonic blocking and the second zone covers the bus and line side of the phase shifter together with the series winding and the exciter unit primary winding. Separate relays are included to cover transformer overload protections and for gas protections covering the series and exciter transformers, and the load tap changer.

Conclusion
This example demonstrates how early involvement and close collaboration of all parties (TSOs – OEM – sub-supplier) results in an optimized solution. The most compact and economical solution for such high MVAr and MVA power flow control of carbon-neutral energy to industrialized urban areas is a phase-shifting transformer with combined in phase regulation.

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BIBLIOGRAPHY

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