Control of Inrush Transients During the Restoration of an Islanded 735 kV System

M. Alawie *, Q. Bui-Van, A. Dumas

***Abstract*—In this paper we will describe a real case study involving high inrush transients during the restoration of an islanded 735kV series compensated system. For the prediction of overvoltages stressing EHV equipment, exhaustive transient simulation study was performed using EMTP-RV (restructured version of EMTP). Finally, the effectiveness of remedy measures for controlling temporary overvoltages and/or inrush currents during transformer energization has also been investigated.**

***Keywords*: Inrush Transients, Inrush Currents, Temporary Overvoltages (TOV), Transformer Energization, System Resonances, System Restoration**

I. Introduction

On November 4th, 2007 an ice storm struck the North-East part of the province of Quebec causing outages of several 735kV lines and creating a dismantled Churchill-Montagnais-Arnaud series-compensated system, as illustrated in Fig. 1. in order to restore this islanded system for supplying the Alouette 910-MVA aluminum smelters from the Arnaud 735/161kV substation, the following operations have to be performed in accordance with the existing system restoration procedure:

- Start up of 4 generators at Churchill Falls and maintain their terminal voltage at 14.4kV.
- Restoration of the local 300-MW load at Churchill Falls.
- Energization of two 735kV series-compensated line sections, Churchill-Montagnais and Montagnais-Arnaud, with two shunt reactors on each line section (165-Mvar and 330-Mvar units).
- Pick up of 40-MW load at Montagnais.
- Energization of the unloaded 700/161kV, 700MVA (T3) and 735/161kV, 700MVA (T5) autotransformers from Arnaud 735kV with circuit breakers equipped with pre-insertion resistor.
- Restoration of the Alouette 910-MVA aluminum smelters and other parts of the power system from Arnaud 161kV.

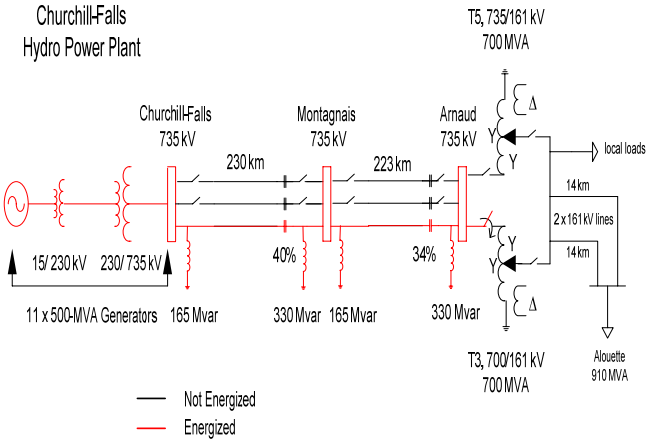

Fig. 1 Churchill-Montagnais-Arnaud islanded 735kV system

II. Inrush Transients During the System Restoration According to the Existing Procedure

For the restoration of the above mentioned islanded system in accordance with the existing procedure, high inrush transients can be predicted during the energization of the unloaded 700/161kV, 700MVA (T3) or 735/161kV, 700MVA (T5) autotransformer from Arnaud 735kV. The two 735kV series-compensated line sections Churchill-Montagnais and Montagnais-Arnaud with two shunt reactors on each line section were previously energized from 4 generator units at Churchill and under steady state condition (see Fig. 1). To obtain the maximum asymmetric condition, the autotransformer T3 (or T5) was energized at zero voltage crossing on one of the three phases and the maximum residual fluxes of +85%, -85% and 0% of the rated flux were set on the three phases of T3 (or T5) prior to the energization, as per [1]. Simulation results shown severe temporary overvoltages (TOV) reaching 1.85p.u. (1p.u. = 600kVpeak) at Arnaud 735kV and high inrush currents (≈ 2000Apeak for first few cycles) during the energization of T3 from Arnaud 735kV, as illustrated in Fig. 2a and 2b.

Similar inrush transients were also observed during the energization of T5 (735/161kV, 700MVA). These TOV and inrush currents can put in danger the existing equipment at the Arnaud substation. Therefore, the analysis of the causes of these inrush transients becomes necessary in order to find remedy measures for controlling TOV and/or inrush currents during transformer energization from Arnaud 735kV.

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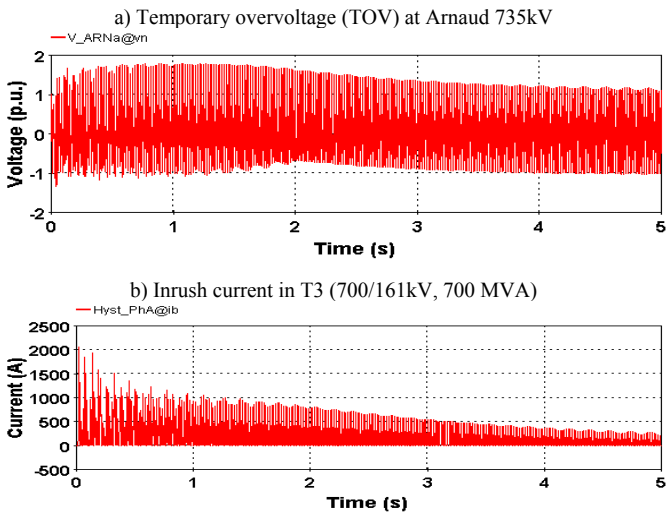


Fig. 2 TOV (a) and inrush current (b) during the energization of T3 from Arnaud 735kV – Residual fluxes of ±85% and 0% on three phases

III. Causes of Inrush Transients at Arnaud 735kV

To understand the causes of inrush transients at Arnaud 735kV, the frequency scan of islanded system impedances in positive sequence seen at Arnaud 735kV with 4 generator units at Churchill and two 735kV series/shunt compensated line sections was performed. Simulation results, as illustrated in Fig. 3, shown clearly two sub-synchronous resonances below 20Hz due to the presence of series/shunt compensation on each line section and a resonance tuned at 120 Hz caused by two unloaded series/shunt compensated line sections and equivalent impedance of Churchill Falls hydro power plant with 4 generator units.

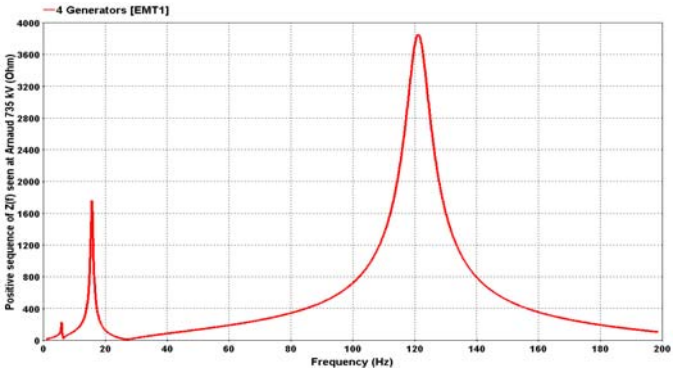


Fig. 3 Frequency scan of positive sequence impedances Z(f) seen at Arnaud 735kV with 4 generators units at Churchill

These resonance conditions are predisposed to high TOV when energizing the unloaded 700/161kV, 700MVA autotransformer (T3) from Arnaud 735kV because of high contents of second harmonic (120 Hz) and dc currents in autotransformer inrush currents. Furthermore, low frequency oscillations due to sub-synchronous resonances, excited by dc current component, were also superimposed to TOV and inrush current waveforms. These resonance overvoltages can be simply expressed using the following Ohm's law:

$$V(f) = Z(f) \times I(f) \qquad (1)$$

Where Z(f) represents the system frequency dependent impedances seen at Arnaud 735kV and I(f) is the harmonic or dc components of autotransformer inrush current. It is also clear that V(f) is superimposed to the 1 p.u. fundamental frequency voltage at Arnaud 735kV in steady state prior to the autotransformer energization.

IV. Contributing Factors to TOV at Arnaud 735kV

In order to control inrush transients during the energization of T3 or T5, several simulations were performed to analyze the contributing factors on the TOV observed at Arnaud 735kV.

A. *Effect of residual fluxes*

The residual fluxes increase the total fluxes in the transformer during the energization. Consequently, the transformer inrush currents as well as their harmonic/dc components will also increase. In comparison to the previous case with maximum residual fluxes, simulation results without residual flux in T3 have shown a decrease of TOV from 1.85p.u. to 1.79p.u. and the inrush current from 2000Apeak to almost 1200Apeak (Fig. 4a and 4b vs. Fig. 2a and 2b).

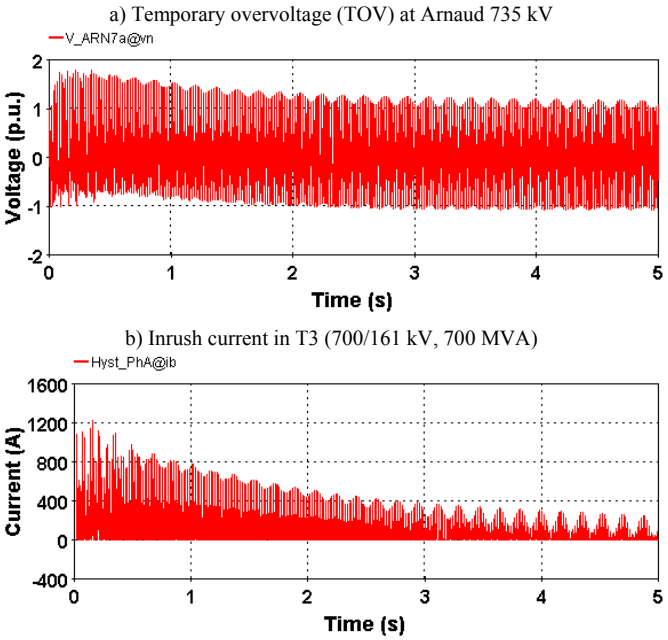


Fig. 4 TOV (a) and inrush current (b) during the energization of T3 at Arnaud 735kV - Without residual flux on three phases

B. *Effect of the system strength*

The system strength at Arnaud 735kV is represented by the short-circuit level at this bus bar. In the Churchill-Montagnais-Arnaud islanded 735kV system, the increase of the system strength at Arnaud 735kV implies the increase of the number of generator units at Churchill. This will have a detuning effect on the system impedances Z(f) far away from 120Hz, as illustrated in Fig. 5. As a result, the 120Hz resonance overvoltages during the energization of T3 or T5 from Arnaud 735kV will be reduced.

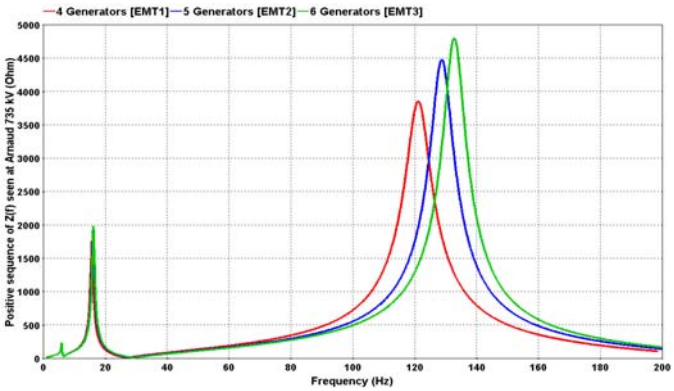
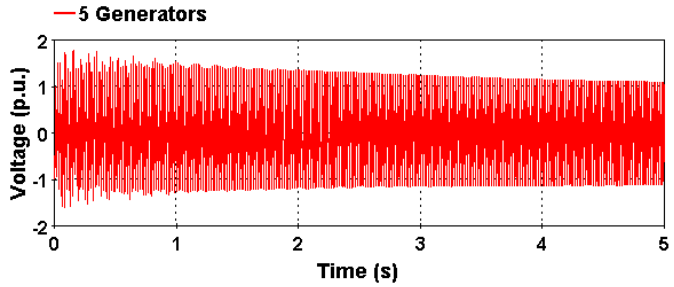


Fig. 5 Frequency scans of positive sequence impedances Z(f) seen at Arnaud 735 kV with 4, 5 and 6 generator units at Churchill.

Indeed, simulation results with 5 and 6 generator units at Churchill shown the TOV of 1.78 p.u. in both cases compared to the TOV of 1.85 p.u. observed in the case with 4 generators units at Churchill. These TOV remain high since in this case, the 120Hz resonance overvoltages were reduced by the detuning effect, whereas low frequency oscillating overvoltages due to sub-synchronous resonances reappear.

a) TOV at Arnaud 735kV with 5 generator units at Churchill



b) TOV at Arnaud 735kV with 6 generator units at Churchill

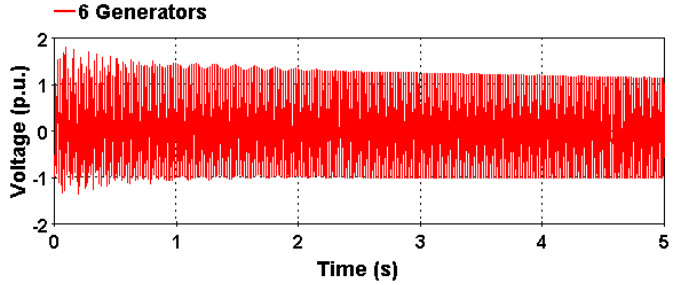


Fig. 6 TOV at Arnaud 735kV during the energization of T3 with (a) 5 generator units at Churchill; (b) 6 generator units at Churchill – Residual fluxes of ±85% and 0% on three phases

C. Effect of series capacitor banks (SCB)

The SCB in conjunction with the shunt reactors (SR) on the two 735kV line sections have the effect of adding two sub synchronous resonances, which can produce low frequency oscillating overvoltages (below 20Hz), when excited with the dc component of inrush currents. Bypassing the SCB in the two 735kV line sections results in eliminating the effect of these sub-synchronous resonances, as illustrated in Fig. 7.

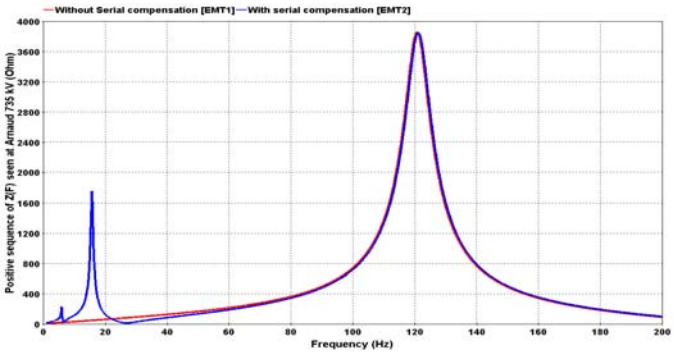


Fig. 7 Frequency scans of positive sequence impedances Z(f) seen at Arnaud 735 kV with and without the SCB on the two 735kV line sections – 4 generator units at Churchill

It should be mentioned that in the case of 4 generator units at Churchill the bypassing of SCB didn't have a significant effect on TOV since the system impedances Z(f) remain tuned at 120Hz (see Fig. 7 and 8).

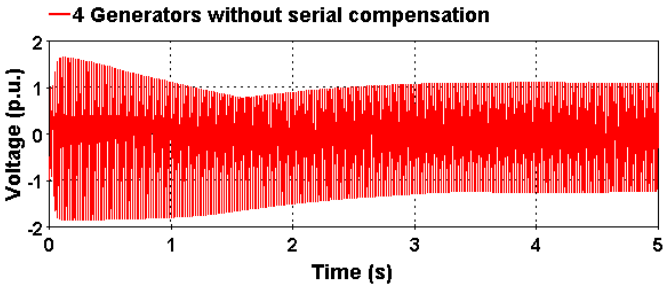
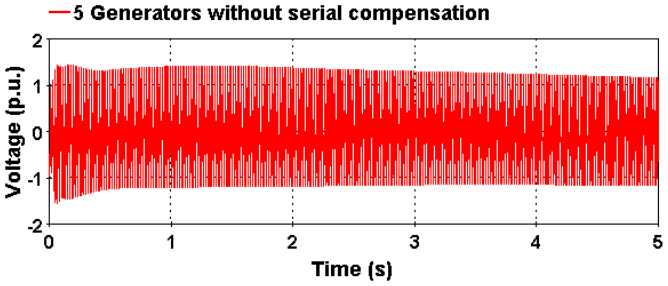


Fig. 8 TOV at Arnaud 735kV during the energization of T3 with 4 generator units at Churchill and all SCB bypassed - Residual fluxes of ±85% and 0% on three phases

However, significant reduction of TOV were observed for the cases with 5 or 6 generator units at Churchill and all SCB bypassed, as shown in Fig. 9a and 9b.

a) TOV at Arnaud 735 kV with 5 generator units at Churchill



b) TOV at Arnaud 735 kV with 6 generator unit at Churchill

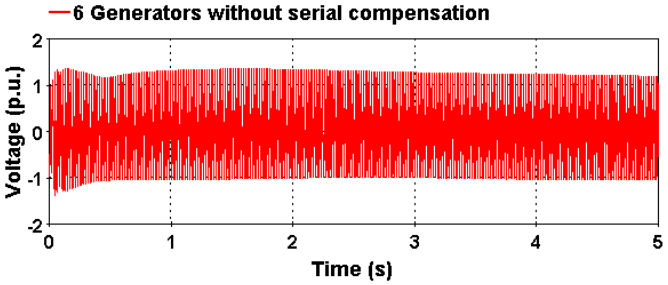


Fig. 9 TOV at Arnaud 735 kV during the energization of T3 without series compensation and with: (a) 5 generator units at Churchill; (b) 6 generator units at Churchill – Residual fluxes of ±85% and 0% on three phases

D. *Effect of an additional shunt reactor at Arnaud*

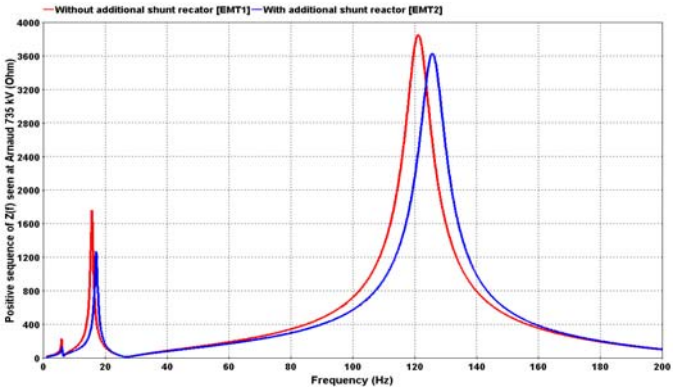


Fig. 10 Frequency scans of positive sequence impedances Z(f) seen at Arnaud 735 kV with and without an additional 330 Mvar shunt reactor - 4 generator units at Churchill

The additional 735kV shunt reactor at Arnaud will shift the actual system resonance frequency to a higher frequency. Indeed, the natural frequency of an LC circuit is given by:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad (2)$$

By adding a 330Mvar shunt reactor at Arnaud 735kV in parallel with the network, the value of L decreases and hence it increases the system natural frequency. Furthermore, the system impedances Z(f) are also slightly reduced with the presence of additional shunt reactor at Arnaud 735kV. These effects are illustrated in Fig. 10. As illustrated in Fig. 11, an additional 330Mvar shunt reactor at Arnaud is not sufficient to reduce TOV to a safe level during the energization of T3 according to the existing procedure. However, by using an additional shunt reactor at Arnaud in combination with other remedy measures it would increase the overall efficiency for the reduction of TOV.

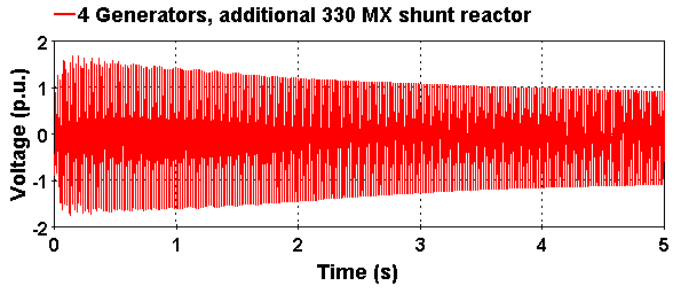


Fig. 11 TOV at Arnaud 735 kV during the energization of T3 with 4 generator units at Churchill and an additional 330Mvar shunt reactor at Arnaud – Residual fluxes of ±85% and 0% on three phases

E. *Effect of pre-insertion resistors*

The use of pre-insertion resistor is one of classical methods to eliminate inrush transients during the energization of a power transformer. By using the existing 735kV circuit breakers (CB) equipped with pre-insertion resistor of 4000Ω - 12ms insertion time for the energization of T3 from Arnaud 735kV according to the existing restoration procedure, the inrush currents as well as TOV at Arnaud 735kV are completely eliminated, as illustrated in Fig. 12a and 12b.

V. Remedy Solutions for the Control of Inrush Transients at Arnaud 735kV

As seen in the previous sections, several factors have a considerable effect on TOV at Arnaud 735kV during the energization of T3 or T5 in accordance with the existing system restoration procedure.

A. *Circuit breaker equipped with pre-insertion resistor*

The use of existing CB equipped with pre-insertion resistor of 4000Ω - 12ms insertion time allows eliminating inrush currents as well as TOV at Arnaud 735kV during the energization of T3 or T5 in accordance with the existing system restoration procedure (See Fig. 12a and 12b). Since the transformer inrush currents are completely eliminated by pre-insertion resistor, it offers a very flexible remedy solution for the restoration of the Churchill Falls-Montagnais-Arnaud islanded system i.e.: with or without SCB, no need of additional shunt reactor at Arnaud 735kV, with fewer generator units (2 or 3) in service at Churchill Falls, etc. Therefore, this solution is recommended for a safe restoration of the Churchill-Montagnais-Arnaud islanded 735kV system.

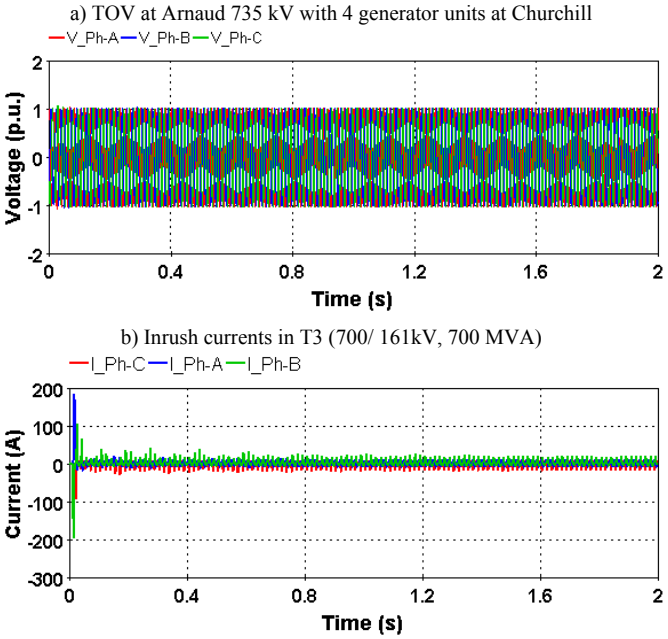


Fig. 12 (a) TOV at Arnaud 735kV and (b) Inrush currents during the energization of T3 according the existing restoration procedure with pre-insertion resistor of 4000Ω – 12ms insertion time – Residual fluxes of ±85% and 0% on three phases

However, the existing 735kV CB equipped with pre-insertion resistor have 17 years old and might require extensive maintenance in order to preserve an acceptable reliability level. Therefore, in the eventuality that the 735kV CB equipped with pre-insertion resistor is not available, alternative solutions have to be implemented for a safe energization of T3 or T5 from Arnaud 735kV.

B. *Modification of the restoration procedure*

The effects of increasing the system strength (or number of generator units at Churchill), an additional 735kV shunt

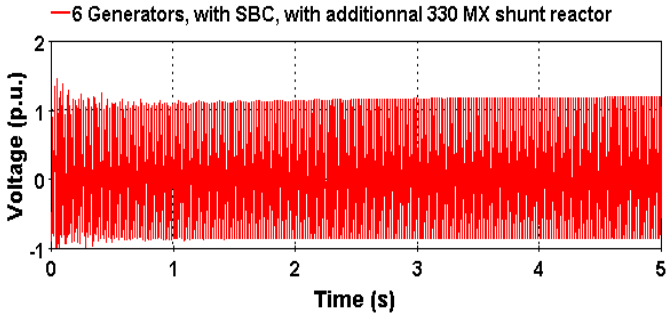
reactor at Arnaud as well as bypassing all the SCB on the two 735kV line sections were thoroughly investigated in the previous sections. None of these measures stand-alone has allowed safely restoring the Churchill-Montagnais-Arnaud 735kV islanded system.

TABLE I
COMBINED EFFECTS OF INCREASING THE SYSTEM STRENGTH, ADDITIONAL SHUNT REACTOR AND/OR SCB BYPASSED ON TOV AT ARNAUD 735kV

Number of generator units at Churchill	TOV at Arnaud 735kV during the energization of T3 or T5			
	With series compensation		SCB bypassed	
	Without additional shunt reactor	With additional shunt reactor	Without additional shunt reactor	With additional shunt reactor
4	1.85 p.u. (0-1 sec)	1.76 p.u. (0-1 second)	1.85 p.u. (0-1 second)	1.65 p.u. (0-1 second)
5	1.78 p.u. (0-1 second)	1.49 p.u. (0-1 second)	1.57 p.u. (0-1 second)	1.16 p.u. (0-1 second)
6	1.78 p.u. (0-1 second)	**1.20 p.u. (0-1 second)**	1.39 p.u. (0-1 second)	**1.12 p.u. (0-1 second)**

Several other simulations without pre-insertion resistor were also performed to analyze the combined effects of two or more of these measures. As indicated by the results with red characters in TABLE I, increasing to 6 generator units at Churchill in combination with an additional 735kV shunt reactor at Arnaud and/or SCB bypassed will reduce TOV during the energization of T3 or T5 to an acceptable level for restoring the Churchill-Montagnais-Arnaud 735kV islanded system although the inrush currents remain higher than the case with pre-insertion resistor, as illustrated in Fig. 13a, 13b, 14a and 14b.

a) TOV at Arnaud 735 kV with 6 generator units at Churchill



b) Inrush currents in T3 (700/ 161kV, 700 MVA)

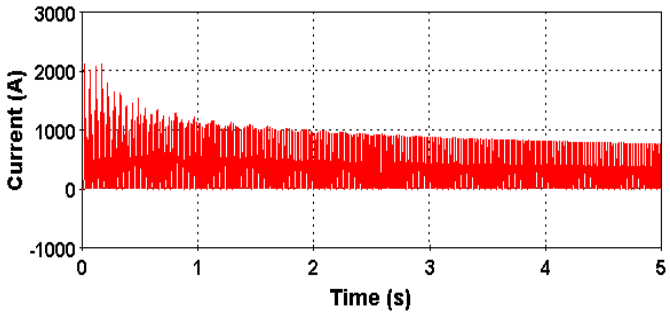
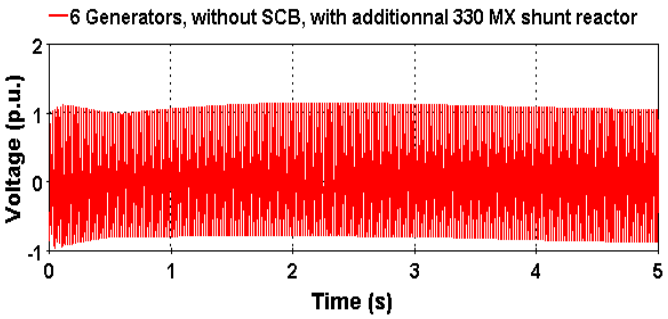


Fig. 13 TOV at Arnaud 735 kV during the energization of T3 with 6 generator units at Churchill, with series compensation and an additional 330Mvar shunt reactor at Arnaud – Residual fluxes of ±85% and 0% on three phases

a) TOV at Arnaud 735 kV with 6 generator units at Churchill



b) Inrush currents in T3 (700/ 161kV, 700 MVA)

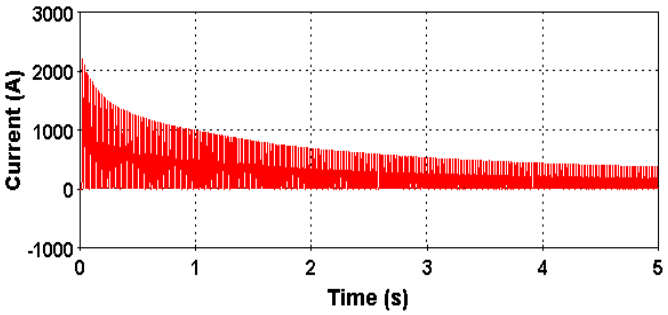


Fig. 14 TOV at Arnaud 735 kV during the energization of T3 with 6 generator units at Churchill, without series compensation and an additional 330Mvar shunt reactor at Arnaud – Residual fluxes of ±85% and 0% on three phases

C. Transformer controlled switching

Transformer controlled switching is considered as an economic and reliable alternative for pre-insertion resistors to control inrush transients during transformer energization. The controlled switching device called SMCT, which was developed at Hydro-Québec TransEnergie for the single or double-break 330kV circuit breakers [2], [3], is based on the measure of transformer residual fluxes to control the optimum closing instants for the three phases of circuit breaker. Unfortunately, this technology is not yet developed, tested and approved for 735kV multi-break circuit breakers. Therefore, the development of this technology for 735kV multi-break circuit breakers would be an interesting avenue for the replacement of 735kV circuit breakers equipped with pre-insertion resistor.

VI. CONCLUSIONS AND RECOMMENDATIONS

Exhaustive transient simulation study was conducted for the evaluation of existing procedure to restore the Churchill-Montagnais-Arnaud islanded 735kV system. In light of the study results, the following conclusions and recommendations could be drawn:

- For a safe restoration of the Churchill-Montagnais-Arnaud islanded 735kV system in accordance with the existing procedure, it is recommended to energize the autotransformer T3 (or T5) with the 735kV circuit breakers equipped with pre-insertion resistor of 4000 Ω - 12ms. TOV and inrush current are both completely eliminated and no supplementary switching operation is required.

- In case of unavailability of circuit breaker equipped with pre-insertion resistor the following modifications, by the order of preference (for the minimization of TOV), should be made to the existing procedure for the safe restoration of the Churchill-Montagnais-Arnaud islanded 735kV system:

  - Scenario A: 2 additional generator units at Churchill Falls (for a total of 6 units), all SCB bypassed and an additional 735kV shunt reactor at Arnaud.

  - Scenario B: 2 additional generator units at Churchill Falls (for a total of 6 units) and an additional 735kV shunt reactor at Arnaud.

  Although the TOV during the energization of T3 (or T5) were reduced to lower than 1.20p.u. with the modifications described in the scenarios A and B, the inrush currents remain much higher than those observed with pre-insertion resistor. Supplementary switching operations, comparing to original procedure, are also required in the case of scenarios A and B.

- The development of a transformer controlled switching device for 735kV multi-break circuit breakers would be an interesting technological avenue for the replacement of existing 735kV circuit breakers equipped with pre-insertion resistor.

VII. REFERENCES

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