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Transformer Limited Fault TRV's field measurements used to validate EMTP transformer models and comparison with TRV calculations based on existing standards (IEEE Std C37.06.1™- 2017 and IEC 62271-100)

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SUMMARY

Interruption of fault currents involving transformers may result in severe TRVs which are mainly determined by the transformer dominant natural oscillating frequencies. IEEE Std C37.06.1™-2017 defines some standard TRV values for TLF conditions for system voltages ranging from 4.76 kV to 800 kV. The TRV values specified in this standard are based on the natural oscillating frequencies of the transformers given by IEEE Std C37.011™-2019 – Annex B. In many cases, the Rate of Rise of Recovery Voltage (RRRV) values specified in this standard exceed by far the standard values defined by applicable Circuit Breaker standards (IEC 62271-100 and IEEE C37.04) for terminal faults T30 and T10 duties.

Annex M of IEC 62271-100 also gives some detailed explanations about TRVs for TLF conditions and provides some standardized values for TRVs for system voltages higher than 1 kV and less than 100 kV & system voltages above 800 kV. Values for voltages classes between 100 kV and 800 kV are still under study.

Transformer manufacturers can also provide on request some EMT models which usually give good accuracy for the frequency range involved in the Transformer Limited Fault studies. Although these models may provide some worthy indications on the frequencies involved, they often give less reliable information on the amplitude and damping factor which determines the TRV peak values.

Recent TRV on-site measurements were performed on two transformers 315-25 kV 100 MVA and 315-25 kV 140 MVA using the so-called power frequency current injection method described in annex F of IEC 62271-100. From these measurements, amplitude factor and rate of rise of recovery voltage were extracted. Measurements were performed on primary and secondary side of the transformers to determine the TRV stresses of the circuit breakers on both sides of the transformers (315 kV and 25 kV). As described in Annex M of IEC 62271-100, measurements were done for two types of TLF: 1- Transformer Fed Fault (TFF) and Transformer Secondary Fault (TSF).

In addition to the TRV field measurements, Sweep Frequency Response Analysis (SFRA) was also achieved from the primary and secondary windings of both transformers. From the SFRA results, simplified RLC transformer models have been be extracted for primary side only due to inadequate measurement set-up on the secondary side. TRV stresses with these simplified models are further compared to the on-site measurement values and also the ones given by IEEE Std C37.011™-2019.

Main objective of this paper was to determine by on-site measurements the TRV stresses for TLF fault conditions for two 315-25 kV power transformers and to compare the results obtained from measurements with the values recommended by IEEE Std C37.011™-2019. In addition, on-site measurements are used to build, validate and adopt simplified EMTP transformer models for TRV

stresses assessment for Transformer Limited Fault conditions for other types of transformer used by Hydro-Quebec.

KEYWORDS

Transient Recovery Voltage (TRV), Transformer Limited Fault (TLF), first pole to clear factor, Transformer Secondary Fault (TSF), Transformer Fed Fault (TFF), amplitude factor, field measurements, Rate of Rise of Recovery Voltage (RRRV), Sweep Frequency Response Analysis (SFRA)

1. Introduction

Hydro-Quebec has recently started some investigations on the TRV stresses for CBs involved in transformer switching. The investigations were based on the transformer's natural oscillating frequencies deducted from IEEE std. C37.011 (figure B.1) [1] which gives a rough idea of the transformer frequencies involved with respect to the voltage levels and the short-circuit current values for faults occurring on the secondary windings. Horton and al. reported in [2] that the TRV frequencies obtained from field measurements on many 230 kV autotransformers were found higher than the ones given by [1], thus giving steeper TRV slopes for Transformer Limited Faults (TLF) than the ones expected from transformer data given by [1]. Other methods using Sweep Frequency Response Analysis (SFRA) have been used to calculate the TRV stresses for TLF [3, 4, and 7]. TRV values for definite purpose CBs such as transformer limited fault interruption are also defined in [5] with generally much higher TRV values than those defined in applicable international CB standards for T30 and T10 test duties.

Before introducing some new TRV requirements during its qualifying process for circuit breakers, Hydro-Quebec performed some field measurements on two transformers in two different substations to assess the values of TRV stresses in comparison with the different methods mentioned earlier. The aim is to validate a method to calculate the TRV stresses using an appropriate transformer model to further avoid specific TRV requirements or to avoid using mitigation methods - such as installing damping capacitors - for coping with high TRV slopes. From a utility standpoint, having a proven method for assessing TRV stresses for TLF duty is indispensable to avoid unnecessary investments for mitigation means and/or to make sure the circuit breakers in place can reliably cope with this type of TRV.

2. Field measurements

The test arrangement was mainly composed of a programmable power source and a fast recovery diode combined with auxiliary switches controlled by a zero-crossing detector. A high speed data acquisition system was used to record the TRV waveforms. Figure 1 presents the details of the test setup.

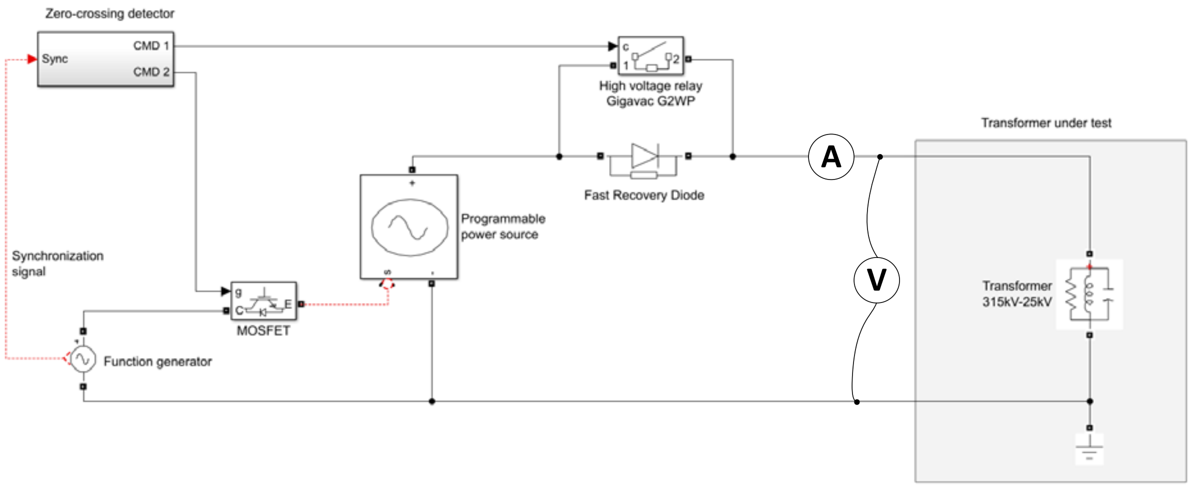

Figure 1 : Schematic of the TRV test setup

The TRV results obtained on the low-voltage winding (TFF faults) are shown in figure 2 for both Bélanger transformer (100 MVA) and De Lorimier transformer (140 MVA).

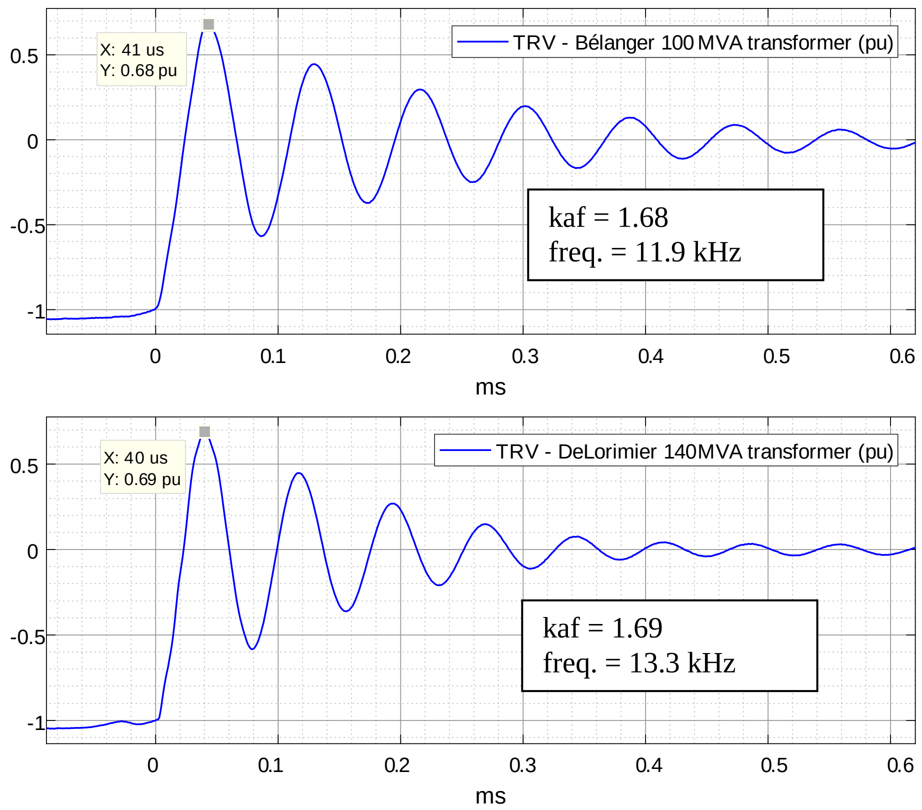

Figure 2 : Transformer-fed fault TRV measurements

The figure 3 shows the TRV results in case of transformer-secondary fault. These measurements were obtained on the high-voltage winding of both transformers.

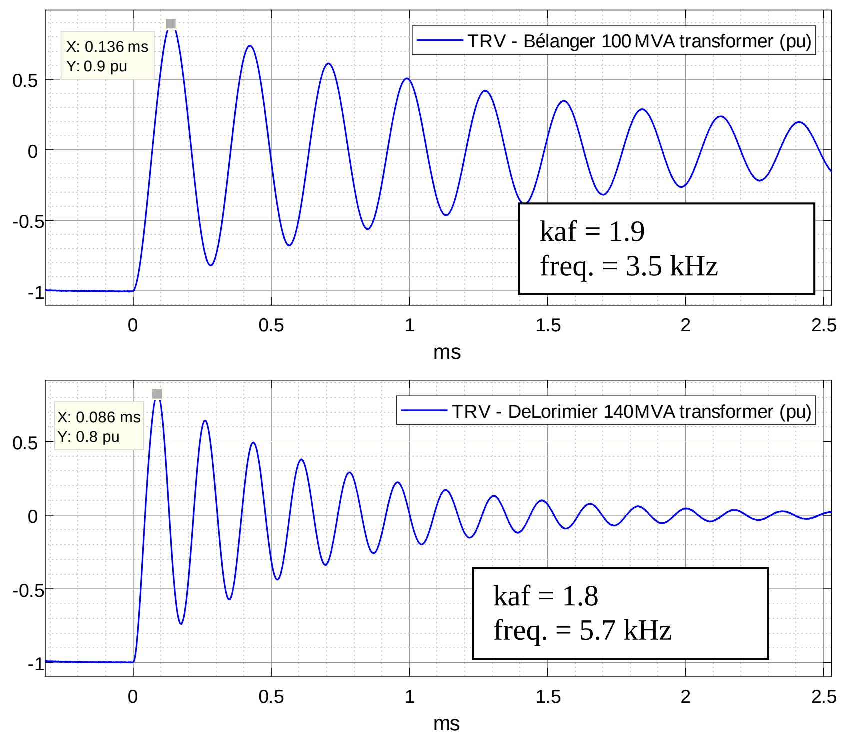

Figure 3: Transformer-secondary fault TRV measurements

3. TRV calculation methods

TRVs for two power transformers 315-25 kV (Bélanger and De Lorimier substations) whose characteristics are presented in Table 1, were calculated with the different methods listed below.

Table 1 : Transformer characteristics

	Winding voltages	Power (MVA)	connections	Direct Impedance (%)	Tap changer
Bélanger	315/26.4	100	Y-Δ	27,9	8 * 1.75% of 315 kV
De Lorimier	315/26.4	140	Y-Δ	27,3	10 * 1.7 % of 315 kV

3.1 From extracted data of C37.011 [1], figure B.1

From C37.011, figure B.1 (90^{th} percentile values), we obtain natural oscillating frequencies of 3.9/4.8 kHz and approximately 50/60 kHz from primary and secondary windings for Bélanger and De Lorimier transformers respectively. Exactness of the values extracted from figure B.1 in the region of the curve covering the secondary side at 26.4 kV is not so clear-cut, thus giving only a rough estimation of the frequencies involved on the secondary side of the transformers.

Table 2 : frequencies deducted from figure B.1 of C37.011 (90^{th} percentile) for both transformers under study

From C37.011 2019		Bélanger/De Lorimier
Fault current (kA)	primary	0.67/0.94
	secondary	7.8/11.2
Frequencies (kHz)	primary	3.9/4.8
	secondary	50/60

Given the mentioned frequencies in Table 2, RLC calculated values (first pole only) for De Lorimier and Bélanger transformers are presented in Table 3. TRVs characteristics were calculated using simplified RLC transformer models based on these RLC values (R values are obtained by comparing the measured TRV damping with the simulation results).

Table 3 : RLC values deducted from C37.011

	Bélanger			De Lorimier		
	R (kΩ)	L (mH)	C (pF)	R (kΩ)	L (mH)	C (pF)
primary	120	734	2 270	163	513	2 140
secondary	10		19.8	7		13.7

3.2 From SFRA measurements

As mentioned earlier, SFRA measurements was only used for primary side TRVs calculation due to improper measurements connections for this duty on the secondary side.
From SFRA measurements, Table 4 shows the RLC values for the simplified transformer models as explained in [4, 6].

Table 4 : RLC values deducted from SFRA

	Bélanger			De Lorimier		
	R (kΩ)	L (mH)	C (pF)	R (kΩ)	L (mH)	C (pF)
primary	120	734	2050	163	513	1372
secondary	-		-	-		-

3.3 From transformer models provided by manufacturers

EMT frequency models for both transformers of Table 1 were provided by the manufacturer. The model consists of three columns, one for each phase which essentially represents the auto and mutual electrical parameters (inductance, capacitance and resistance) of each physical coil of the transformer.

In fact, each coil has been segmented into 4 serially connected segments. This model is then assembled to form the tri-phased transformer in an YNd1 connexion.

3.4 From capacitance measurements during insulation tests

As reported by Horton & al. [2], simplified models using capacitance measurements during insulation tests are used to evaluate the TRVs for TLF conditions. Horton suggests to use 40% of the capacitance values measured at 60 Hz to represent the equivalent capacitance for higher frequencies involved for TRV evaluations.

4. Transformer models

4.1 Simplified RLC models

Either from extracted data of C37.011, SFRA measurements or by capacitance measurements during insulation tests, a simplified RLC model as shown in fig. 4 is used to simulate the TRV stresses for TLF type faults. Both transformers are two-windings transformers and only the first oscillating pole is represented by the simplified RLC models.

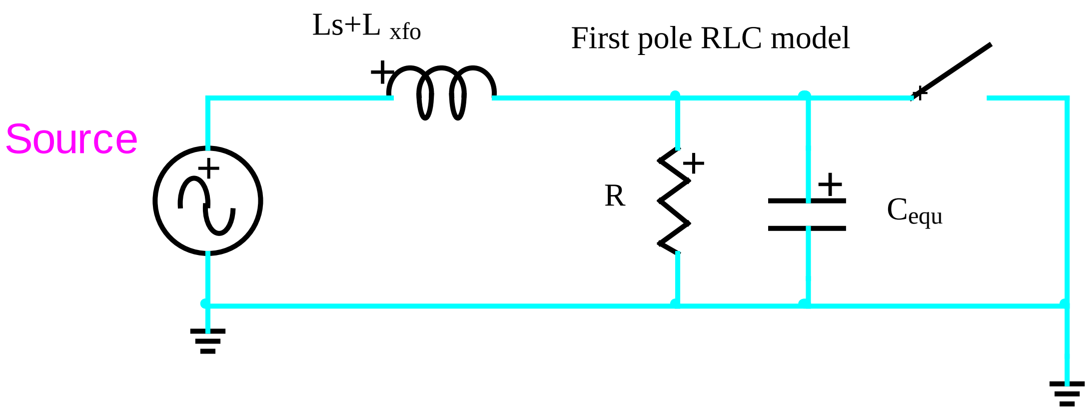

Figure 3 : simplified RLC model

4.2 Frequency model from manufacturers (same manufacturer for both transformers)

Manufacturer provided some EMT frequency model (grey box models) for both transformers. Results of frequency scan for both transformers are presented in figures 5 and 6.

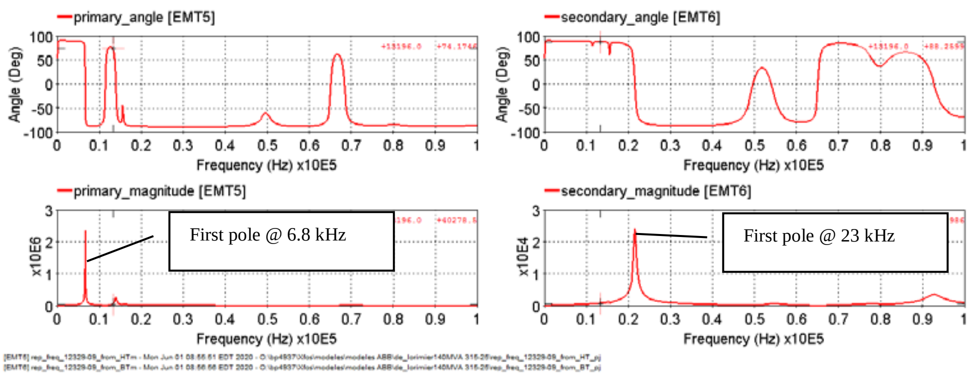

Figure 4 : frequency response from manufacturer model for De Lorimier transformer

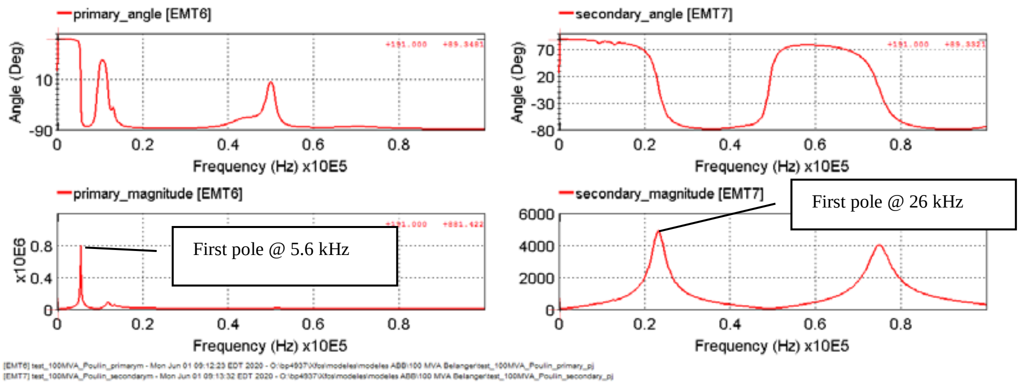

Figure 5 : frequency response from manufacturer model for Bélanger transformer

5. Comparison of TRV results with different methods and field measurements

In order to compare the simulation results using different transformer models with on-site measurements, every element between the transformer and the CB is carefully considered and represented in the simulations. The capacitances of the considered elements are presented in Table 5. However, measurements for De Lorimier transformer were performed with the transformer completely disconnected from the network (primary and secondary), no capacitive elements were then considered for this case; making comparison with manufacturer's model for De Lorimier case more accurate given the fact that no capacitive elements intervene in the measured values. Table 6 give the TRV frequencies for every method considered in the study.

Table 5: capacitance (C_{add}) between the transformer and the CB (pF)

	Busbar (min/max)	CT and PT	Grounding bank	Disconnect and grounding switch	insulators	Surge arrester	CB	Total (pF)
secondary								
De Lorimier	No capacitive elements for TRV measurements (only transformer)							
Bélanger	2019/3 209	286	3700	26	32/48	84	24	6171/7277
primary								
De Lorimier	No capacitive elements for TRV measurements (only transformer)							
Bélanger	1103/1 583	434	-	-	-	-	-	1537/2017

Table 6 : TRVs frequencies (1st pole) vs method considered *

	From primary		From secondary	
	Bélanger	De Lorimier	Bélanger	De Lorimier
RLC from C37.011	3.8/2.9	4.8/3.5	50/12.1	60/22.7
Manufacturer models	5.6/3.5	6.8/4.4	-/14.7	23.0/17.7
RLC from capacitance measurements (40%)	4.0/2.9	5.2/3.6	25.0/12.2	29.4/15.6
RLC from SFRA	4.1/2.9	6.0/3.9	-	-
Measurements	3.5	5.7	11.9	13.3
RLC from C37.011	3.8/2.9	4.8/3.5	50/12.1	60/22.7

* values without C_{add} / with C_{add}

Tables 7 and 8 present the results of TRV stresses with the different methods used for the study. TRVs are evaluated for three-phase grounded fault for the first pole to clear in each case. Results considering added surge capacitance indicated in Table 5/and without added capacitance are given in Table 7 and 8.

Table 7 : summary of TRV results from different methods on secondary side *

Method	TRV peak value (kV)		RRRV (kV/µs)	
	Bélanger	De Lorimier	Bélanger	De Lorimier
RLC from C37.011	59.8/59.5	57	4.1/2.0	-/3.6
Manufacturer models	45.2	46.1/49.1	-/1.8	2.7/2.3
RLC from capacitance measurements (40%)	58.1/59.5	59.1/59.6	4.0/2.0	4.9/2.5
RLC from SFRA	-	-	-	-
Measurements**	52.4/-	-/52.3	1.4/-	-/1.77
ANSI C37.06.1 (Table 1B, row 11)	58		5.27	
IEC 62271-100 (T30) S1/S2	50.6/55		2.57/3.04	

Table 8 : summary of TRV results from different methods on primary side*

Method	TRV peak value (kV)		RRRV (kV/µs)	
	Bélanger	De Lorimier	Bélanger	De Lorimier
RLC from C37.011	630/640	588/597	7.0/5.0	7.8/5.8
Manufacturer models	433/488	450/483	7.1/4.8	8.5/5.6
RLC from capacitance measurements (40%)	629/639	587/596	7.0/5.1	7.9/6.0
RLC from SFRA	600/616	579/593	7.0/5.2	9.5/6.6
Measurements**	637	578	6.0	8.9
ANSI C37.06.1 (Table 3, row 13)	718		16.0	
IEC 62271-100 (T10)	678		7.0	

* values without C_{add} / with C_{add}

** Measurements for DeLorimier transformer was achieved directly at the transformer without any surge capacitance. For Bélanger transformer, the measured values considered the capacitance indicated in Table 5.

6. Conclusions

For the secondary side CBs, the measured peak values of TRV slightly exceed the standardized values from IEC 62271-100 for T30 duty for S1 class. The values obtained by simulations are higher than the measured values except for the case with the manufacturer's model. The measured values for rate of rise of recovery voltage are in all cases lower than the values obtained by simulations.

For the primary side CBs, measurements of TRV stresses for both transformers confirmed high values exceeding in some cases the values given by the applicable Circuit Breaker standards for T10 test duty. This is particularly the case the De Lorimier transformer when interrupting a fault on the secondary side without considering any surge capacitance between the transformer and the circuit breaker (C_{add}). The measured TRV peak values are in all cases very close to the TRVs obtained by simulations except for the case with the manufacturer's models which are approximately 16% and 32% lower than the measured values for De Lorimier and Bélanger transformer respectively. The measured values for rate of rise of recovery voltage (RRRV) is generally higher than the values obtained by simulations. When a minimum surge capacitance (C_{add} given in Table 5) is considered, the RRRV and the TRV peak values do not exceed the standardized values from IEC 62271-100 for T10 duty.

ANSI C37.06.1 largely covers the TLF measurements for the secondary and primary side circuit breakers.

For a two-winding transformer such as DeLorimier and Bélanger, simulations results with the simplified RLC transformer model obtained from capacitance measurements during transformer insulation tests gives the closest results with the measured values. Some further investigations for a three-winding or autotransformer would be necessary to conclude on the TRV stresses for these cases. Steurer and al. reported in [7] that for autotransformers and three-winding transformers, a single frequency approach may not be appropriate since the autotransformer or three-winding transformer show more than one significant resonant frequency.

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