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Modelling Autotransformers for TRV studies- Lessons learned

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SUMMARY

In this paper, the impact of autotransformer modelling to determine Transient Recovery Voltages (TRV) is investigated through simulation studies of a Gas Insulated Substation (GIS) located in New York. TRV is the voltage difference that appears across the terminals of circuit breakers during fault current interruptions. TRVs are characterized by their peak value and Rate-of-Rise of Recovery Voltage (RRRV) across the breaker terminals which are highly impacted by the system parameters like the effective stray capacitance of the equipment.
One of the most severe TRV conditions occur when circuit breakers clear faults that happen immediately after a transformer, named Transformer Limited Fault (TLF), where RRRV may exceed the standard permissible constraints. To study TLFs, the transformer and its stray capacitances to earth should be accurately modelled. Transformer's frequency-dependent models provide highly accurate response over a wide range of frequencies; however, these models are obtained from the transformer Frequency Response Analysis (FRA) which is not available in most cases. The transformer impedance model with stray capacitances (second-order model) is a simplified model that is commonly used for TRV simulations. IEEE Std. C37.011 provides an estimation methodology to obtain typical stray capacitance of a transformer. The typical stray capacitance values provided for transformers in IEEE Std. C37.011 are based on experimental tests on transformers of various ratings conducted in early 1970s and widely used in TRV studies. However, some research work has demonstrated that the IEEE methodology could be inaccurate especially for autotransformers. In fact, the values are from old transformer designs and only a few autotransformers were included in the test set. EPRI has developed an improved methodology to estimate the stray capacitance of the autotransformers using the measured capacitances during insulation integrity tests which are commonly available in transformer test reports. This paper reports the lessons learned from TRV studies on the breakers connected to a three-winding 345/138/13.8 kV autotransformer in a GIS. The autotransformer was initially modelled based on IEEE Std. C37.011 which led to marginal RRRVs below the limits for the transformer limited faults. To confirm that no mitigation is required, the improved EPRI autotransformer model was deployed which led to violation of RRRV limits in some cases. Based on the study results, addition of a 2000 pF capacitor at the gas-to-air bushing of the GIS was proposed to the GIS manufacturer to mitigate the high RRRVs associated with TLFs in this substation. Detailed models of the GIS and the grid connected to it were developed in PSCAD/EMTDC. The comparison studies show that accurate modelling of the autotransformer especially when RRRV is close to the standard constraints can alter the corrective measures to be taken in the substation design.

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KEYWORDS

Autotransformer, Gas Insulated Substation, Stray Capacitance, Transient Recover Voltage (TRV), Transformer Limited Faults(TLF)

1. Introduction

Transient recovery voltage (TRV) is the voltage that appears across the terminals of a pole of a circuit breaker immediately after current interruption. In power grids, the TRV is the difference in the power system response voltages on each side (source side and load side) of the circuit breaker [1-2]. Longitudinal insulation breakdown occurs if the system TRV reaches the voltage withstand limit of the gap between the breaker contacts, which lead to reignition and restrike. The TRV level and the Rate of Rise of Recovery Voltage (RRRV) are the key factors in determining whether the fault can be cleared successfully. These characteristics are highly impacted by the nature of the circuits and elements connected to the breakers.

Transformer Limited Fault (TLF) is a condition where the fault current is fed or limited by a transformer without any transmission lines or cables connected in parallel with the transformer. Interruption of TFLs could generate severe TRVs and RRRVs [3].

As the TRVs are characterized by a high frequency content, the stray capacitances of the equipment surrounding the breaker play an important role in determination of TRVs. To study TRVs resulting from interrupting TLFs, it is paramount to model the transformers accurately. Several transformer models have been introduced in the literature for TRV studies, e.g., second-order impedance models and frequency dependent models [4]. Frequency dependent models are the most accurate models, but the transformer Frequency Response Analysis (FRA) is required to parametrize these models. FRA data is not readily available in most cases. IEEE Standard C37.011 [1] provides a method to estimate the effective capacitance of a transformers based on the transformer nameplate ratings and impedance values. However, this method has been proven to be inaccurate especially in case of autotransformers [5]. Therefore, a new autotransformer model for TRV studies has been proposed in [5]. The model represents the multifrequency behaviour of an autotransformer. The accuracy of the model was verified using FRA data obtained from factory tests.

This paper reports the lessons learned from TRV studies of a Gas Insulated Substation in New York. It is demonstrated that selection of an accurate model for the autotransformer can change the TRV study results. The autotransformer model proposed in [5] is used for the studies in this paper. The detailed model of the GIS and its surrounding power system, including a three-winding 345/138/13.8 kV autotransformer is developed in PSCAD. The autotransformer is modelled by the IEEE method provided in [1], and the proposed improved model in [5]. It is observed that IEEE results does not lead to conservative TRV simulation results.

2. Transient Recover Voltage (TRV)

When a circuit breaker is clearing a fault, voltage appears across the terminals of each pole during and after interruption. This voltage consists of an interval during which a transient recovery voltage (TRV) exists which is the difference in the system voltage responses at the two sides of the breaker poles. TRV is followed by an interval during which a power frequency voltage alone exists. The breaking operation is deemed successful if the circuit breaker is able to interrupt the fault current and is also able to withstand the TRV and the power frequency recovery voltage.

TRV waveshapes can be oscillatory, triangular, exponential, or a combination of them depending on the circuit being interrupted and the lumped and distributed elements. In fact, TRV is the point-by-point voltage difference of the load side and source side of the circuit breaker. The most severe oscillatory or exponential recovery voltages tend to occur across the

first pole to clear of a circuit breaker interrupting a three-phase symmetrical fault at its terminal when the system voltage is maximum [1].
The TRV capability of circuit breakers vary with the breaker voltage rating and short circuit current interrupting level. Normally, the circuit breaker TRV capabilities at 10%, 30%, 60%, and 100% of rated short-circuit interrupting current, corresponding to terminal fault test duties T10, T30, T60, and T100, are given usually given in standards [2-3].

3. Transformer Limited Faults

Transformer Limited Fault (TLF) is a condition where the fault current is fed or limited by a transformer without any transmission lines or cables connected in parallel with the transformer. Two states might occur for circuit breaker as shown in Figure 1.

Figure 1: Transformer Limited Faults [1]

As shown in Figure 1, the fault and the circuit breaker can be at the same voltage level (Transformer Fed Fault) or different voltage levels (Transformer Secondary Fault). In such cases, the interrupting current is limited by the transformer impedance, and short circuit current levels are much lower than the circuit breaker rated short circuit current. However, both the peak voltage and RRRV voltage may exceed the TRV capability limits specified in [3-4]. In fact, close placement of the transformer and the circuit breaker and the low stray capacitances in these configurations lead to high frequencies dominated by natural frequency of the transformer which is determined by the surge capacitance and leakage inductance of the transformer. Therefore, it is important to model the transformers as accurately as possible for TLF studies.

4. Transformer Models in TRV Studies

The TRVs resulted from the interruption of a TLF are generally characterized by a single frequency transient and typically modelled using the second-order equivalent circuit. The simplified models including the transformer leakage inductance and stray capacitance of different elements like transformer, bus work, and instrument transformers are widely used in TRV studies. The transformer surge capacitance is the dominant portion of effective stray capacitance of the system. In IEEE Standard C37.011, the 50th and 90th percentile frequencies versus fault current for system voltages from 15 kV to 800 kV are shown as a set of curves, Figures B.1 and B.2. It is recommended to use these graphs to estimate TRV frequencies of transformer-limited faults and to calculate the effective capacitances from those frequencies when required [1]. However, this data has been obtained based on the research and tests in early 1970 on a limited number of transformers. Testing of several autotransformers in the BPA system has shown that simplified models may not be valid for TRV studies because multiple resonant frequencies were found in some tests [5].
The model parameters can also be derived from Frequency Response Analysis (FRA). FRA tests covers a wide range of frequencies, so these models are suggested to be used for TRV studies [4]. However, these models are generally L-C multi-mesh circuits composed of a large number of elements and calculation of the element values is not straightforward. In addition, FRA data is not readily available for model parametrization. In [5], an improved multi-

frequency model has been developed for autotransformers. The FRA data is not required to develop this model and the parameters are calculated using the transformer impedance data and measured capacitance during insulation tests.

5. Improved Autotransformer model

The improved model proposed in [5] for a three-wining autotransformer is shown in Figure 2.

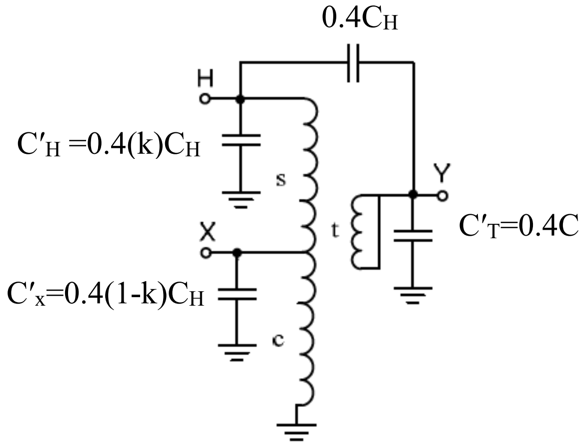

Figure 2: Autotransformer model for TLF studies [5]

Where $K=(V_H-V_X)/V_H$.

This method uses the measured capacitances during transformer insulation tests which is readily available in transformer test reports. The following capacitances are measured during the tests:

1. C_H the total capacitance to ground of the common and series winding
2. C_{HT} the total capacitance between the common and series winding and the tertiary winding
3. C_T the capacitance to ground of the tertiary winding to ground

CH is split between series and common windings properly as shown in Figure 2. In addition, due to the complexity of the relationships between the stray capacitance-to ground, the internal winding capacitance, and leakage inductance, the terminal response of the transformer cannot be determined accurately using parameters measured at nominal frequency. Typically, the apparent capacitance for lower order transformer models used in TRV studies is assumed to be 40% of the value obtained during power frequency insulation integrity tests [5]. Therefore, all measured capacitance values are scaled by a factor of 0.4.

6. **Simulation Studies**

The TRV studies are performed on a Gas Insulated Substation located in New York. The GIS consists of a four-element ring bus configuration connected to two 345kV lines as shown in Figure 3. The 420 kV GIS switchgear connects to a 138 kV yard through one 345/138/13.2 kV, 268.8/358.4/448 MVA autotransformer.

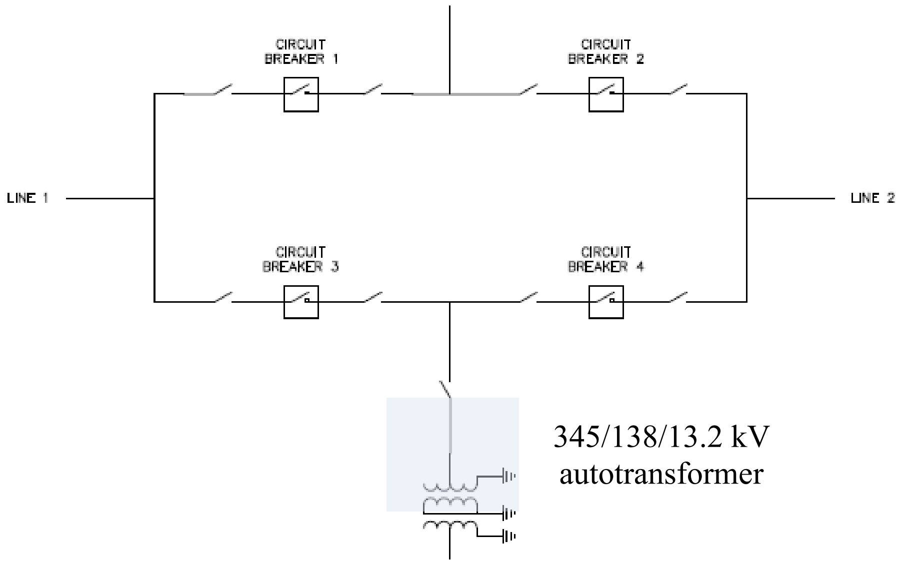

Figure 3: GIS Schematic

For TRV studies, the GIS and the power grid connected to it is modelled in PSCAD. The GIS elements, i.e., bus ducts, ground switches, voltage and current transformers are modelled with the distributed parameters obtained from the GIS manufacturer. The effective capacitance of air insulated apparatuses like Sectionalizers, surge arresters, capacitive voltage transformers and line traps are also modelled. Frequency dependent models are used to present the overhead transmission lines up to two buses away from the GIS.
The effective capacitance of 345/138/13.2 kV autotransformer was initially approximated by the method provided in [1] (curves B.1 and B.2) and added as a lumped capacitor at primary winding.

For the transformer limited faults at the 138 kV side of the autotransformer, the circuit breakers 3 and 4 will interrupt the fault current. When either circuit breakers 3 or 4 is out of service and TLF current is interrupted by the in-service circuit breaker RRRV is high yet within the 10% fault duty (10T) TRV capability limits.

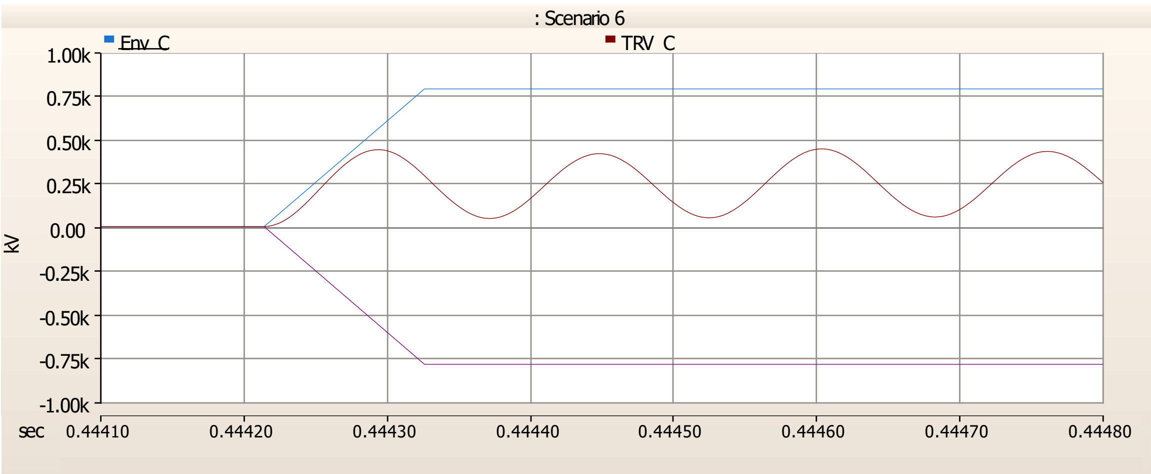

Figure 4 : TRV of circuit breaker 3 during interruption of a Transformer Limited Fault (IEEE Std. C37.011 transformer model). No violation of T10 capability curve

Figure 4 demonstrates TRV of circuit breaker 3 when it clears a three-phase-to-ground fault on the 138 kV side of the autotransformer and circuit breaker 4 is out of service. The

marginal TRV results and the significant impact of transformer model in TLF studies, motivated the authors to investigate for more accurate validated transformers models to confirm the results.
The model proposed in [5] were used, and the stray capacitances of the autotransformer were calculated as shown in Figure 2.
For 345/138/13.2 kV autotransformer used in the project, the measured capacitances during insulation tests are provided by the manufacturer in the transformer test report as listed in Table 1.

Table 1: Effective Capacitance of the Autotransformer Windings

Measured capacitance	Measured capacitance (pF/phase)	Calculated capacitance	(pF/phase)
C_H	5539.8	C'_H	1329.36
		C_x	886
C_{HT}	7429.4	C'_{HT}	2,971.76
C_T	6783	C'_T	2713.2

The simulation study is performed with the updated autotransformer model. The results are shown in Figure 5.

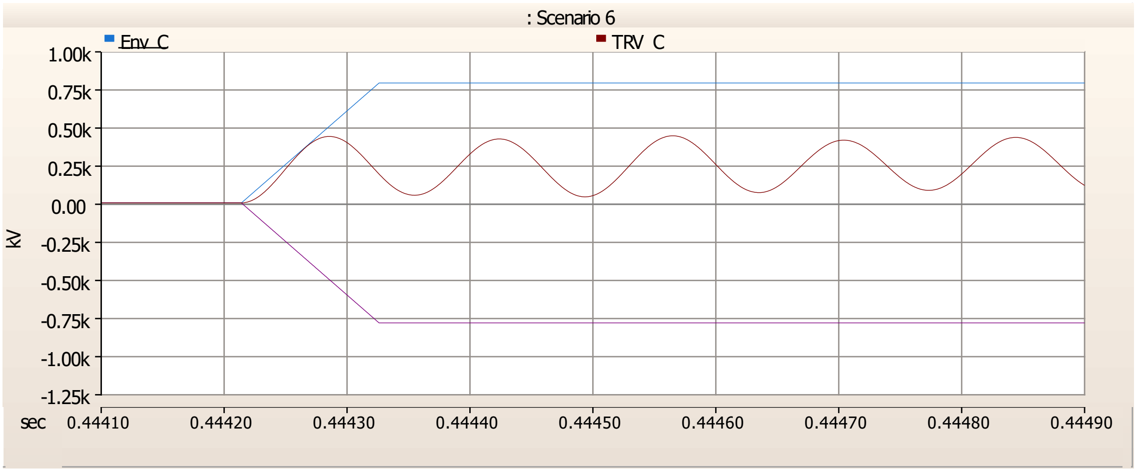

Figure5 : TRV of circuit breaker 3 during interruption of a Transformer Limited Fault (improved autotransformer model [5]). RRRV violation of T10 capability curve

The TRV results with the improved autotransformer model show a violation of the RRRV for TLF faults. The results were discussed with the GIS manufacturer and a 2000pf capacitor was added to the Gas-to-Air bushings of the GIS.

7. Conclusion

This paper investigates the importance of accurate modelling of autotransformers for Transient Voltage Recovery (TRV) studies especially when circuit breakers are interrupting Transformer Limited Faults (TLFs). Stary capacitance of the transformer is a key factor in accuracy of the transformer model for TLF studies. Two methods to calculate the stray capacitance of the transformers are compared:

1- IEEE Standard C37.011: Empirical TRV frequencies for transformer secondary faults are provided based on the transformer impedance and voltage level. The effective capacitance of the transformer can be calculated from the provided data.

2- Improved autotransformer model [5]: the model uses the measured capacitance values during insulation tests to estimate the windings capacitances.

The models are used for TRV studies of a 420 kV GIS project in New York. The project has a 345/138/13.2 kV autotransformer and faults that occur at the 138 kV side (transformer limited faults) are cleared by the operation of a 420 kV circuit breaker of the GIS which results in high RRRVs. The system is modelled in detail in PSCAD. The autotransformer is modelled based on the abovementioned methods. It is observed that IEEE Standard C37.011 model results in less sever RRRVs when compared to the improved model. Since underestimating TRVs can lead to catastrophic events and damage to equipment, it is proposed to deploy more accurate transformer models like the autotransformer model proposed in [5]. This model can be easily developed based on the available data in the transformers test report and its accuracy has been proved in [5]. Based on the results of these studies, the GIS manufacturer was convinced to add TRV capacitors at the gas-to-air bushings to reduce the risk of TRVs.

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